STUDY OF PASSIVE ENERGY DISSIPATION DEVICES FOR SEISMIC RESISTANCE OF STRUCTURE

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Major Project

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For the degree of

Master of Technology in Civil Engineering
(Computer Aided Structural Analysis & Design)

By

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CERTIFICATE

This is to certify that the Major Project entitled "Study of Energy Dissipation Devices for Seismic Resistance of the Structure" submitted by Mr. Akhil.M.Jhalani (05MCL003), towards the partial fulfillment of the requirements for the degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) of Nirma University of Science and Technology, Ahmedabad is the record of work carried out by him under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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ABSTRACT

During an earthquake a large amount of energy is imparted into the structure. To reduce the response of structure undergoing vibrations it becomes important for the structure to absorb or dissipate the energy. Historically, aseismic design has been based upon a combination of strength and ductility. For small, frequent seismic disturbances, the structure is expected to remain with in elastic range, with all stresses below yield level. However, it is not reasonable to expect that a traditional structure will behave elastically when subjected to a major earthquake. Design considerations rely on inherent ductility of building to prevent catastrophic failure, which may render the building non functional after the earthquake.

The actual dynamic nature of environmental disturbances demands more advanced structural protective systems. Structural protective system can be divided into three major groups, Passive Energy Dissipation Devices, Semi-active and Active Systems. The present study is an attempt to understand the behavior of energy dissipation devices in addition to inherent structural damping of the R.C.C frame building. Two types of dampers namely Viscous and Viscoelastic were undertaken as additional damping members. The modeling and analysis of R.C.C building with attached dampers was done through commercially available software SAP-2000 (Version 9.1).The analysis methodology adopted was Response Spectrum Method based on IS:1893-2002 (Part-I).

Various parameters like Displacement, Drift, Base shear, Force carried by the dampers and energy dissipation capacities were studied in detail. In addition to these, parameters like influence of variation of storey height, temperature variation, location and cost of damper was also calculated. At last comparative study of viscous and viscoelastic damper has been done. It was observed that about 25% of the Lateral load was carried by the dampers with only 5% additional damping. It was also found that displacement response of the structure reduces to a considerable extent.

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ABBREVIATION NOTATION AND NOMENCLATURE

Symbol	Description
K_d	Stiffness of a Viscoelastic Damper
G'	Storage Modulus of Viscoelastic Material
G''	Loss Modulus of Viscoelastic Material
t_d	Thickness of Viscoelastic material
A_d	Area of Viscoelastic Pad
C_d	Additional damping provided by Viscoelastic Damper
ω_d	Operating Frequency for Dampers
γ	Shear strain of Viscoelastic material
ξ	Desired damping ratio for Dampers
η_d	Loss Factor for Viscoelastic material
β_{eff}	Effective damping desired for Viscous Damper
β	Inherent damping in case of Viscous Damper
ϕ_j	Angle of inclination of Viscous Damper with horizontal
ϕ_i	First mode displacement at floor level i
C_0	Damping coefficient of Fluid Viscous Damper
D^*	Relative Velocity at the ends of the device
D	Relative Displacement at the ends of the device
α	Velocity exponent of Viscous Damper.

1. INTRODUCTION

1.1 GENERAL

Dynamic load produces vibration in the structure which causes the damage or collapse of the structure. A large amount of energy is imparted into structure during these vibrations. To reduce these vibrations it becomes important for the structure to absorb or dissipate energy. Conventional design philosophy seeks to prevent collapse by allowing structural members to absorb and dissipate the transmitted energy by inelastic cyclic deformations in specially detailed regions. Structural members which are specially detailed to absorb and dissipate the transmitted energy by inelastic cyclic deformations will not be capable of sustaining severe excitation and thus this strategy implies that some damage may occur, possibly to the extent that the structure is no longer repairable. Therefore, to reduce unwanted vibration in a structure some mechanism is required Damping is the process by which free vibration steadily diminishes in amplitude, i.e. it is an energy dissipating mechanism.

In the last two decades, special protective systems have been developed to enhance safety and reduction of damage of structures. These alternative approaches are aimed to control the structural response and energy dissipation demand on the structural members by modifying the dynamic properties of the structural system. In recent years, serious efforts have been undertaken to develop the concept of energy dissipation, or supplementary damping, using a workable technology, and a number of these devices have been installed in structures throughout the world. In general, such systems are characterized by a capability to increase energy dissipation in the structural systems in which they are installed. This effect may be achieved either by conversion of kinetic energy to heat or by transfer of energy among the different modes of vibration.

Presently research in the development of structural response control system has made significant progress resulting in the reduction of the overall response levels of civil structures subjected to dynamic load. Control studies in civil engineering can be divided into two categories, those which address serviceability issues & those whose main concern is safety. When serviceability is the main concern, control is used to reduce structural acceleration in order to increase occupant comfort during relatively mild wind or earthquake excitation. However, for those controllers developed for stronger excitation where occupant safety is the main concern, the goal is to improve structural response by reducing peak inter story drift or reducing vibration amplitudes or by increasing energy dissipation capacities of the structure.

1.2 BACKGROUND AND RECENT DEVELOPMENT IN STRUCTURAL CONTROL SYSTEMS

Various means of controlling structural vibrations produced by earthquake, wind or other dynamic loads have been investigated. These means include modifying rigidities, masses, damping, or deflected shapes through the provision of counteracting forces. A structure that is designed solely on the basis of strength requirements does not necessarily ensure that the building will respond dynamically in such a way that the comfort and safety of the occupants is maintained. For the application of control techniques in structures. Knowledge has largely been adapted from both the aerospace and automobile industries, where a significant amount of research and applications have been done. In structural engineering, the means of vibration control have taken several forms, for an example, the use of base isolation for low and medium height structures for seismic protection. For taller, more flexible structures, particularly those susceptible to high winds, the addition of supplemental dampers have been successfully employed. An example of successful implementation of Viscoelastic damper was the world trade centre of New York City.

Special considerations distinguish the application of control to civil engineering structures as opposed to other engineering applications. One such difference lies in the fact that civil structures are anchored to the ground and so are statically stable. In contrast, space structures when deployed require active control for stability. Also, environmental disturbances, such as winds and earthquakes, are highly uncertain with respect to both their occurrence and intensity.

1.3 MOTIVATION OF THE STUDY

According to a report by BBC, Loss of life caused by earthquake between May 2000 to May 2006 is summarized in Table 1.1

Table 1.1 Deaths Due To Earth Quake

Year	Total Deaths
2000	231
2001	21357
2002	1686
2003	33819
2004	284010
2005	89313
2006	5070
Total	435486
Average	62212.28

It is evident from the above mentioned Table 1.1 that more than sixty two thousand people lost their lives per year. To decrease the death toll, improvement in technology is required and therefore there is need of study in this sector of structural engineering that promises the safety of life. Although there are various analytical methods available to analyze the structure equipped with these devices but, to calculate the required size of these devices and to get its optimal performance is not an easy task, even with linear energy dissipation devices to get its optimal size is not straight forward, such procedures are iterative and based on trial and error.

There is a need to develop systematic approaches to popularize the use of these very effective devices in practice of structural Engineering, With currently available computing facilities, it now seems quiet possible to design building structures installed with passive energy dissipation devices.

1.4 OBJECTIVE OF STUDY

As per review papers & to IS 1893-2002(Part-I) majority area (approx 60%) of the country falls under a category of higher seismic hazards. Also, as population of country is increasing at a very rapid pace therefore construction of taller building is inevitable. The tall buildings are able to carry gravity load but susceptible to lateral loads due to wind or earthquake. In order to control large drift and to assure occupant safety and comfort there is need to study some protective /control systems for the buildings.

The current project is an attempt to understand the influence of supplementary damping (additional) damping in R.C.C building in addition to its own inherent capacity of energy dissipation.

The work comprises of modeling analysis & design of energy dissipation devices like Viscous & Viscoelastic dampers. The overall objective of project is to bring out the distinct features of such buildings in R.C.C building.

1.5 SCOPE OF WORK

In view of the above objective following scope of work was derived

- Study various literatures for exploring the need of Energy dissipation devices, implementation and working of such devices.
- Two types of R.C.C frame building G+3 & G+9 were considered as a problem in high seismicity zone.
- Modeling of 3-D frame building using SAP-2000(v 9.1) is to be done.
- The analysis and design of 3-D building as per Indian standards IS: 456-2000 & IS: 1893-2002(Part-I) is to be carried out.
- The compilation of Results without considering supplementary damping is to be taken up and verification for the same with conventional method is to be performed.
- The mathematical model of various damping devices namely Viscous & Viscoelastic need to review from literature and same to be implemented through SAP-2000(v9.1).
- The analysis of 3-D frame with additional dampers using Response Spectrum Method is to be carried out.
- Compilation of results related to Displacement, Drift, Base shear etc is to be done.
- Parametric study is to be taken up to know the influence of various parameters, on overall response of the RC frame building.
- Estimation of cost for dampers to understand its economic feasibility is to be reviewed.

1.6 ORGANISATION OF WORK

The Dissertation is organized into six chapters as follows

Chapter 1 deals with the introduction, motivation and objective of the study to give a broader idea regarding the project, reason to choose this subject. A brief introduction of energy dissipation devices and previous work done in this field is also reviewed.

Chapter 2 presents the various latest research papers along with their abstracts. Also, an introduction to various types of passive energy dissipation devices which are prevalent till now is included. Lastly, guidelines for passive energy dissipation devices by FEMA-273 are also added.

Chapter 3 presents the geometry formation for RCC building and provides the description of geometrical and material properties of various structural elements.

Chapter 4 in detail, includes general features of damping devices like various types of material, temperature susceptibility, Force- Displacement relationship, various analysis procedures for damper equipped structures their modeling and design.

Chapter 5 enlists the results for response of building equipped with dampers in terms of parameters like Displacement, Drift, and Base shear. Also effect of temperature, Locations, Storey height, Comparison of reinforcement and Cost aspect etc. The results are discussed in detail.

Chapter 6 reports conclusion drawn from the dissertation work and includes further work that can be carried out for the work undertaken.

2. LITERATURE REVIEW

2.1 INTRODUCTION

This chapter describes various energy dissipation devices that can be used to mitigate the response of the structure during earthquake and various research paper, and literature in other forms available in this field.

