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Comparative Review of a Force Based and Direct Displacement Based Design of Base Isolated Systems

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Abstract*—Earthquakes are potentially devastating natural events that threatens lives, destroy property, and disrupt life-sustaining services and societal functions. Many methods have been proposed for mitigating the harmful effects of strong earthquakes. The conventional approach requires that the structures passively resist earthquakes through a combination of strength, deformability and energy absorption. In situations where the building should remain functional even after an earthquake, such as a hospital building, this approach is not practical. An alternate approach involves the inclusion of supplementary energy dissipation devices at the base or in the frame of the stricture. In this paper, the requirements and various methods of isolation techniques are discussed. Force Based Design (FBD) and Direct Displacement Based Design (DDBD) is reviewed. The steps involved in the design of both the methods are provided.

***Index Terms*—Force Based Design, Direct Displacement Design, Base Isolated Structure, Comparative FBD and DDBD.**

I. INTRODUCTION

In conventional structures, the level of damping is very low and hence the amount of energy dissipated through elastic behavior is very low. During strong earthquakes, these structures deform well beyond the elastic limits and remain intact due to their ability to deform inelastically. The inelastic deformation takes the form of localized plastic hinges which results in increased flexibility and energy dissipation. Therefore much of the energy is absorbed by the structure through localized damage of the lateral force resisting system.The Basic Principle of Seismic Base Isolation is to increase the Structure's Natural Time Period leading to decrease in its Natural Frequency of Vibration to that of its corresponding fixed based structures and that of the predominant period of soil at the site too.Conceptually, isolation reduces response of the superstructure by “decoupling” the building from the ground. Typical isolation systems reduce forces transmitted to the superstructure by lengthening the period of the building and adding some amount of damping.Decrease in frequency of vibration also decreases the pseudo-acceleration of structures thereby reducing the base shears.

II. BRIEF HISTORY

Frank Lloyd Wright was the first person to implement the idea of base isolation, by applying it to the foundation design for the Imperial Hotel in Tokyo. It was one of the few Western style buildings that survived the devastating Tokyo earthquake in 1923. The flexible first storey approach was another early approach to structural isolation of building proposed by Martel in 1929. However in later studies the concept was shown to be impractical. Rubber was first used for earthquake protection in 1969 in a school building in Yugoslavia. The weight of the building caused the rubber to bulge sideways. Because the rubber is of same stiffness in all directions, the building bounces and rocks backwards and forwards. Later these bearings were reinforced with steel plates to overcome these difficulties.

Modern base isolated structures are supported by horizontally flexible but vertically rigid bearings interposed between the base of the structure and its foundation. These bearings are known as isolation device or an isolator system. It was shown by Derhamet *al*[1] in 1985 that a building on rubber bearings will be protected simultaneously from unwanted vibration and from earthquake attack.

Researches by Skinner led to a number of isolation concepts in which earthquake resistance of buildings can be increased by the mechanism of special components which act as hysteretic dampers. During moderately severe earthquakes, these dampers can act as stiff members which reduce the structural deformations; while during very severe earthquakes, these dampers act as energy absorbers which limit the quasi-resonant build-up of structural deformations and forces. Later researches have helped in the development of many types of isolation systems like Roll-in-cage isolator, recentering type isolation systems, hybrid dampers etc.

III. BASIC REQUIREMENTS OF A BASE ISOLATION SYSTEM

The basic requirements that a good isolation system should satisfy can be summarized as follows.

1. The bearing must support the dead load of the structure and must have high vertical stiffness.
2. The horizontal stiffness of the bearing must be such as to confer on mounted structure a low horizontal natural frequency so that the building will not

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respond to the destructive components of the ground motion. From the response spectra from previous researches, it is clear that under a wide range of conditions, a horizontal natural frequency of 0.5 Hz is suitable.

3. Some earthquake energy will always occur at or near the horizontal natural frequency, the system must contain sufficient damping to limit translational movement to an acceptable level.

