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Comparative Behavior of Structure with and without Base Isolation Devices and Detailed Study on Retrofitting of Structures using Software

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ABSTRACT

In recent years considerable attention has been paid to research and development of structural control devices with particular emphasis on mitigation of wind and seismic response of buildings. Many vibration-control measures like passive, active, semi-active and hybrid vibration control methods have been developed. Passive vibration control keeps the building to remain essentially elastic during large earthquakes and has fundamental frequency lower than both its fixed base frequency and the dominant frequencies of ground motion. Base isolation is a passive vibration control system.

Free vibration and forced vibration analysis was carried out on the framed structure by the use of computer program Staad Pro Vi8 and validating the same experimentally. The results of the free vibration analysis like time period, frequency, mode shape and modal mass participating ratios of the framed structure were found out. From modal analysis the first mode time period of fixed base building is found to be 0.56 sec whereas the first mode period of isolated building is found to be 3.11s (approximately 6 times the fixed- base period!). This value is away from the dominant spectral period range of design earthquake. Forced vibration analysis (non-linear time history analysis) was done to determine the response of framed structures and to find out the vibration control efficiency of framed structures using lead rubber bearing. Isolation bearings in this study are modeled by a bilinear model. Under favorable conditions, the isolation system reduces the inter-storey drift in the superstructure by a factor of at least two and sometimes by a factor of at least five. Acceleration responses are also reduced in the structure by an amount of 55-75% although the amount of reduction depends upon the force deflection characteristic of the isolators. A better performance of the isolated structure with respect to the fixed base structure is also observed in floor displacements, base shear (75- 85% reduction), floor acceleration relative to the ground(less acceleration imparted on each floor and their magnitude is approximately same in each floor), roof displacement.

Introduction of horizontal flexibility at the base helps in proper energy dissipation at the base level thus reducing the seismic demand of the super structure to be considered during design.

Retrofitting of existing structures with insufficient seismic resistance accounts for a major portion of the total cost of hazard mitigation. Thus, it is of critical importance that the structures that need seismic retrofitting are identified correctly, and an optimal retrofitting is conducted in a cost effective fashion. Once the decision is made, seismic retrofitting can be performed through several methods with various objectives such as increasing the load, deformation, and/or energy dissipation capacity of the structure. Conventional as well as emerging retrofit methods are briefly presented in the following subsections.

I. INTRODUCTION

For seismic design of building structures, the traditional method, i.e., strengthening the stiffness, strength, and ductility of the structures, has been in common use for a long time. Therefore, the dimensions of structural members and the consumption of material are expected to be increased, which leads to higher cost of the buildings as well as larger seismic responses due to larger stiffness of the structures. Thus, the efficiency of the traditional method is constrained. To overcome these disadvantages associated with the traditional method, many vibration-control measures, called structural control, have been studied and remarkable advances in this respect have been made over recent years. Structural Control is a diverse field of study. Structural Control is the one of the areas of current research aims to reduce structural vibrations

Retrofitting reduces the vulnerability of damage of an existing structure during a future earthquake. It aims to strengthen a structure to satisfy the requirements of the current codes for seismic design. In this respect, seismic retrofit is beyond conventional repair or even rehabilitation. The principles of seismic retrofit refer to the goals, objectives and steps. The steps encompass condition assessment of the structure, evaluation for seismic forces, selection of retrofit strategies and construction. The applications include different types of buildings, industrial structures, bridges, urban transport structures, marine structures and earth retaining structures during loading such as earthquakes and strong winds.

In terms of different vibration absorption methods, structural control can be classified into active control, passive control, hybrid control, semi-active control and so on. The passive control is more studied and applied to the existing buildings than the others. Base isolation is a passive vibration control system that does not require any external power source for its operation and utilizes the motion of the structure to develop the control forces. Performance of base isolated buildings in different parts of the world during earthquakes in the recent past established that the base isolation technology is a viable alternative to conventional earthquake-resistant design of medium-rise buildings. The application of this technology may keep the building to remain essentially elastic and thus ensure safety during large earthquakes. Since a base-isolated structure has fundamental frequency lower than both its fixed base frequency and the dominant frequencies of ground motion. The first mode of vibration of isolated structure involves deformation only in the isolation system whereas superstructure remains almost rigid. In this way, the isolation becomes an attractive approach where protection of expensive sensitive equipments and internal non-structural components is needed. It was of interest to check the difference between the responses of a fixed-base building frame and the isolated-base building frame under seismic loading. This was the primary motivation of the present study.