2.2 PASSIVE ENERGY DISSIPATION DEVICES

2.2.1 General

Passive energy dissipation is an emerging technology that enhances the performance of the building by adding damping (and in some cases stiffness) to the building. The primary use of energy dissipation devices is to reduce earthquake displacement of the structure. Energy dissipation will also reduce force in the structure- provided that structure is responding elastically –but would not be expected to reduce force in structures that are responding beyond yield. For most applications, energy dissipation provides an alternative approach to conventional stiffening and strengthening schemes, and would be expected to achieve comparable performance levels. In general these devices would be expected to be good candidates for the projects that have a performance level of life safety, or perhaps immediate occupancy, but would be expected to have limited applicability to projects with performance levels of collapse prevention.

All vibrating structures dissipate energy due to internal stressing, rubbing, cracking, plastic deformation and so on, larger the energy dissipation capacity smaller is the amplitude of vibration. Some structures have very low damping on the order of 1% of critical damping and therefore they experience large amplitude of vibration even for moderately strong earthquakes. Methods of increasing the energy dissipation capacity are very effective in reducing the amplitudes of vibration, Many different methods of increasing damping have been utilized and many others have been proposed during recent past. Passive energy dissipation systems encompass a range of materials and devices for enhancing damping, stiffness and strength and can be used both for natural hazard mitigation and for rehabilitation of aging or deficient structure. In general, these devices are characterized by their capability to enhance energy dissipation in the structural system to which they are installed. This may be achieved by various methods either conversion of kinetic energy to heat or by transferring of energy among vibration modes .The first method includes devices that operate on principles such as frictional sliding, yielding of metals, phase transformation in metals, deformation of viscoelastic solids or fluids and fluid orificing. The later one includes supplementary oscillators which act as dynamic vibration absorber. A passive control system does not require an external power source. Passive control devices impart forces that are developed in response to the motion of the structure.

2.2.2 Base Isolation

In recent years base isolation has become an increasingly applied structural design technique for buildings and bridges in highly seismic areas.

There are two basic types of isolation systems. The system that has been adopted most widely in recent years is typified by the use of elastomeric bearings. The elastomer made of either natural rubber or neoprene. In this approach, the building or structure is decoupled from the horizontal components of the earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and the foundation. This layer gives the structure a fundamental frequency that is much lower than its fixed-base frequency and also much lower than the predominant frequencies of the ground motion. The first dynamic mode of the isolated structure involves deformation only in the isolation system, the structure above being to all intents and purposes rigid. The higher modes that will produce deformation in the structure are orthogonal to the first mode and consequently also to the ground motion. These higher modes do not participate in the motion, so that if there is high energy in the ground motion at these higher frequencies, this energy cannot be transmitted into the structure. The isolation system does not absorb the earthquake energy, but rather deflects it through the dynamics of the system. This type of isolation works when the system is linear and even when undamped; however, some damping is beneficial to suppress any possible resonance at the isolation frequency.

The second basic type of isolation system is typified by the sliding system. This works by limiting the transfer of shear across the isolation interface.

2.2.3 Viscous Damper

Viscous dampers operate on the principle of resistance of viscous fluids to flow through a constrained opening. These devices have been adapted for seismic structural applications due to their abilities to dissipate large amount of the input earthquake energy by viscous heating. Another advantage attributed to the viscous dampers is that, their rate dependent viscous forces are out of phase with other displacement dependent forces and do not directly adds to the maximum forces developed in the main structural member. Figure 2.1 shows a typical viscous damper. The viscous damper can be designed to exhibit linear behavior over a broad range of operating frequencies. They can be designed to be nearly unaffected by the changes in ambient temperature or internal temperature rise due to the heat generated during earthquakes excitations.

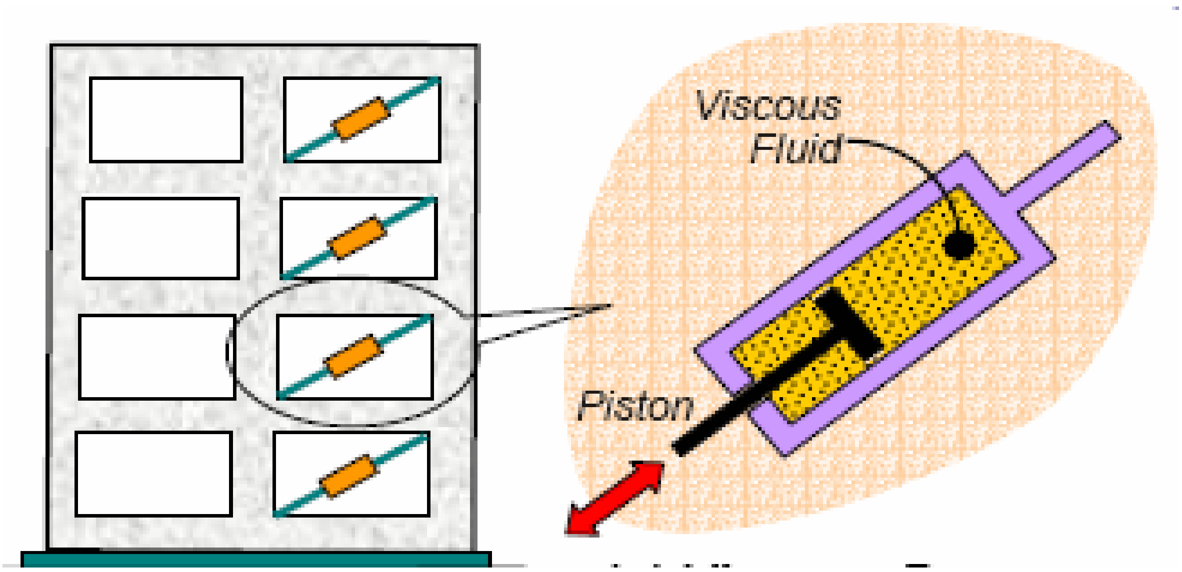
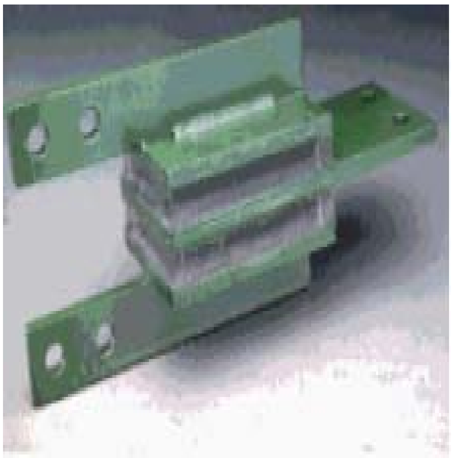


Fig 2.1 Typical Viscous Dampers and Its Installation in Building

2.2.4 VISCOELASTIC DAMPER

There is a class of viscoelastic solid material that can be used to dissipate energy at all deformation levels. Therefore viscoelastic damper can find application in both wind and seismic protection. Viscoelastic material used in civil engineering structures are typically copolymers or glassy substances. A typical viscoelastic damper developed by 3M Company Inc is shown in the Fig 2.2 and Fig 2.3. It consist of viscoelastic material bonded between steel plates. These dampers when mounted in a structure, energy dissipation takes places place due to shear deformation of material sandwiched between Steel plates. when structural vibration induces relative motion between outer steel flanges and the centre plate.



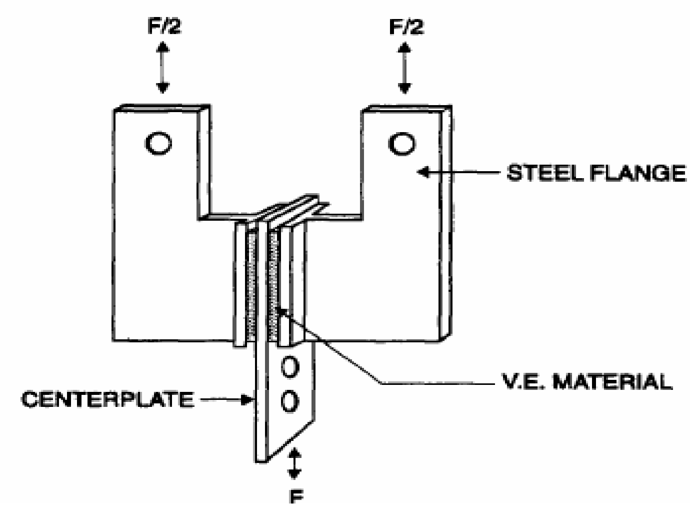


Fig 2.2 Viscoelastic Damper Rendered View

Fig 2.3 Isometric View with Components

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2.2.5 Friction Damper

Friction provides an excellent mechanism for energy dissipation and has been used for many years in automotive brakes to dissipate kinetic energy of motion. In structural engineering a wide variety of devices have been proposed and developed differing in mechanical complexity and sliding material. In the development of friction damper it is important to minimize stick slip phenomena to avoid introducing high frequency excitation, also compatible materials must be employed to maintain a consistent coefficient of friction over the intended life of the device. The Pall device as shown in Figure 2.4 is one of these damper elements utilizing the friction principle which can be installed in a structure in an X- bracing. Force–displacement responses of the pall dampers have been studied extensively. The dampers are designed not to slip during wind storms or moderate earthquakes. Under severe earthquakes the devices slip at a predetermined optimum load before yielding in primary structural members. These devices provide good performance and their behavior is not significantly affected by loading amplitude, frequency or even the number of loading cycles.