IV. METHODS OF BASE ISOLATION

A. The isolators can be classified as (i) Elastomeric Bearings (ii) Isolation system based on sliding (iii) Dampers

B. Elastomeric Bearing

Natural Synthetic Bearings (NRB): The internal structure of an elastomeric bearing consists of a sandwich of mild steel shims and rubber molded as one unit. Elastomeric bearing pads compress on vertical load and accommodate horizontal rotation and provide lateral shear movement. Natural Synthetic Rubber Bearings are made of alternating elastomeric layers that are made of natural rubber or neoprene and steel shims vulcanized or glued together. The elastomeric layers provide lateral flexibility and elastic restoring force. The steel plates reinforce the bearing by providing vertical load capacity and preventing lateral bulge. A rubber cover protects the ensemble. Mounting plates connect the device to the structure above and below.

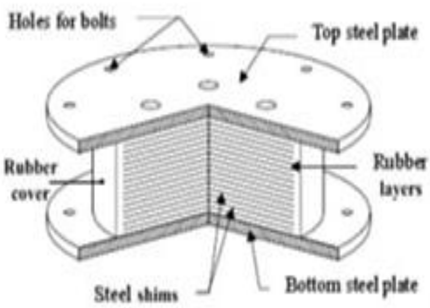

Fig 1 Natural Rubber Bearing

Lead Rubber Bearings (LRB): Plain elastomeric bearing provides flexibility but not significant damping and they tend to move against service loads. LRB overcomes this deficit. They are similar to the NRB, but contain a lead core force fitted into a preformed hole in an elastomeric bearing. The lead core provides rigidity under service loads and energy dissipation under high lateral loads. Top and bottom steel plates thicker than the internal shims are used to accommodate mounting hardware. The entire bearing is encased in cover rubber to protect from the environment. When subjected to low lateral force the lead rubber bearing is stiff both horizontally and vertically.

Fig 2 Lead Rubber Bearing

C. Friction Pendulum Bearing

In this system, the weight of the structure is supported on a spherical sliding surface that slide relative to each other. Current devices are mainly based on friction between stainless steel and Teflon. Depending on their sliding surface geometry, two kinds of sliding bearings are distinguished: Flat Slider Bearings and Curved Slider Bearings. Flat slider bearings does not have recentering capacity and hence may have residual displacements after major earthquake. Hence they need to be provided with supplementary recentering devices. On the other hand, in a curved slider bearing, the potential energy stored by the superstructure which has been pushed to top automatically results in recentering the bearing into neutral position.

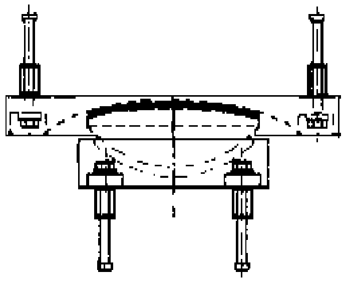

Fig 3 a. Flat slider bearing.

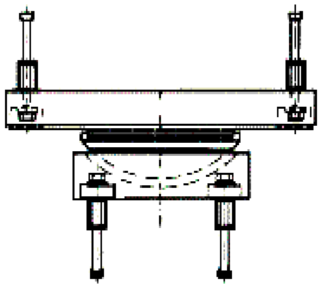

Fig 3b. Curved slider bearing

D. Damping Devices

Buckling Restrained Brace (BRB): The main characteristic of a BRB is its ability to yield both in compression and tension without buckling. It consists of a slender steel core, a concrete casing designed to continuously support the core and prevent buckling under axial compression, and an interface region that prevents undesired interactions between the two.

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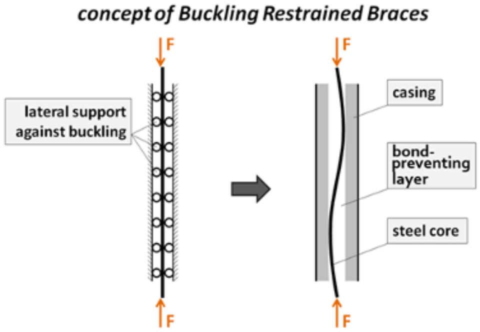

Fig 4 Buckling Restrained Braces

Fluid Dampers: It consists of a closed cylinder with a viscous fluid inside. When input force moves the piston rods, the fluid volume is reduced. It causes a heating of the damper's fluid and mechanical parts, and this heat energy is harmlessly transferred to the environment. When the input force tries to move the piston rods, the fluid volume is reduced. This reduction in fluid volume is accompanied by the development of a restoring force.