Importance of Present Study

Civil Engineers are still unable to rigorously predict even in a probabilistic way the loads which structures may have to withstand during their useful life. All structures are subjected to vibration. Recent destructive earthquakes in California and Japan have shown how vulnerable our structures and societies remain to natural phenomena. The enormous losses inflicted by such catastrophes have motivated ever more stringent requirements on the performance of structural systems, in an effort to reduce the cost of repair and disruption. The cost and performance requirements for both buildings and equipment have motivated advances in the field of Structural Control, which deals with methodologies for the protection of high performance structural systems. The vibration isolator is a device that is designed to effectively isolate such structures from harmful vibrations.

Vibration Control

Vibration control is the mechanism to mitigate vibrations by reducing the mechanical interaction between the vibration source and the structure, equipment etc. to be protected

Structural control relies on stiffness (i.e. energy storage) and damping (i.e. energy absorption/dissipation) devices in a structure to control its response to undesirable excitations caused by winds and moderate earthquakes. This control has in most cases, been achieved passively by means of bracing systems and shear walls, which do not require any additional external energy input. More recently, we have seen the emergence of more modem passive structural control systems. The tuned mass damper and base isolation systems are examples of such relatively modern passive systems.

II. Basic Isolation of Structures

Concept of base isolation

A fixed base building (built directly on the ground) will move with an earthquake and sustains damage as a result. But when a building is built away from (Isolated) the ground, resting on the flexible bearings known as base isolators, it will move a little or not move during an earthquake.

Seismic base isolation of structures such as multi-storey buildings, nuclear reactors, bridges, and liquid storage tanks is done to preserve structural integrity and to prevent injury to the occupants and damage to the contents by reducing the earthquake induced forces and deformations in the superstructure. This is a type of passive vibration control.

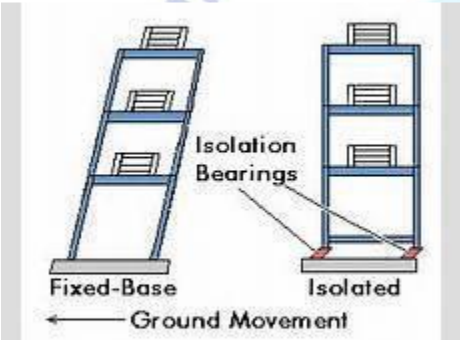


Fig 1.1 Building with fixed base and isolated base

The performance of these systems depends on two main characteristics:

(1)The capacity of shifting the system fundamental frequency to a lower value, which is well remote from the frequency band of most common earthquake ground motions.

(2)The energy dissipation of the isolator.

Types of Bearings

Following types of bearings are available as per literature as per their materials:

a. Flexible Columns.
b. Rocking Balls.
c. Springs.
d. Rubbers.
e. Other materials than rubber.

Rubbers are further divided into four categories,

a. Rubber Bearing
b. Steel laminated rubber bearing (RB).
c. Lead rubber Bearing (LRB).
d. High damping rubber bearing (HDRB).

Lead rubber bearings were developed as base isolators. Lead rubber bearing consist of three basic components-a lead plug, rubber and steel which are placed in layers.

Rubber provides flexibility through its ability to move but return to its original position. Lead was chosen because of its plastic property. It may deform with the movement of an earthquake and it will return to its original shape without losing the strength. Steel and rubber are placed in layers. At the top and bottom of an isolator there were two mounting plates made up of steel. Also in isolation system seismic dampers are placed to absorb or dissipate the energy that the base obtains during the earthquake. When an earthquake occurs, the isolation bearing deform because of elastic property (but the superstructure will be rigid) and the isolation bearing return to its original shape and position after the earthquake thus keeping the structure safe. Lead rubber bearing is shown in the fig 1.2.