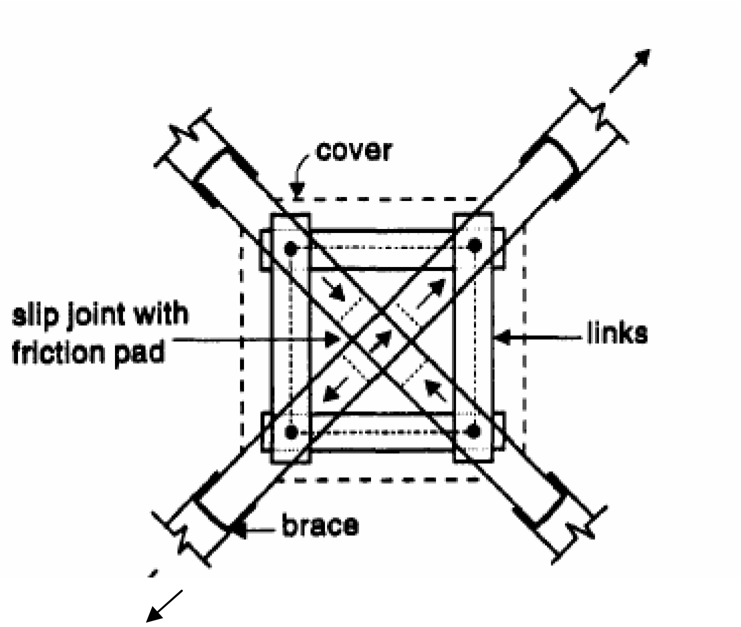
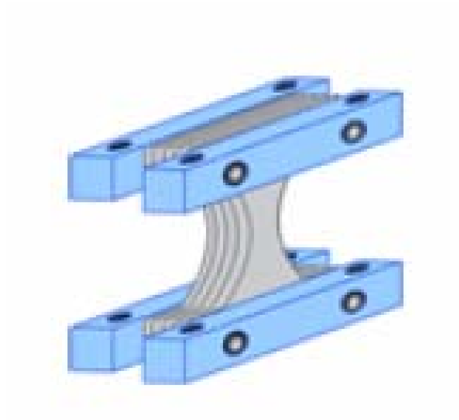


Fig 2.4 Friction Damper

The details of the friction damper are shown in the Figure 2.4. It consists of a diagonal brace element with a friction interface at their intersection point, which are connected together by horizontal and vertical link elements. These link arms ensure that when the load applied to a device via the braces is sufficient to initiate slip on tension diagonal, then compression diagonal will also slip an equal amount in opposite direction. The friction resistance of the device requires a normal force on the sliding interface, and this is achieved through a bolt at the intersection of the diagonal arms.

2.2.6 Metallic Damper

One of the effective mechanisms available for dissipation of energy input to a structure from an earthquake is through inelastic deformation of metals. The idea of utilizing added metallic energy dissipaters with in a structure is to absorb a large portion of seismic energy. These devices usually use mild steel as plates with triangular or hourglass shapes so that yielding is spread almost uniformly through out the material. A typical X – shaped plate damper or added damping and stiffness (ADAS) device is shown in the Fig 2.5.Some of the desirable features of these devices are stable hysteric behavior, low cycle fatigue property, long term reliability and relative insensitivity to environmental temperature.



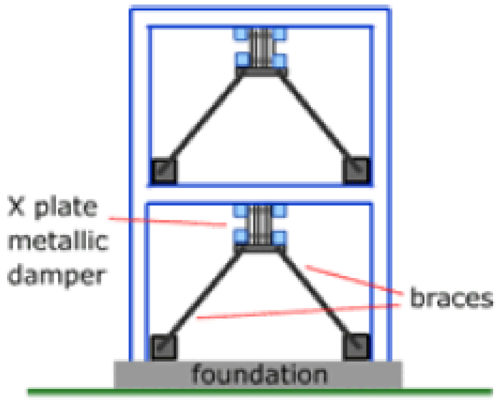


Fig 2.5 Typical X Shaped Plate Damper and Its Installation in a Building

During cyclic deformations, the metal plates are subjected to hysteretic mechanism and the plastification of these plates consumes a substantial portion of the structural vibration energy. Moreover, the additional stiffness introduced by metallic elements increase the lateral strength of the building with consequent reduction in deformation and damage of main structural member. The introduction of these devices in a structure will render it to behave nonlinearly, even if the other structural elements are designed to remain linear.

2.2.7 Tuned Mass Damper

These dampers are massive elements connected to the main structure. In such a way that connection allows the relative motion between the mass damper and the structure, so the big inertia forces involved partially cancel the external forces on the structure. To do this, the natural period of the added mass must be close to the fundamental period of the structure. This is the principle of the tuned mass damper (TMD). These elements have been mostly proposed to reduce horizontal vibrations of tall and/or slender structures (Skyscrapers, TV Towers, Chimneys etc). Mass dampers are usually more effective when installed on the top of the structure to control the first mode. The advantage of tuned mass damper is that since no mechanical parts are involved, little or no maintenance is required. However because additional mass is introduced, a tuned mass damper added to an existing structure increases the overall mass of the system. Tuned Mass Damper is shown in the Fig 2.6.

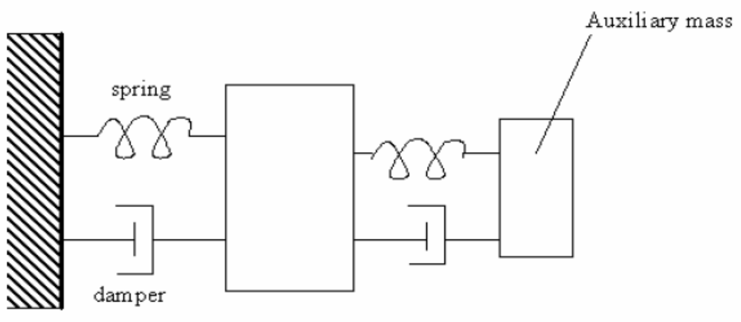


Fig 2.6 Tuned Mass Damper

2.3 LITERATURE REVIEW

This section presents the brief review of various books, papers, journals on the use and behavior of passive energy dissipation devices in a structure. The basic aim of literature review is to understand how passive energy dissipation devices /dampers are incorporated in a structure, its modeling and types of analysis procedures can be used for analyzing the structures with dampers.

2.3.1 Understanding the Basics of Energy Dissipation Devices

M.C CONSTANTINOU [1] describes that **Passive Energy Dissipation Devices** are classified as hysteric, viscoelastic and others. Examples of hysteric systems include devices based on yielding of metals or through sliding friction. The simplest models of hysteric behavior involve algebraic relations between force and displacement (FEMA, 1997).Viscoelastic energy dissipation system includes devices consisting of viscoelastic solid materials, viscous fluids. These devices exhibit stiffness and damping coefficients which are frequency dependent, moreover damping force in these devices is proportional to velocity.

ROBERT D.HANSON [2] presented the broad categorization of various measures to improve the earthquake response of the structure. These measures were classified as active system, passive systems and hybrid systems. An active system is that which requires the active participation of mechanical devices whose characteristics are made to change during the building response on the basis of current response measurement. Passive system comprises of energy dissipation devices and base isolation which does not require any external output. The Hybrid systems which is a combination of the passive and active system, so that, safety of building is not compromised even if active system fails.

2.3.2 Modeling of Energy Dissipation Devices

JULIUS MARKO[3] defined modeling procedures for viscoelastic, friction and hybrid system which consist of both viscoelastic and friction damper, Viscoelastic dampers were modeled as a linear spring and dashpot in parallel (known as Kelvin model) where spring represents stiffness and dashpot represents damping Abbas and Kelley defined stiffness and damping coefficients as

$$k_d = \frac{G' \times A_d}{t_d}$$

$$c_d = \frac{G'' \times A_d}{\omega_d \times t_d}$$

Where A_d is the shear area of VE material, t_d is the thickness of VE material, ω_d is the frequency of the damped system G' and G'' are Storage and Loss Modulus of viscoelastic material The following expression were used to obtain the moduli of VE material as defined by **Abbas and Kelley**

$$G' = 16.0\omega^{0.51}\gamma^{-0.23}e^{(72.46/T)}$$

$$G'' = 18.5\omega^{0.51}\gamma^{-0.20}e^{(73.89/T)}$$

Where T is operating temperature and γ is shear strain and ω is natural frequency of undamped system.

JAMES .M.KELLEY [4] defined simplified modeling approaches for viscoelastic damper. It was explained that the force–deformation characteristics of a viscoelastic damper is strongly dependent on ambient temperature, excitation frequency and shear strain amplitude. This behavior produces a degree of complexity in modeling viscoelastic dampers for dynamic analysis since damper is subjected to the excitation of multiple frequency components of earthquake ground motion and its temperature varies with energy dissipation during loading

(**Kasai et. al**)So, a simplified model is used to represent the viscoelastic damper the model is based on the assumption:-

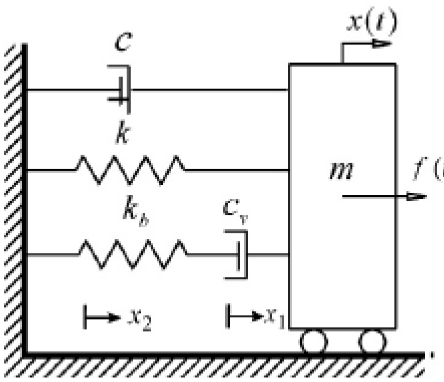
1) The viscoelastic material is assumed to have linear stiffness for a shear strain amplitude of 100% to 150% **Aiken and Kelley**, studied the variation of viscoelastic damper stiffness with shear strain for several earthquake ground motions, concluding that a large decrease in stiffness occurs in the 0-50% strain range, whereas the stiffness remains constant for strain ranges of 50%-200%. This observation provides sufficient grounds for the assumption of an effective constant damper stiffness for shear strain amplitudes ranging from 50%-200%.

2) It was observed by **(Lin et al)** that the temperature in the damper consisted of the ambient temperature and a temperature rise during excitation. Experimental evidences show that the variation in the damper temperature due to dynamic excitation becomes negligible after several loading cycles as an equilibrium temperature was reached between the surrounding and the damper. Also, the effect of frequency on properties of viscoelastic material is insignificant, since most earthquakes are in low and narrow frequency ranges.

3) This is a simplified model in which effect of all these factors were considered, where frequency of dominant mode may be assumed to represent the frequency of excitation. Shear strain amplitude may be taken equal to the maximum relative displacement in the structure. Accordingly, viscoelastic damper can be modeled as an elastic spring and a dashpot acting parallel.

DAVID.I.G.JONES [5] illustrated various classical models of viscoelastic dampers these were based on combination of elastic and viscous elements ranging from basic discrete systems such as Maxwell and Vogt models.