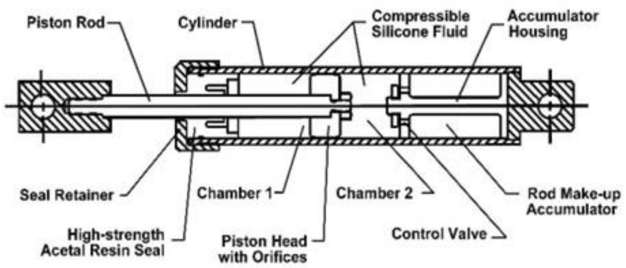

Fig 5 Schematic Fluid Damper

Visco Elastic Dampers: The dampers dissipate part of the total incoming energy from the ground motion, reducing the dynamic response of the structure when it is compared with a building constructed without these devices. Visco Elastic dampers are constructed from co-polymers and they dissipate energy through deformation of the damper.

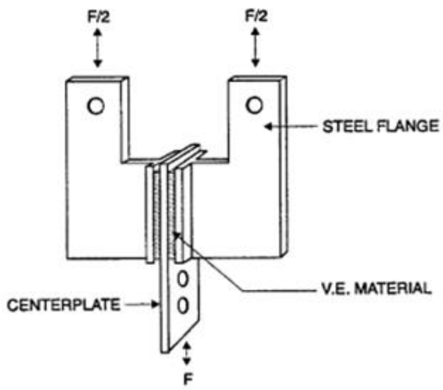

Fig 6 Visco Elastic Damper

Friction Dampers: In this system, the bracing system and the frictional forces developed between the frictional surfaces of steel plates and friction pad materials will resist the horizontal motion. When the frame structure is moved to the left the left damper is lengthened while the right damper is shortened and both dampers dissipate energy and vice versa.

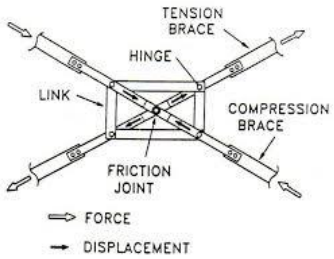

Fig 7 Components of a Friction Damper.

V. LITERATURE REVIEW

C.J. Derham, J.M. Kelly and A.G. Thomas (1985) [4] investigated the vertical and horizontal accelerations in 1/24th model of a containment structure by carrying out SIMQUAKE II (explosive experiment to study earthquake like ground motion) test program. No damage was evident for a displacement up to 38 cm which represents a shear strain of 125%. The horizontal and vertical stiffness of the bearings as tested were found to be exactly the same as the rubber from which they were fabricated. The damping depended upon the frequency of the test.Young J. Park, Andrei M. Reinhorn and Sashi K. Kunnath in 1989 [39] derived a formula for measuring the seismic damage of each component as well as storey level damage using a Damage Index, based on the linear combination of maximum deformation ratio and energy dissipation during cycle loading. The proposed technique implies identification of component properties by micro modelling or testing, integration of component properties to macro-models with dynamic characteristics, step-by-step inelastic response analysis of macro models and quantitative assessment of damage using a combined energy and ductility based index. In the same year Rafeal Riddell, Pedro Hidalgo and E. Cruz[30]studied the elastic and inelastic response spectra for various sets of earthquake records to study the response reduction factor to account for the energy dissipation capacity of the structures. It has been shown that the response reduction factor is not constant for the whole range of periods, and that a simple model can be devised to represent its variation in the short period range. It was also shown that the use of a constant reduction factor is un-conservative for reduction factor values equal to or greater than 4 for structures with period less than 0.4 seconds.