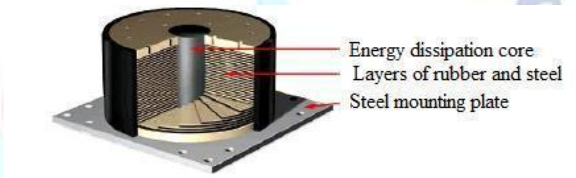


Fig 1.2 Lead rubber bearing-the isolator used.

III. RESPONSE OF THE BUILDING UNDER EARTHQUAKE

Building frequency and period

The magnitude of Building response mainly accelerations depends primarily upon the frequencies of input ground motions and Buildings natural frequency. When these are equal or nearly equal to one another, the buildings response reaches a peak level. In some cases, this dynamic amplification level can increase the building acceleration to a value two times or more that of ground acceleration at the base of the building. Generally buildings with higher natural frequency and a short natural period tend to suffer higher accelerations and smaller displacement. Buildings with lower natural frequency and a long natural period tend to suffer lower accelerations and larger displacement. When the frequency content of the ground motion is around the building's natural frequency, it is aid that the building and the ground motion are in resonance with one another. Resonance tend to increase or amplify the building response by which buildings suffer the greatest damage from ground motion at a frequency close to its own natural frequency.

Building stiffness

Taller the building, longer the natural period and the building is more flexible.

Ductility

Ductility is the ability to undergo distortion or deformation without complete breakage or failure. In order to be earthquake resistant the building will possess enough ductility to withstand the size and type of earthquake it is likely to experience during its life time.

Damping

All buildings possess some intrinsic damping. Damping is due to internal friction and adsorption of energy by buildings structural and non-structural components. Earthquake resistant design and construction employ inserts damping devices like shock absorbers to supplement artificially the intrinsic damping of a building.

Methodology

a. A thorough literature review was done to understand the seismic evaluation of building structure, application of time-history analysis and Modal analysis.
b. Selected an aluminum frame for the analytical and experimental case study.
c. The selected aluminum frame was modeled in computer software STAAD PRO VI8.
d. Modal analysis of a Benchmark Problem was carried out to validate the accuracy of steps involved in STAAD PRO VI8 software package and then modal analysis of the selected frame was carried out to obtain the dynamic properties of the frame.
e. Modal analysis result of the selected frame was validated experimentally with the help of FFT Analyses and shake table test.
f. Time-history analysis of a fixed base structure and similar base isolated structure was carried out.

IV. LITERATURE REVIEW

Jangid and Matsagar [62] computed the variation of top floor absolute acceleration and bearing displacement for different isolation systems during impact upon the adjacent structures under different earthquakes to study the behavior of the building during impact and comparative performance of various isolation systems. Variation of system parameters like size of gap, stiffness of impact element, superstructure flexibility and number of stories of base-isolated building effecting impact response of isolated building was also studied.

Experimental Study on Elastomeric Isolation Bearings

Nagarajaiah et al. [63] experimentally determined the effect of horizontal displacement or shear strain on critical load and studied the validity of the approximate correction factor. It is shown that the critical load decreases with increasing horizontal displacement or shear strain. It is also shown that substantial critical load capacity exists at a horizontal displacement equal to the width of the bearing.

Buckle and Nagarajaiah [64] stated combination of rubber layers and reinforcing steel shims gives a device that is axially very stiff but soft laterally. But increasing the shear flexibility of these short columns can lead to relatively low buckling loads, which may be further reduced when high shear strains are simultaneously imposed.

Abrams et al. [65] presented the Results of an experimental study that help to illustrate the effectiveness of using base isolators for reducing the lateral-force demand for engineered masonry building structures in areas of high seismicity.

Kelly et al. [66] proposed a novel isolation system which can be used in certain low rise buildings to isolate the horizontal and vertical ground motions.

Aiken et al. [67] overviewed the studies at the Earthquake Engineering Research Center of the University of California at Berkeley describing the different types of devices, the results of the shake table experiments, and associated analytical work.

Aiken [68] proposed energy dissipation devices by which damage to the built environment can be mitigated.