J.P.OU [6] presented approaches to model damper brace assembly of viscous and viscoelastic dampers



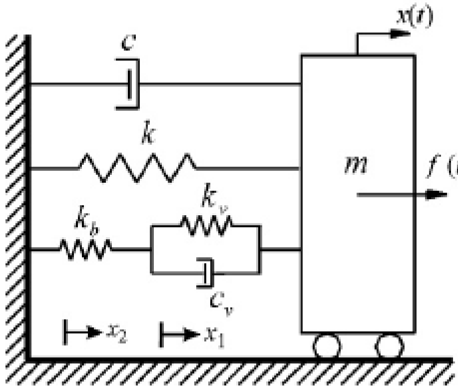


Fig 2.7 Model of Structure With Viscous Damper

Fig 2.8 Model of Structure with Viscoelastic Damper

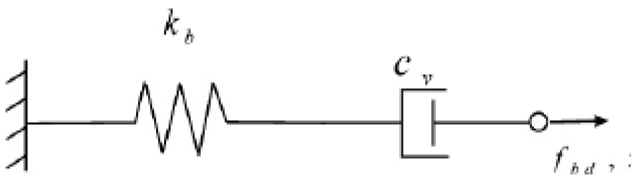


Fig 2.9 Viscous Damper-Brace Component

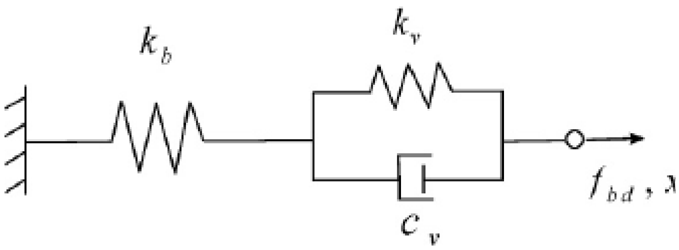


Fig 2.10 Viscoelatic Damper Brace Component

2.3.3 Analysis & Design of Energy Dissipation Devices

K.L SHEN & T.T SOONG [7] presented simplified design procedures for viscoelastic damper based on Model Strain Energy Method. The design procedure is almost same as conventional one except that the damping ratio is considered as an additional design parameter. The dampers with larger area of VE material layer will provide more additional damping to the structure and are stiffer. Following simplified formulas are presented for design of viscoelastic damper

$$k' = \frac{2\xi}{\eta_D - 2\xi} k_s$$

$$A = \frac{k' \times h}{G' n}$$

Where ξ is the desired damping ratio and η_d is the loss factor, n is number of dampers A is area of viscoelastic material h is height of storey k' and k_s are the stiffness provided by the damper at each storey and storey stiffness of structure respectively.

JAMES .M .KELLEY [8] explained that the response spectrum method can be used for analysis of a structure with dampers, and also guidelines for the distribution of dampers. It is explained that the volume of viscoelastic material should be distributed through out the height of the structure, using one design of damper and equal number of dampers at each level of structure.

EUGENE.I.RIVIN [9] given various factors to be incorporated in design of viscoelastic dampers for various types of bracings like chevron brace, toggle brace , scissor jack bracing , upper toggle bracing etc.

2.4 GUIDELINES OF FEMA-273 FOR DAMPER

2.4.1 Velocity Dependent Dampers

The force-displacement response of a velocity dependent device is primarily a function of the relative velocity between ends of each device

Solid Viscoelastic Devices [10]: - The cyclic response of Viscoelastic solids is generally dependent on the frequency and amplitude of motion, and the operating temperature (including temperature rise due to excitation).

Solid Viscoelastic dampers can be modeled using a spring and dashpot in parallel called **Kelvin Model**. The spring and dashpot constants selected should adequately capture with fundamental frequency of the building.

The force in Viscoelastic device may be expresses as:

$$F = K_{eff} D + C D^{*}$$

Where C is the damping coefficient for Viscoelastic device, D is the relative displacement between each end of the device, D^{*} is relative velocity between each end of the device and k_{eff} is the effective stiffness of the device.

Fluid Viscoelastic Devices: - The cyclic response of Viscoelastic fluid devices is generally dependent on the frequency and amplitude of motion and operating temperature (including temperature rise due to excitation).

Fluid Viscoelastic devices may be modeled using spring and dashpot in series (Maxwell Model) the spring and dashpot constants selected should adequately capture frequency and temperature dependence of device consistent with fundamental frequency of building.

Fluid Viscous Devices: - The cyclic response of fluid viscous devices is dependent on the velocity of motion: may be dependent on the frequency and amplitude of motion; and is generally dependent on operating temperature (including temperature rise during excitation). Fluid Viscous dampers may exhibit some stiffness in frequencies of cyclic loading. Linear fluid viscous damper exhibiting stiffness in the frequency range 0.5 f_1 to 2.0 f_1 should be modeled as fluid viscoelastic device.

In absence of stiffness in the frequency range 0.5 f_1 to 2.0 f_1 the force in the fluid viscous device may be expressed as:

$$F = C_0[D^{*}]^{\alpha}\,\mathrm{sgn}(D^{*})$$

Where C_0 is the damping coefficient for the device, α is the velocity exponent for the device, D^{*} is the relative velocity between each end of the device, and sgn is the signum function that, in this case, defines the sign of the relative velocity term.

2.4.2 Displacement Dependent Dampers

The force-displacement response of a displacement dependent device is primarily a function of relative displacement between each end of the device. The response of such a device is substantially independent of the relative velocity between each end of the device, and/or frequency of excitation.

Displacement – dependent devices should be modeled in sufficient detail so as to capture their force- displacement response adequately, and their dependence, if any, on axial shear interaction, or bilateral deformation response.

For the purpose of evaluating the response of a displacement- dependent device from testing data, the force in a displacement –dependent device may be expressed as

$$F = k_{eff} D$$

Where k_{eff} is the effective stiffness of the device. D is the relative displacement between ends of the device.

3. PROBLEM IDENTIFICATION AND IMPLEMENTATION

3.1 INTRODUCTION

To understand the influence of energy dissipation devices in a structure, a 3-D R.C.C building was decided to undertake. The building undertaken was symmetric in plan. To understand the response of different height building with energy dissipation devices a G+9 building was also analyzed. Hence the implementation of damping devices was applied to G+3 building and is G+9 buildings respectively.

3.2 GEOMETRY OF BUILDING

Architectural Layout and Structural layout for G+3 and G+9 3-D RC Framed building are shown in Fig 3.1, Fig 3.2 and Fig 3.3 respectively, the general information regarding building is as follows

➢ Type of building	:	Shopping Complex (Ground +3-storey)
➢ Location of building	:	Thara (Gujarat)
➢ Height of building	:	12.0 m
➢ Typical storey height	:	3.0 m
➢ Dimension of building	:	
Width (B)	:	50 m (in X – direction of plan)
Depth (D)	:	30 m (in Y – direction of plan)
➢ Soil type	:	Medium soil

Building was symmetrical in plan & used for commercial purpose. Brick masonry was used as an infill panel. Building was used for commercial purpose. On the basis of the architectural plan of typical floor level and sectional elevation, structural layout of typical floor level was prepared. Structural layout of typical floor level is given Fig.3.2. Building was analyzed as bare frame and the weight of brick masonry was added into consideration of beam elements. To avoid the case of non- proportional damping in a structure the building chosen is symmetrical in plan, which eventually helps damping devices to be distributed symmetrically in a building.