A correction suitable for code formulation is proposed to obtain realistic inelastic design spectral values in the short period range. Later in 1991, Uang[5] derived the basic formulas for establishing the response modification factor R and the displacement amplification factor Cd used in the National Earthquake Hazards Reduction Program (NEHRP) recommended provisions.Inaudi and Kelly in 1993 [14] had defined a procedure for the optimum damping in linear isolation systems. Their studies revealed that the optimum damping presents the following characteristics under different dominant excitation frequencies: while stiff filters produce a decrease in the optimum damping, soft filters render high levels of optimum viscous damping. Miranda and Berteroin

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1994 [8] has confirmed the above study by the results from 30 years of site investigations. The evaluation of results indicate that the strength reductions are primarily influenced by the maximum tolerable displacement ductility demand, the period of the system and the soil condition at site.Calvi and Kingsley in 1995[9] presents a displacement-based seismic design procedure for MDOF structures, with example designs of regular and irregular bridges. The displacement-based design process offers several advantages over a force-based process, among them the ability to consider explicitly the displacement demand (i.e. damage) in each member rather than assigning a single, force-based global behaviour factor to the structure. Later in 1997, Masaru and Ian [23] proposed an analytical hysteresis model for elastomeric seismic isolation for the purpose of accurately predicting the response of seismic isolated structure.Good agreement between the experimental and analytical results shows that the model can be an effective numerical tool to predict not only the peak response value but also the force displacement relationship of the isolators and floor response spectra for isolated structures. In 1999, Simon Kim and Enzo D' Amore[32] has critically examined the fundamental assumptions on which the push over analysis procedures are based and the accuracy of the procedure has been assessed through a case study. The case study illustrated that the predictions of the distribution of damage in the structure during earthquakes between the push over analysis procedure and the time history analysis is not always in agreement. In spite of that, it has been concluded that push over analysis is more realistic than existing code procedure. During the same period, Whittaker, Gary Hart and Christopher Rojahn[37] has arrived at a draft formulation that represents the response modification factor as the product of factors related to reserve strength, ductility, and redundancy. The formulation splits R into factors related to reserve strength (Rs), ductility (Rm), and redundancy (RR). A year later in 2000, Medhekar and Kennedy[22] reviewed the conceptual basis of the spectral acceleration-based design method currently used in seismic codes and its limitations. An alternative method that uses displacements as the basis for the design procedure was presented by them. R.D. Bertero and V.V. Bertero in 2002 [31] discussed the main requirements that a reliable Performance Based Seismic Design (PBSD) should satisfy and presented a conceptual comprehensive numerical procedure for the PBSD of buildings.Oscar M. Ramirez, Michael, C. Constatinou, and Chriz Z. Chrysostomou[28]in the same year had undertaken studies to support the development of the 2000 NEHRP (National Earthquake Hazards Reduction Program) Provisions for the design of buildings with energy dissipation systems. The numerical simulations made use of 20 earthquake histories that were scaled to match on average the 2000 NEHRP spectrum for SDS=1.0 (Short Period), S1=0.6 (one Second Period), and Ts=0.6 second.Tysh Shang Jan (2002) [34] proposed in his study, a new simplified pushover analysis procedure, which considers higher mode effects. The basic features of the proposed procedure are: the response spectrum-based higher mode displacement contribution ratios, a new formula for determining the lateral load pattern and the upper-bound (absolute sum) modal combination rule for determining the target roof displacement.Y.Y. Lin, M.H. Tsai, J.S. Hwang and K.C. Chang in 2003 [38] presented a seismic displacement-based design method for new and regular buildings equipped with passive energy dissipation systems (EDS). Using the substitute structure approach for the building structure and simulating the mechanical properties of the passive energy dissipation devices (EDD) by the effective stiffness and effective viscous damping ratio, a rational linear iteration method was proposed.[33] T.J. Sullivan, G.M. Calvi and M.J.N. Priestly in 2004[33] has explored the basis and performance of initial stiffness and secant stiffness based DBD methods. The paper identifies various challenges associated with the application of both initial stiffness and secant stiffness based DBD methods and considers whether one form is more effective than the other.Bommer and Mendis (2005) [16] reasoned that direct displacement-based seismic design and assessment require input in the form of displacement response spectra over long period ranges (up to the product of the yield period and the square root of the ductility demand factor) and for a number of damping levels (up to about 30% of critical). Spectral displacements for long periods and high damping levels are also directly relevant to the design of bridges and buildings with base isolation and supplementary damping devices. In seismic design codes, the spectra for damping levels higher than 5% are obtained by applying scaling factors to the ordinates of the 5% damped spectrum. These factors have been shown to be weakly dependent on response period other than in those regions where the spectral displacements converge to zero or to Peak Ground Displacement. At intermediate response periods, the spectral scaling factors are currently defined only in terms of the damping ratio and there is significant disagreement amongst the proposed factors. Mehmet Inel and Hayri Baytan Ozmen (2006) [24] carried out a study to investigate the possible differences between push over analysis of default hinge and user defined hinge models. The observations showed that the user defined hinge model is better than the default hinge model in reflecting non-linear behavior compatible with element properties.Asgarian and Shokrgozarin 2009 [3] evaluated the overstrength, ductility and response modification factor of buckling restrained braced frames with various number of stories and type of bracing. The response modification factor decreased as the height of the building increased. In buckling restrained braced frames, the ductility of the building increased with height. Next year, D. Cardone, M. Dolce and G. Palmero (2010)[7] designed a procedure for Direct Displacement Based Design (DDBD) for buildings equipped with seismic isolation system. The key aspect for the proposed procedure is the definition of the target displacement profile for the structure. It is assigned by the designer in order to accomplish given