Aiken and Kikuchi [69] proposed a hysteretic model for elastomeric isolation bearing for accurately predicting the seismic response of base isolated structures. Extensive series of experimental tests were carried out to fully identify the mechanical characteristics.

Aiken [70] discussed the important characteristics of isolation devices and the influence of these characteristics on testing, in terms of such factors as displacement, force, rate of loading, and test temperature.

Aiken et al. [71] carried out a study to understand how and why this change in engineering and construction practice has taken place. It is clear that the Kobe earthquake helped to trigger the acceptance of new technologies in the Japanese seismic design community, but the occurrence of severe earthquake shaking is not by itself enough to change the direction of engineering and construction practice

V. STUDY ON RETROFITTING OF STRUCTURES

Introduction

Case studies are useful elements in any manual. They present real-life problems that were tackled. Case studies thus help to show how the textbook knowledge can be usefully applied in real life action.

Retrofitting of buildings for improved performance in earthquakes is a relatively new concept in our country, although in California simple retrofitting measures such as anchoring of roof parapets were made obligatory by law over half a century ago. Further, more complex retrofitting applications have been added over the past few decades, which are based on sound engineering analysis.

In India, although some work was done on retrofitting as far back as the late 1960s after the Koyna earthquake, this option received official recognition only during the post-Latur earthquake rehabilitation program. More recently, the Kutch (Gujarat) earthquake of 2001 brought much-needed visibility to the concept of retrofitting. In spite of all this, the extent of actual application of retrofitting remains limited. A large number of structures that can easily be retrofitted are still being demolished and replaced, or continue to remain in use in a highly vulnerable state.

The purpose of presenting case studies in this manual is to share the learning from cases that are relevant to the present-day scenario of high-level seismic risk in the State of Jammu and Kashmir. These studies will help the reader develop practical aspects of retrofitting and of the retrofitting scheme for the building as a whole unit, rather than just the individual measures described in the preceding chapters. The specific details that have emerged from these individual cases can help to eliminate the need for reinventing solutions. These case studies will also help to establish good practices in this emerging field and build readers' confidence in these new concepts.

The case studies presented here include two public buildings. Both are typical Kashmiri buildings, one of them is rural and the other is more urban. Figures related to the retrofitting of these structures are shown below.

Fig 3.1 School building before retrofitting

Fig 3.2 Preparing WWM with 6 mm bars

Fig 3.3 Installing WW mesh from a roll

Fig 3.4 Tying encasement reinforcement to shear connector dowel

Fig 3.10 Vertical reinforcement

Fig 3.11 Retrofitted building

Fig 3.12 Retrofitting of hospital building

Fig 3.13 Retrofitted hospital building

VI. RESULT AND DISCUSSION

Modal Analysis of a Benchmark problem

First modal analysis of a benchmark problem is solved using STAAD PRO. The benchmark problem is taken from literature (Bezerra and Carneiro, 2003). Modal analysis of a typical building structure frame is done to determine the dynamic parameters like natural frequency, time period, modal participating mass ratios and their corresponding mode shapes. Typical building structure frame (Fig 5.1) made of reinforced concrete has four floors and composed of columns 3.0m height and of cross section 30×50 cm2 with I = 3.1×10-3m4, and beams with span of 4.5m, cross-section 24x55 cm2, and inertia I = 3.5×10-3m4. The first natural frequency of the building is 2.3Hz.

From the modal analysis time period, frequencies are noted for modes with considerable mass participation. These are the important modes of consideration. The first natural frequency of the building found in STAAD PRO is 2.3195 Hz. (Table 5.1)