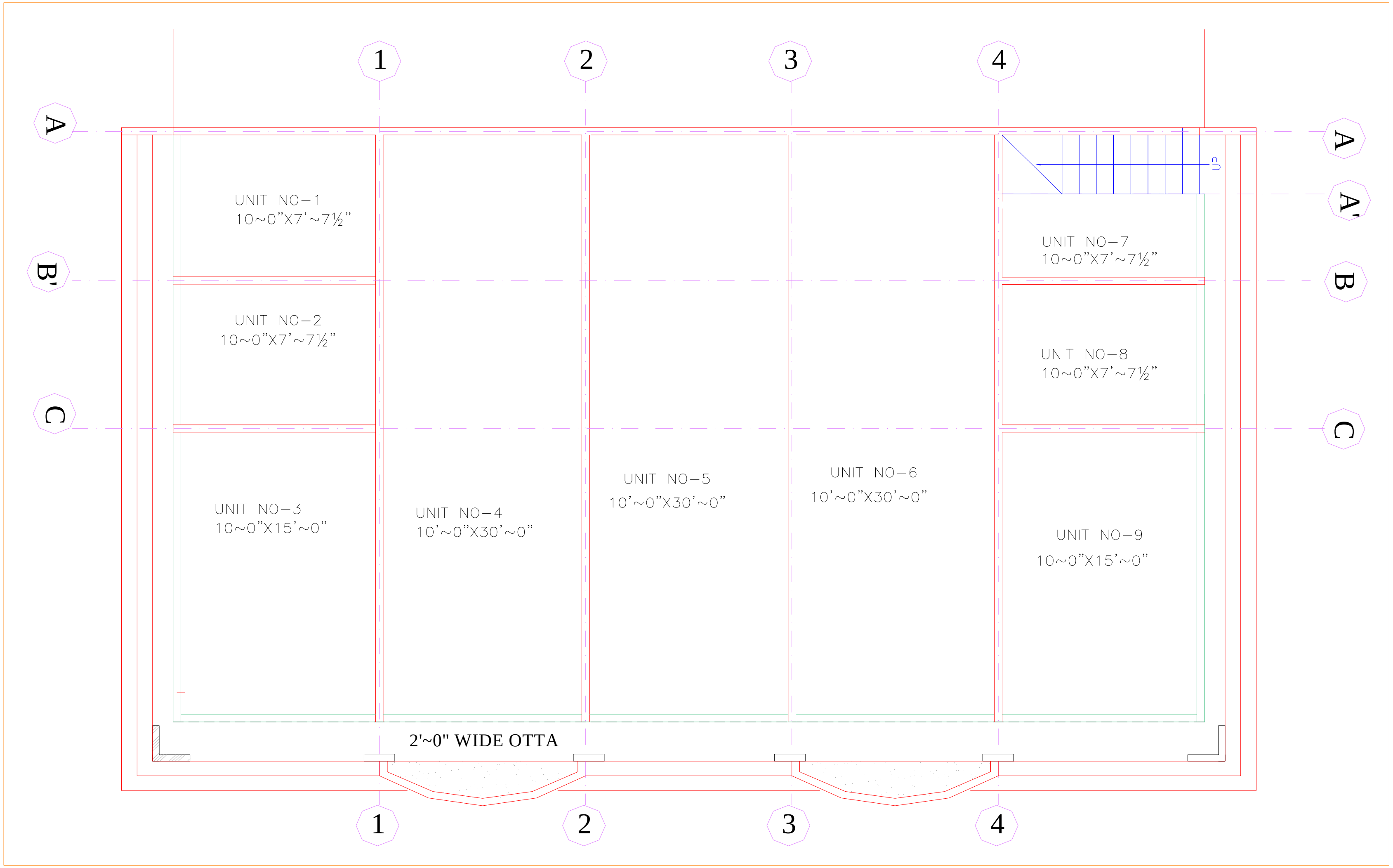


Fig 3.1 Architectural Layout of the Building

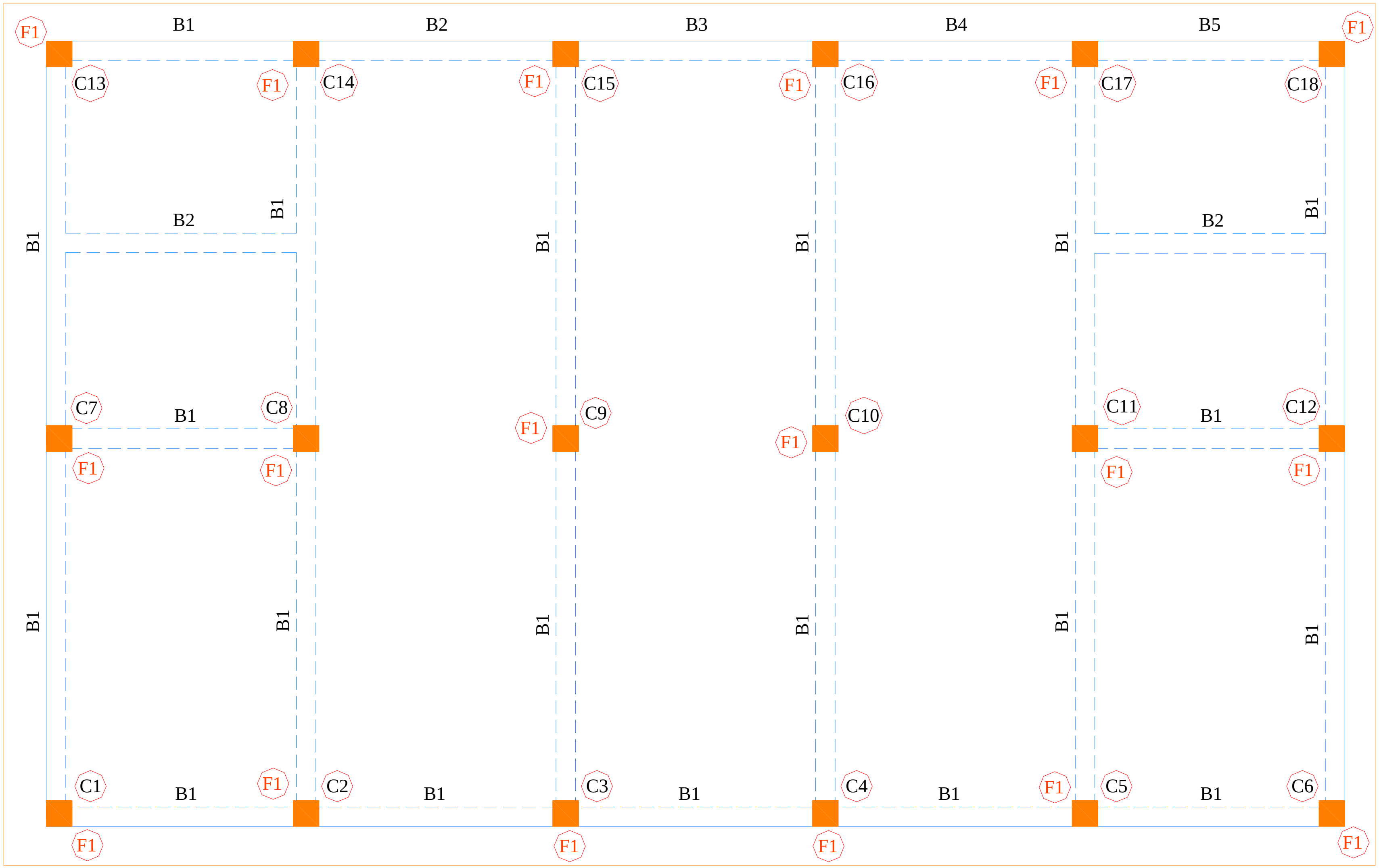


Fig 3.2 Structural Layout of G+3 Storey Building

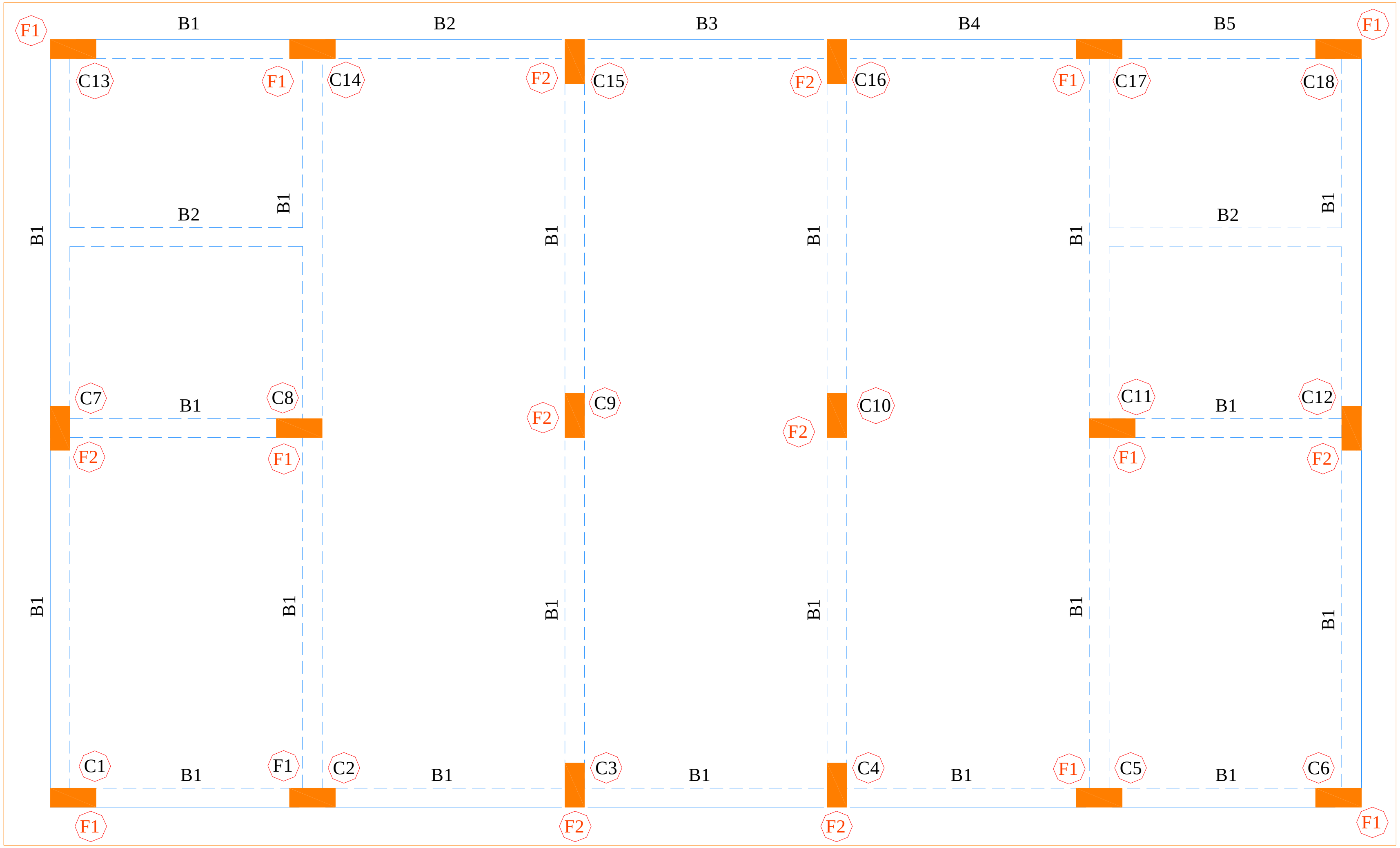


Fig 3.3 Structural Layout of G+9 Storey Building

3.3 MATERIAL PROPERTIES OF RC FRAMED BUIDING

The material & loading data consider are enlisted below.

Material Data

- Density of concrete : 25 kN/m^3
- Grade of concrete : M20
- Density of Brick : 20 kN/m^3
- Yield strength steel : 415 N/mm^2

Loading Data

Dead load

- Thickness of slab : 130 mm
- Self weight of slab : 3.25 kN/m^2
- Floor finish : 1.0 kN/m^2
- Total : 4.13 kN/m^2

Live load : 4.0 kN/m^2

Wall load

- 230 mm thick wall : 12.4 kN/m

Earthquake load [11]

- Earthquake zone : V
  - Zone factor : 0.36
- Important factor : 1.0
- Ordinary moment resisting frame
  - Response reduction factor : 5.0

Load cases

- Dead load
- Live load
- Earthquake load

Load combination

Following load combinations as specified by IS: 1893 -2002(Part –I) were used for analyzing the building

- 1.5 DL+ 1.5 LL
- 1.5 DL+1.5 EQ+X
- 1.5 DL+1.5 EQ–X
- 1.5 DL +1.5 EQ+Y
- 1.5 DL +1.5 EQ-Y
- 1.2 DL+1.2LL+1.2EQ+X
- 1.2 DL+1.2LL+1.2EQ-X
- 1.2 DL+1.2LL+1.2EQ+Y
- 1.2 DL+1.2LL+1.2EQ-Y
- 0.9DL+1.5EQ+X
- 0.9DL+EQ-X
- 0.9DL+EQ+Y
- 0.9DL+EQ-Y

Sectional properties

Two types of beam sizes were used for both G+3 & G+10 building for the purpose of analysis the beam taken were rectangular and sizes are given below in the table 4.1 and table 4.2. Where B1 is primary beam and B2 is secondary beam In case of column Square column of same dimension was used for G+3 building and two types of columns were used for G+9 building. Column sizes were rectangular in section

Table-4.1 Approximate Sizes of Beam and Column for G+3 Building

Col.	Size of Column (mm)	Beam	Span of Beam (m)	Size of Beam (mm)
F_1	300 x 300	B1	4.572	230 x 450
		B2	3.048	230 X 350

Table-4.2 Approximate Sizes of Beam and Column for G+9 Building

Col.	Size of Column (mm)	Beam	Span of Beam (m)	Size of Beam (mm)
F_1	230 x 500	B1	4.572	230 x 500
F_2	500 x230	B2	3.048	230 X 450

Boundary condition

The boundary condition imparted for the analysis was fixed support at base, i.e. movement in x, y & z direction restricted.