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performance levels, expressed in terms of maximum Isolator (IS) displacement and maximum inter-storey drift. The proposed design procedure has been developed for different idealized force-displacement cyclic behaviors, which may be used to describe the response of a wide variety of IS's, including: Lead-Rubber Bearings, High-Damping Rubber Bearings, Friction Pendulum Bearings and combinations of Flat Sliding Bearings with different re-centring and/or dissipating auxiliary devices. A.B.M. Saiful Islam, Mohammed Jameel and Mohammed ZaminJumat (2012) [1] examined the cost benefit of seismic isolation. tThey have concluded that seismic base isolators increase the building costs with its price as well as installation cost. Reinforcements required for grade beams increase slightly (5–7%) than for similar sections installed without isolators. But the cost reduction for reinforcement in upper floors for horizontal and vertical members (i.e., beams and columns) makes up for that cost. Thus, reinforcement yields a cost savings of 19–25%, considering isolator and reinforcement yields a net cost savings of 5–10%. Again, using isolator member sections can be decreased, depending on architectural requirements. The rate of cost savings decreases as the number of stories increases. Jared Weisman and Gordan P. Warn (2012) [13] arrived at a procedure to assess the stability using a ratio of areas, referred to as the overlapping area method, to determine the critical load capacity of elastomeric and lead rubber bearings at a given lateral displacement that must be greater than a combination of axial forces imposed on the bearing. Young-Sun Choun, Junhee Park and In-Kil Choi (2014) [40] studied the effects of variability of the mechanical properties of lead rubber bearings on the response of a seismic isolation system. Material variability in manufacturing, aging, and operation temperature is assumed, and two variation models of an isolation system are considered. Recently in 2015, ImaMultaji, FransiscusAsisi and Kevin Willyanto[10] has studied the performance of Force Based Design and Direct Displacement Based Design on a concrete special moment resisting frame. It was concluded that DDBD performed better than FBD in predicting seismic demand of the structure iestorey drift because it deliberately designs the structure to achieve a given performance limit state. FBD requires several design process repetitions in order to achieve acceptable performance as specified by the code. In this point of view DDBD procedure is more effective in predicting seismic demand of concrete special moment resisting frame. Also in the same year, Somwanshi and Pantawane[26] demonstrates how an isolation system can be efficient, evaluating its effectiveness for the building in terms of maximum shear force, maximum bending moment, base shear, storey drift and storey displacement reductions. Cancellara and Angelis in 2016[6] has proposed a base isolation system for structures subject to extreme seismic events characterized by anomalous values of intensity and frequency content. In their work, they have presented a high damping hybrid seismic isolator (HDHSI) obtained by the assembly in series of a lead rubber bearing (LRB) and a friction slider (FS) characterized by a high friction coefficient.The base isolated superstructure is thus endowed with a significant level of robustness and with a reserve for resisting to extreme seismic actions by preserving its functionality both in terms of resistance and in terms of deformation.