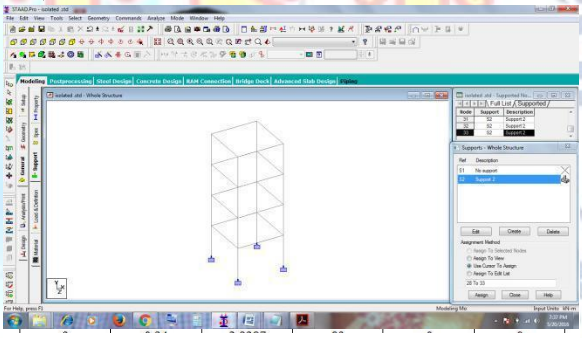


Table 5.1 Time period and frequency of building for the first three modes

Mode	T(s)	f(cps)	UX (%)	UY (%)	RZ (%)
1	0.43	2.3195	0	86	0
2	0.35	2.8713	0	0	85
3	0.34	2.9387	83	0	0

	f(cps)	
	Bezerra and cameiro	Staad output
First mode	2.3	2.3195

Vibration Measurement

Details of the Test Frame

The Aluminum frame present in the structural engineering laboratory, NIT Rourkela is taken into consideration for analysis. Natural frequency and mode shapes of the fixed base frame were found out by carrying out modal analysis method using Staad pro software package. The result of the test was validated by experimental work with the help of FFT Analysis and shake table test. Fig 5.2 presents the 3-D view of the aluminum frame modeled in Staad pro.

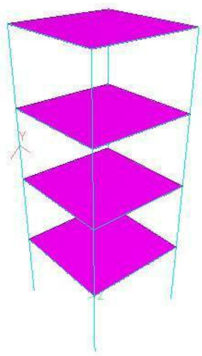


Fig 5.2 Computational model of the Aluminum frame

FFT Analyzer

From the Time (Excitation) input graph, Auto-spectrum (Excitation) input graph it is found that the object has been stroked properly. From the Time (Resonance) input graph, it is found that the object has been stroked properly and any overloaded response is avoided. From Auto spectrum (Excitation) window the approximate smoothness of the curve indicates the single hitting by hammer. From other graphs like frequency response, frequency resonance input graph the free vibration properties are obtained whose value approximately coincides with the value obtained from software package Staad Pro vi8

Fig 5.4 Experimental set up for the Shake table test

Fig 5.5 Response of the Experimental set up for the Shake table test.

Time-history analysis of the Frame

The response (i.e. Displacement, Velocity, and Acceleration) of the Aluminum frame subjected to a selected earthquake ground motion was found out by non-linear time history analysis using Staad Pro vi8. The selected earthquake ground motion is Northridge Earthquake record. (Northridge Earthquake, January 17, 1994, Reseda, a neighborhood city of Los Angeles, California, USA).

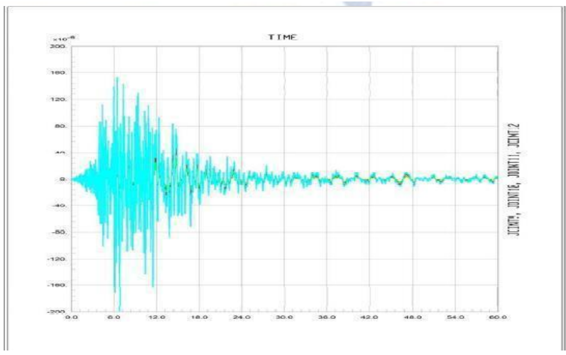
Response of the frame

Displacement

Displacement of the frame subjected to time history analysis is recorded in each node in both X-direction and Y-direction. No displacement is recorded at the base since the base is in the fixed condition. It is to be noted that that maximum displacement is achieved at all the nodes at the same time i.e. at 6.44 sec or at time step 322 along X-direction. Inter-storey drift are calculated and plotted graphically as shown Graph 5.3. From the graph it is clear that inter-storey drift is more in the first storey which goes on decreasing in successive upper floors. Inter-storey drift was shown in Table 5.3. Displacement of the frame in each node in Y-direction is found to be very less as compared to the displacement of the frame in the X-direction when it is subjected to time history force. Graph 5.4 shows Time history of displacement response of the Aluminum frame along Y-direction.