4. MODELING ANALYSIS AND DESIGN OF DAMPERS

4.1 STRUCTURAL DAMPING

4.1.1 Importance of Structural Damping

Estimation of damping in structural system poses a most difficult problem in structural dynamics. Unlike mass and stiffness characteristics of a structure, damping does not relate to unique physical phenomena. Modern high–rise buildings designed to satisfy lateral drift requirement may oscillate during wind storms. It may not be significant enough to cause structural damage but may cause discomfort for the building occupants.

Structural damping is a measure of energy dissipation in a vibrating structure that results in bringing it to quiescent state. There are as many damping mechanism as there are modes of converting mechanical energy into heat. The most important among these are material damping and interfacial damping. The material damping contribution comes from a complex molecular interaction with in the material, thus the damping is dependent on the type of material, methods of manufacturing and final finishing processes. The complexity of the situation is further enhanced by the simple reality that material property may vary from model to model resulting possibly in significant differences in energy losses among distinct members of a structural system. The interfacial damping mechanism is coulomb friction between members and connections of a structural system.

Thus, it is desirable for all structures to have sufficient damping so that their response to the expected excitation is acceptable. Increasing the damping in a structure will reduce its response to a given excitation. The damping into a system can be incorporated by following ways

(1) Inherent damping (2) additional damping

4.1.2 Modeling through SAP-2000

As adopted by many researchers widely accepted value of damping is 5% for R.C.C structures and 2% for steel structures. Therefore modeling of damping is an important issue. The software used SAP-2000(v 9.19) does take care of damping on assigning the value as % of critical damping. As material used for all structural elements of 3-D R.C frame building was concrete only, therefore 5% of critical damping was assigned through out. Fig 4.1 shows the way to incorporate damping value for the model. It is important to note that the damping values used here is an inherent damping of building contributed by various structural elements. However additional damping allocated requires special attention. The additional damping provided by supplementary dampers need to analyze for expected level of damping and designed for actual implementation. Following sections in detail focuses analysis and design procedures of supplementary dampers quiet in detail.

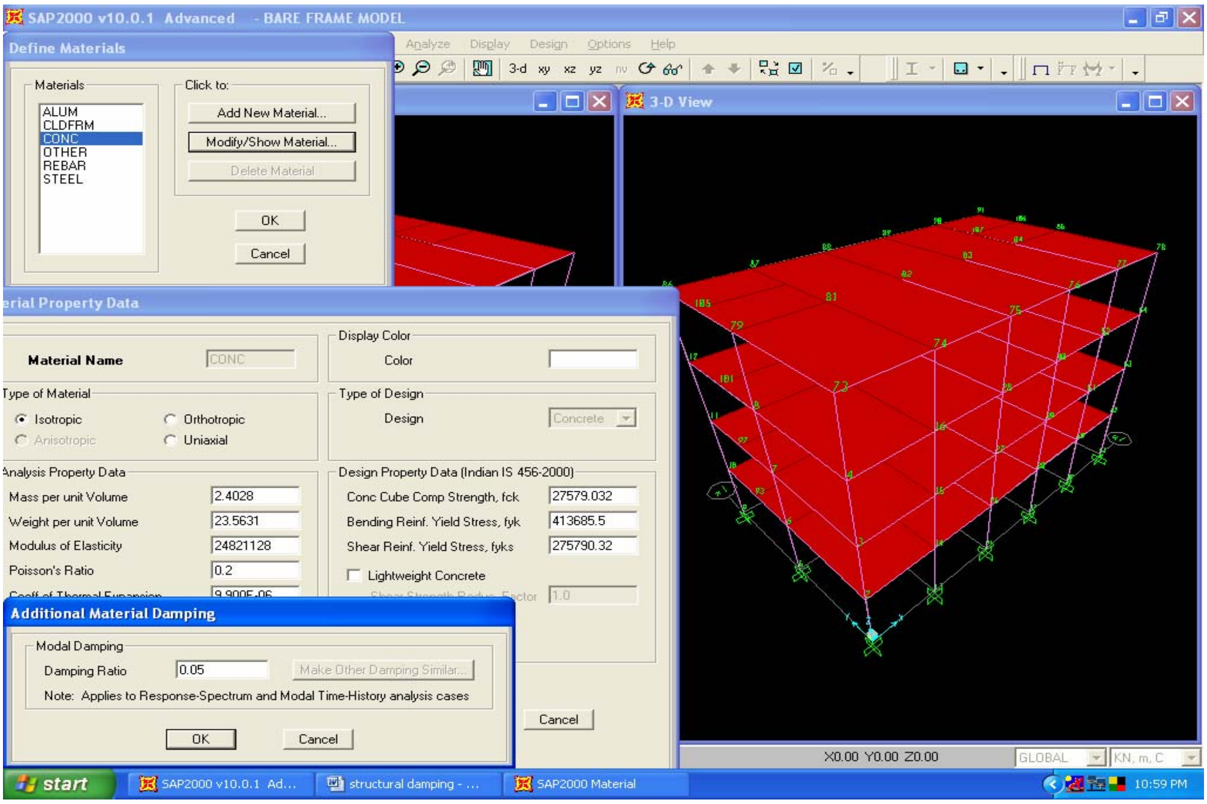


Fig 4.1 Assigning Structural Damping

4.2 VISCOUS DAMPER

4.2.1 Introduction

This section deals with analysis, design and modeling of Viscous damper as per FEMA-273. SAP-2000 provides tools to model various energy dissipation devices with in a building. Initially design of viscous damper is done for specified amount of damping and the calculated properties were used to model viscous damper in SAP-2000 through Nonlinear Link Properties [12].

4.2.2 Analysis Procedure for Viscous Damper (FEMA -273)

The design of viscous damper comprises of distribution of damping throughout the building. The distribution is usually done symmetrically so as to avoid the case of non- proportional damping. Damping is distributed in the structure as per formula given in FEMA -273.

$$\beta_{eff} = \beta + \frac{T \sum_i C_j \cos^2 \theta_j \phi_{rj}^2}{\pi \sum_i \left(\frac{w_i}{g} \right) \phi_i^2} \qquad \text{... (4.1)}$$

Where β_{eff} is the equivalent viscous damping, β is the damping in framing system and is set equal to 0.05 for reinforced concrete building, C_j is damping constant for device j, θ_j is the angle of inclination of device to the horizontal ϕ_{rj} is the first mode relative displacement between ends of device j in horizontal direction, w_i is the relative weight of floor level i, ϕ_i is the first mode displacement at floor level i.

4.2.2 Modeling through SAP-2000

There are two important properties of a damper stiffness and damping. The damper can be modeled by using “Nonlinear Link Element” command, since viscous damper only contributes damping to a building, it was calculated by above mentioned equation 4.1, and the calculated damping was distributed through out the building through additional damper installation. However, stiffness provided by the damper will remain zero. The mass of the viscous damper is generally taken as 300kg (source:-Taylors Devices). Damper were assigned in both X & Y direction symmetrically as per guidelines of FEMA -273 as shown in Fig 4.2

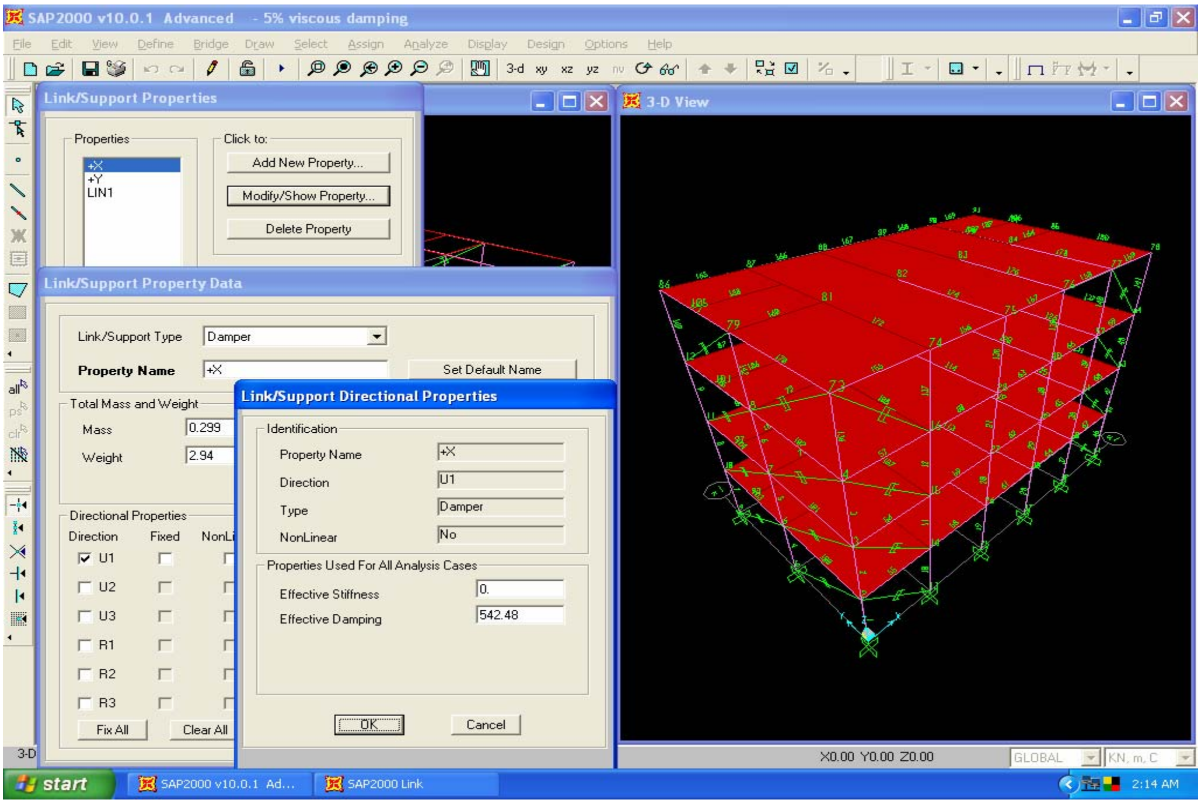


Fig 4.2 Defining a Viscous Damper

4.3 VISCOELASTIC DAMPER

4.3.1 Features of Viscoelastic Damper

The salient features of viscoelastic dampers are as enumerated in the following:-

1) Viscoelastic dampers are lateral load carrying elements and are designed such that part of the mechanical energy of the building motion is transferred into heat, which results in reduction of amplitude of the vibratory motion. The medium in which this transfer of energy takes place is a viscoelastic material.