VI. FORCE BASED DESIGN

Force based design focus on the seismic force acting on the structure. Design procedure is carried out for the seismic force acting on the system. Stiffness, time period and damping are the initial properties of design. Linear elastic analysis is performed for the lateral force calculated. Expected performance is not achieved since seismic risk levels are not generalized.

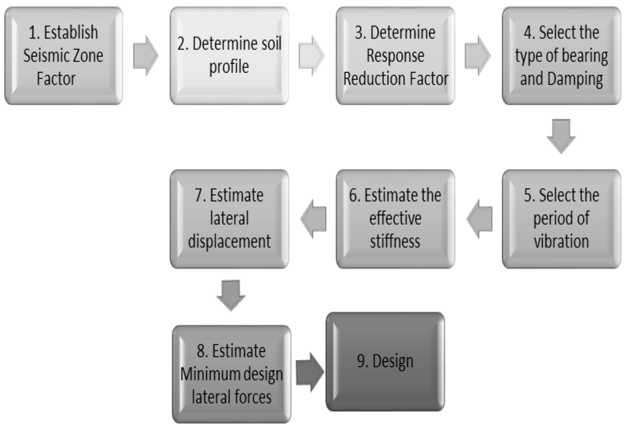

Fig 9 Flow of Force Based Design

VII. DIRECT DISPLACEMENT BASED DESIGN

This is a performance based design approach. Performance level is described in terms of displacement as damage is correlated to displacement rather than forces. The fundamental goal is to obtain a structure which will reach a target displacement profile when subjected to earthquakes consistent to a given reference response spectrum. The performance level of the structure are governed through the selection of suitable values of maximum displacement.

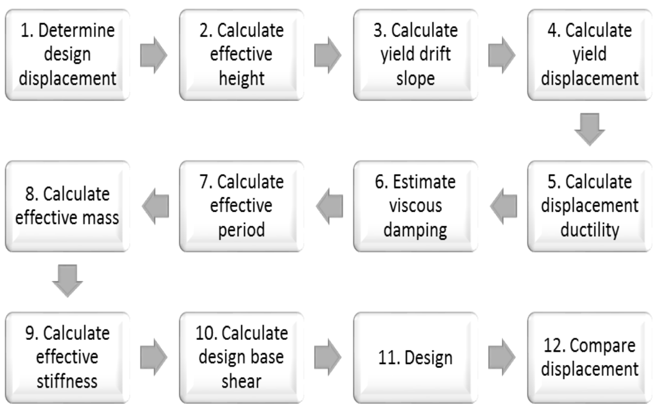

Fig 10 Flow of Direct Displacement Based Design

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VIII. CONCLUSION

It can be concluded that extensive works have been carried out in this fields from the beginning of 20th century, when Frank Lloyd Wright designed the first base isolated structures. There have been continuous innovations and extensive researches have been done in studying the effectiveness of various types of dampers. Recently, the research interest has been shifted to the Direct Displacement Based Design of Moment Resisting Frames. Comparative studies of Force Base Design and Displacement Base Design of a Fixed Based Structures are available. Several studies have been conducted describing the design steps of a Force Based Isolated Structure and a Displacement Based Isolated Structure. Merits of DDBD in using viscous damping and secant stiffness is explained. A comparative parametric study ofForce Based Design and Displacement Based Design of a base isolated structure using various isolation methods can be a direction of future analysis.

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