Table 5.3 Inter storey drift of aluminum framed structure

Storey no	Floor no	Storey height (m)	Displacement (mm)	Inter-storey displacement (mm)	Inter-storey drift (%)
1	0	0.4	0	9.23	2.30
	1		9.23		
2	1	0.4	9.23	7.20	1.80
	2		1.64		
3	2	0.4	1.64	3.82	0.95
	3		2.02		



Graph 5.4 Time history of displacement response of the Aluminum frame along Y-direction

Results

- Modal analysis of the fixed base aluminum frame was done to determine its natural frequency and mode shape followed by its time-history analysis using time history record of Northridge earthquake (January 17, 1994 in Reseda, a neighborhood city of Los Angeles, California, USA) at an interval of .02 sec for 60 sec. duration to determine the response of the frame under dynamic loading.
- It was concluded that the responses (displacement, inter-storey drift, velocity, acceleration) of the structure is more in lower storey as compared to the upper storey's.
- Maximum displacement was achieved at all the nodes at the same time i.e. at 6.44 sec or after 322 time history steps. Envelope of velocity and acceleration response was plotted.
- Inter-story drift is more in lower floors and it goes on decreasing in the successive upper floors.
- For dynamic loading design of building structures, we have to consider the dynamic loading response demand and go for the methods like strengthening the stiffness, strength, and ductility of the structures which has been in common use for a long time. Therefore, the dimensions of structural members and the consumption of material are expected to be increased, which leads to higher cost of the buildings as well as larger seismic responses due to larger stiffness of the structures.
- Base isolation decreases the dynamic loading response demand of the structure to a certain extent as compared to its bare frame by absorbing and dissipating the energy imparted on the structure due to dynamic loading.

VII. Conclusion

Modal analysis study: From the modal analysis study natural frequency and the mode shape of the framed structure was obtained. The determination of mode shape is essential to analyze the behavior of the structure under applied dynamic loading. From the modal analysis of the Aluminum frame natural frequency, mode shapes and corresponding modal participating mass ratios were obtained. The mode shapes for which modal participating mass ratios were maximum are taken into consideration. Staad Pro Vi8 is very effective tool to validate the results obtained experimentally. From the modal analysis first mode time period of fixed base building is found to be 0.56 sec whereas the first mode period of isolated building is found to be 3.11s (approximately 6 times the fixed-base period!). This value is away from the dominant spectral period range of design earthquake. Similar Shift was also observed in the higher modes, which shows the effectiveness of base isolation.

Time history analysis study: By conducting the nonlinear time history analysis it was shown that base isolation increases the flexibility at the base of the structure, which helps in energy dissipation due to the horizontal component of the earthquake and hence superstructure's seismic demand drastically reduced as compared to the conventional fixed base structure. The lead core present at the centre increases the energy absorption capacity of the isolator. The area of each cyclic loop represents the energy dissipated per cycle. Here floor displacement and roof displacement response curves of the isolated structure were plotted which are equivalent and it indicates the rigidity of the superstructure above the isolator. Base isolation reduces the base shear by 75-85% and reduces the velocity, acceleration response by 55-75%. It also reduces inter story drift as compared to the conventional fixed base structure. It reduces the force imparted on the structure at each floor and the force imparted is equivalent at each floor as compared to the fixed base structure.

Future Scope of Study

The vibration control technology is developing and its application is spreading in various fields of engineering structures. Factories, hospitals and residential houses will be protected from environmental vibration. It is evident that this technology will be progressed and become more important in the coming century. In the present study natural frequency, mode shape, modal mass participating ratios of the structural model and nonlinear time history analysis was carried out to determine the behavior of the structure under dynamic loading. Effectiveness of base isolation was studied by considering bilinear model of the LRB and modeling the same and superstructure by Staad Pro Vi8. The future scope of the present study can be extending as follows:

- Introduction of analysis software such as ETABS, SAP 2000 and LARSA, Staad Pro vi8 help in explicit modeling of isolators which exhibit mildly nonlinear behavior during dynamic loading.

- More research in earthquake time history records will help to study the behavior of the structural model under a given loading.
- With recent advancement in material technology, more study can be focused on material qualities used in isolators like their strength, durability, high vertical stiffness, low horizontal stiffness and high energy dissipating capacity.

Development in testing methodology of the isolator to predict more accurate behavior of the isolator under a given loading is of prime importance which needs a considerable attention in future. A boom of base isolation study in Japan will be over soon, but more steady study and research will be continued for aiming earthquake free structures

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