2) The damping achieved is mostly due to shear deformation of viscoelastic material.

3) The most common type of VE damper is formed of two layers of viscoelastic material bonded between a central driving plate and two outer plates. These devices significantly increase the capacity of the structure to dissipate energy, but have the little influence on the natural periods, which are shortened by about 10% to 20%. Fig 4.8 shows the shear deformation of viscoelastic material. The Fig 4.9 shows damper installed in the diagonal bracing of a structure. Energy is

dissipated by relative motion between the outer steel flanges and the center plate of the device.

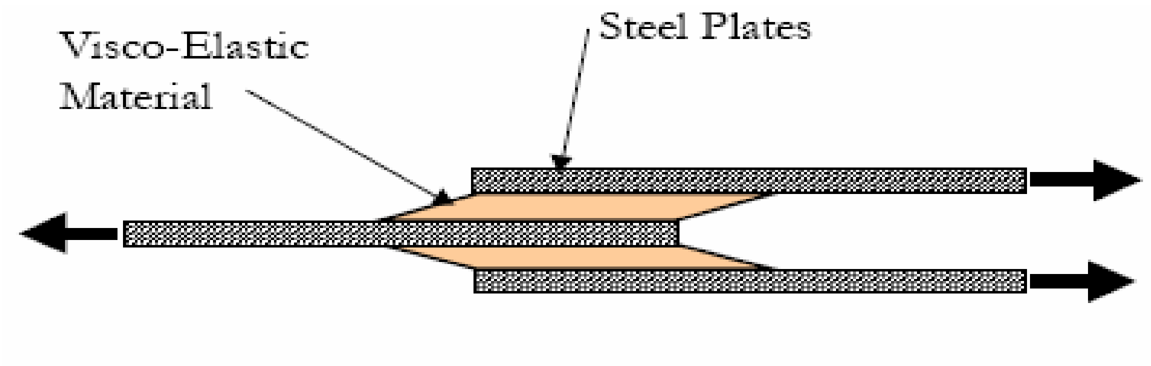


Fig 4.3 Shear Deformation of Viscoelastic Material

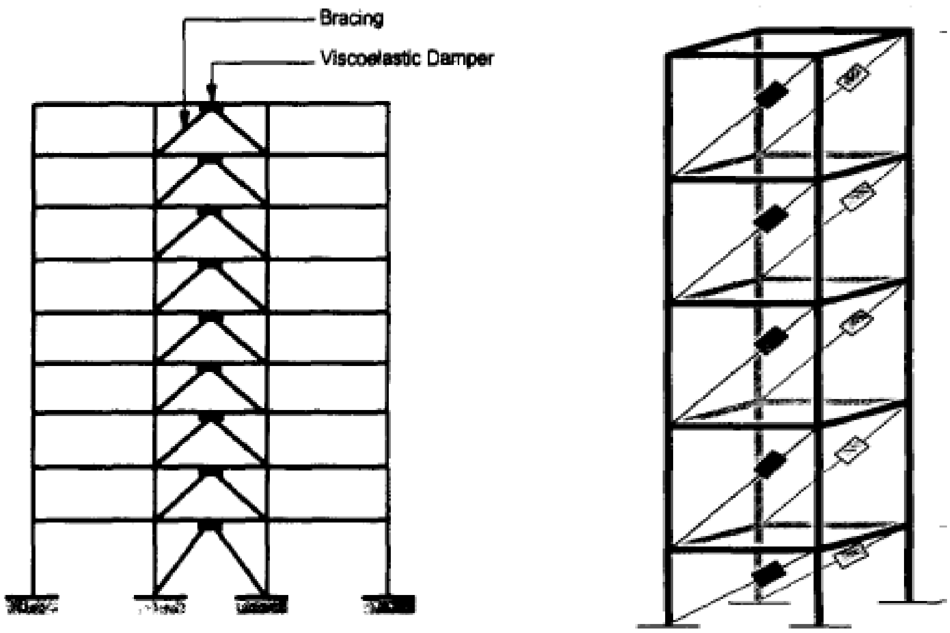


Fig 4.4 Typical Layout of Viscoelastically Damped Structure.

4) Viscoelastic dampers show significant potential for providing economic structures, which can behave elastically and develop small drifts even when subjected to a major earthquake thereby protecting both structural and non structural components.

5) Viscoelastic dampers provide velocity dependent damping force which increases the damping in structure and results in reduction of vibration. The viscoelastic damper has another benefit of adding stiffness to the structure. Thus,

the addition of viscoelastic dampers consistently reduces the displacement demands and thus decreases or eliminates the nonlinear response in the primary structure.

6) Extensive parametric analysis on viscoelastic damper show that the acceleration, displacement, ductility and energy dissipation response of viscoelastically damped structures can be significantly influenced by: the period of primary structure, earthquake ground motion characteristics, loss factor of viscoelastic material, ambient temperature and the strength of the primary structure.

4.3.2 Viscoelasticity

A viscoelastic material is characterized by possessing both viscous and elastic behavior. A purely elastic material is one in which all the energy stored in the model during loading is returned, when the load is removed. As a result, the stress and strain curves for elastic materials move completely in phase. For elastic materials, Hooke's Law applies, where the stress is proportional to the strain, and the modulus is defined at the ratio of stress to strain.

A complete opposite to an elastic material is a purely viscous material. This type of material does not return any of the energy stored during loading. All the energy is lost as "pure damping" once the load is removed. In this case, the stress is proportional to the rate of the strain, and the ratio of stress to strain rate is known as viscosity. These materials have no stiffness component, only damping.

All others that do not fall into one of the above extreme classifications are viscoelastic materials. Some of the energy stored in a viscoelastic system is recovered on removal of the load, and the remainder is dissipated in the form of heat. Viscoelastic materials encompass a broad range of materials, including, pressure sensitive adhesives, epoxies, rubbers, foams, thermoplastics, enamels and mastics. Their common characteristic is that, their modulus is represented by a complex quantity, possessing both a stored and dissipative energy component. This complex modulus reveals the material's stiffness and damping properties as a function of temperature and frequency.

4.3.3 Various Types of Viscoelastic Material

Most of the homogenous isotropic polymer material exhibit damping behavior which depends strongly upon temperature and frequency but is linear with respect to vibration amplitude. Polymers are the material composed of long intertwined and cross linked molecular chain, each containing thousand or even millions of atom. The intermolecular interactions which occur during deformation give rise to microscopic properties such as stiffness and energy dissipation during cyclic deformation. The class of polymer is extremely wide and includes commercially available products ranging from natural rubber, through various adhesives to stiff plastics Table 4.1 lists few of the categories of polymer available for manufacture of stable material damping system.

Table 4.1 Types of Viscoelastic Materials

Sr.No.	List of some polymer types
1	Acrylic rubber
2	Butadiene rubber(BR)
3	Butyl rubber
4	Chloroprene
5	Chlorinated Polyethylenes
6	Ethylene –Propylene
7	Fluorosilicone rubber
8	Fluorocarbon rubber
9	Nitrile rubber
10	Natural rubber
11	Polyethylene
12	Polystyrene
13	Polymethyl Chloride(PVC)
14	Polymethyl Methacrylate(PMMA)
15	Polybutadiene

4.3.4 Properties of Viscoelastic Damper

Properties of the viscoelastic damper are determined by testing the damper under sinusoidal excitations at prescribed frequencies, temperatures and strains. Test results show that, in general damper properties are functions of temperature, loading frequency and strain. The properties of VE damper are usually described in terms of its storage shear modulus (G'), loss of shear modulus (G'') and loss factor (η_d). Some major properties of damper, which are important for further analysis, are defined in the following subsections.

4.3.4.1 Force – Displacement Relationship

The best method of evaluating the properties of the damper is to evaluate its hysteresis loop from test results, which is the plot of periodic displacement and the corresponding shear force on an x-y recorder as shown in Fig 4.5.

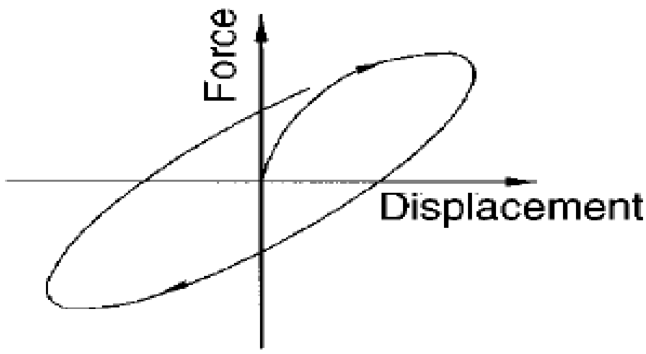


Fig 4.5 Idealized Force-Displacement Loop for VE Damper.

The area enclosed in loop represents the energy dissipation by the damper per cycle. The energy loss per cycle is proportional to the volume of viscoelastic material, which is given by the expression,

Energy loss $$W = \pi \times \gamma d^2 \times G'' \times V$$ ... (4.2)

Based on load deformation relation obtained from tests on damper, the important dynamic parameters of the damper such as energy dissipation per cycle, damping etc. at each ambient temperature and excitation frequency have been calculated by researchers. In order to consider all factors affecting properties of VE dampers in design, James .M. Kelley proposed the empirical formula for Shear modulus , loss modulus and loss factor based on regression analysis using data obtained from tests on dampers.

.. $$G' = 16.0\omega^{0.51}\gamma^{-0.23}e^{(72.46/T)}$$ ... (4.3)

$$G'' = 18.5\omega^{0.51}\gamma^{-0.20}e^{(73.89/T)} \quad \ldots (4.4)$$

$$\eta_d = G''/G' \quad \ldots (4.5)$$

Where, η_d is the ratio of loss of shear modulus to the storage shear modulus ω is frequency of dominant mode of vibration γ is shear strain and T is operating temperature.

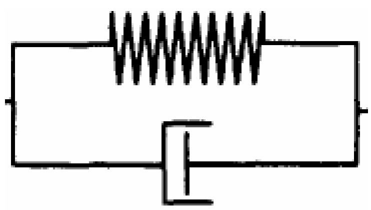
4.3.4.2 Damping Force Provided By the Viscoelastic Damper

The VE damper is modeled as an elastic spring and dashpot acting in parallel as shown in Figure 4.6 .This is as per model suggested by Kelvin The force in the damper is the sum of the elastic and viscous force and both elements are subjected to same deformation. The stiffness of the elastic spring and the damping coefficient of dashpot for viscoelastic damper are defined as,

$$k_d = \frac{G' \times A_d}{t_d} \quad \ldots (4.6)$$

$$c_d = \frac{G'' \times A_d}{\omega_d \times t_d} \quad \ldots (4.7)$$

k_d



c_d

Fig 4.6 Model For Viscoelastic Damper.

VE damper provides a velocity dependent damping force but possesses an elastic stiffness in addition to this damping**.** Damping force provided by the VE damper is given by,

$$Fd = (k_d \times u_d) + (c_d \times u_2) \qquad \dots (4.8)$$

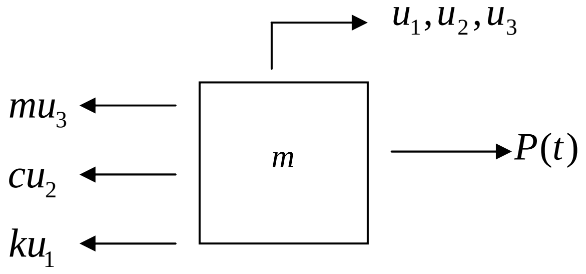


Fig 4.7 Free Body Diagram of SDOF

Where,

mu_3 Inertia force

cu_2 Damping force

ku_1 Elastic restoring force

$P(t)$ External Force

u_d Shear deformation of VE damper, which is controlled by maximum shear strain of damper, which is given by,

$$u_d = t_d \times \gamma_d \qquad .. (4.9)$$

The thickness of VE damper (t_d) has a lower bound to prevent VE damper from shear failure.The stiffness and damping coefficient of VE damper vary with the frequency of the dynamic load. Although dynamic loads such as earthquake and wind have a large number of frequency contents, in many structures structural response to these loads are dominated by a single vibration mode. Based on this observation, damping coefficient of VE damper is assumed to be constant and is calculated for the natural frequency of the dominant vibration mode.

4.3.4.3 Relationship between Temperature Rise and Nonlinearity of Viscoelastic Damper

After a series of tests performed, it became apparent that the viscoelastic material's loss in shear modulus G'' and hence energy dissipation per cycle varies inversely with temperature. Loss factor reduces with increases in temperature and thus loss of shear modulus also reduces with temperature. When VE material is subjected to a large strain excitation, a portion of the mechanical energy is dissipated and converted into heat, the temperature in the VE material raises as the by-product and the VE material softens, that will then behave nonlinearly.

As number of loading cycles increase temperature increases. Test results show that the relationship seems to be approximately linear for the first 100 cycles as shown in Figure 4.8. After about 400 cycles a steady state of heat loss to the surrounding environment is maintained, and it is safe to assume that G'' (loss of shear modulus) or the loss factor or the energy loss per cycle remains constant beyond this point.

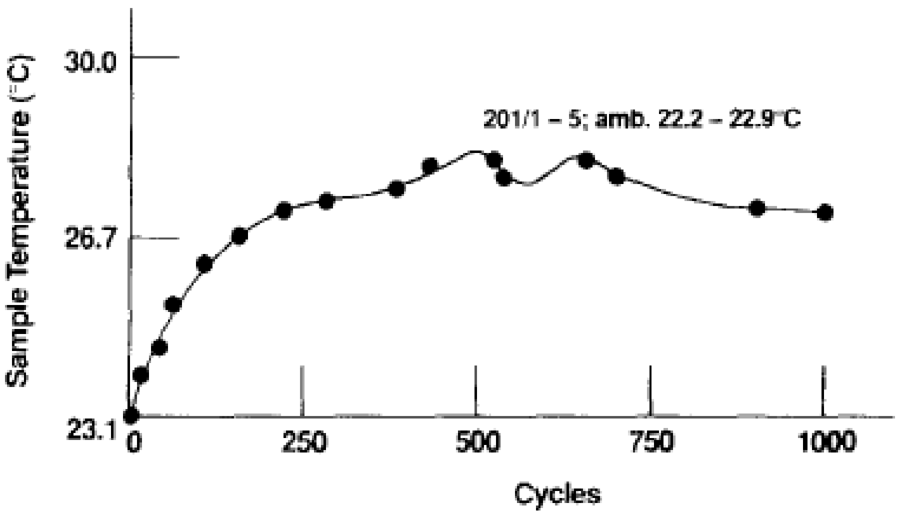


Fig 4.8 Variation of Temperature of VE Material Sample with Load Cycle

In fact, the temperature rise effect on the material properties is temporary since experiments show that the material returns to its original properties as the heat in the material is dissipated.

4.3.4.4 Equation of Motion for Viscoelastically Damped Structure

To solve equation of motion for a system with viscous damping, we take the value of damping coefficient as a certain percentage of critical damping. For consideration of viscoelastic damper in the equation of motion; the equation is to be modified by changing damping force term in general equation [13]

1. General equation of motion for SDF system is given by

$$mu_3 + cu_2 + ku_1 = P(t) \quad \text{... (4.10)}$$

Now substituting damping force provided by viscoelastic damper this equation of motion will become

$$mu_3 + F_d + ku_1 = P(t) \quad \text{... (4.11)}$$

Substituting Equation we get

$$mu_3 + (k_d \times u_d + c_d \times u_2) + ku_1 = P(t) \quad \text{... (4.12)}$$

2. Dampers are generally placed in the inclined bracing as shown in Figure which is most effective in achieving large energy dissipation and thus reducing storey drift.

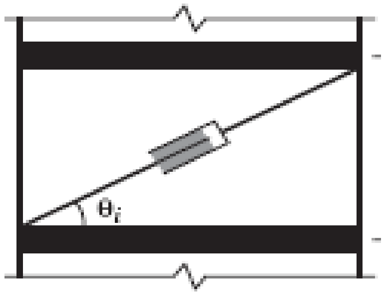


Fig 4.9 Placement Of Viscoelastic Damper.

When damper is placed in the inclined bracing, with angle of inclination θ_i with horizontal floor, displacement of viscoelastic damper (u_d) horizontally in terms of storey displacement, will be given as,

$$u_d = u_1 \times \cos\theta_i \quad \text{... (4.13)}$$

Thus, Equation becomes,

$$mu_3 + (k_d \times u_1 \times \cos\theta_i + c_d \times u_2) + ku_1 = P(t)$$

Thus, final equation of motion for viscoelastically damped frame can be given as,

$$mu_3 + (k_d \times \cos\theta_i + k)u_1 + c_d \times u_2 = P(t) \quad \text{... (4.14)}$$

3. Comparing Equations, total stiffness of viscoelastically damped frame can be given as,

$$k_{d1} = k_d \times \cos\theta + k$$

... (4.15)

Thus Equation will become

$$mu_3 + c_d \times u_2 + k_{d1} \times u_1 = P(t) \qquad \dots (4.16)$$

4. For MDF system, general equation of motion and with reference to Equation can be modified for viscoelastically damped structure as follows,

$$M\{u_3\} + C_d\{u_2\} + K_d\{u_1\} = \{P(t)\} \qquad \dots (4.17)$$

Where,

Total stiffness matrix (K_d) and damping matrix C_d for the viscoelastically damped frame can be developed. The common form of matrix for n storey can be given as,

Total Stiffness Matrix

$$K_D = K_d \times \cos\theta_i + K \qquad \dots (4.18)$$

Where, K_d is the stiffness matrix of dampers

And C_d is the damping matrix of dampers

$$C_d = \begin{bmatrix} c_{d1} + c_{d2} & -c_{d2} & 0 & 0 \\ -c_{d2} & (c_{d2} + c_{d3}) & 0 & 0 \\ 0 & -c_{d3} & 0 & -c_{dn} \\ 0 & 0 & -c_{dn} & c_{dn} \end{bmatrix}$$

4.3.5 DESIGN OF VISCOELASTIC DAMPER

Viscoelastic dampers have been used successfully in several high rise buildings for the effective reduction of earthquake or wind induced response. Both analytical and experimental studies have shown that a significant reduction in a structure's response to earthquake excitation can be achieved by adding properly designed viscoelastic dampers. Following design procedure illustrate the parameters like number, size and required properties of damper for any structure to achieve target structural response.

.

Steps for Designing of Viscoelastic Damper

1) Prior to design it is required to decide, desired damping ratio that should be achieved to reduce prescribed response level of structure. For this, the 3-D RC frame Building was analyzed for assumed damping ratio Z_n and checked for the

Response quantities. If these quantities are with in acceptable limits then that structural system will have to be designed for assumed damping ratio.

2) The required stiffness of viscoelastic damper was found from the following expression, which gave the damper of particular stiffness, for design damping ratio.

$$k' = \frac{2\xi}{\eta_D - 2\xi} k_s \qquad \text{... (4.19)}$$

Where k' was stiffness provided by the damper at each storey level ξ was the desired damping ratio, η_D was the loss factor, k_s was the storey stiffness of the structure without added dampers.

3) Determination of thickness of damper: The thickness of VE material can be determined based on the maximum allowable damper deformation. This is controlled by maximum allowable storey drift ratio. Damper thickness is also controlled by maximum allowable strain in material (γ). Final thickness can be given as,

$$t_d = \frac{0.005 \times h_s \times \cos\theta}{\gamma_d} \qquad \text{... (4.20)}$$

Where t_d is the thickness of one layer of viscoelastic material in a damper and h_s is the typical storey height, θ is angle of inclination of damper and γ_d is the allowable shear strain in the material which is assumed to remain constant at 100%.

4) Determination of the Damper Area: The area of damper can be determined from the Equation 4.6 page no. 34 Thus, damper size can be decided by assuming width and then finding required length of damper.

5) Determination of Damper properties: Properties of damper like Shear Modulus, Loss Factor can be decided as per the temperature for which damper is to be

designed. Maximum allowable strain in VE material will also change as per design temperature, to avoid the nonlinear behavior of VE material.

6) The 3-D frame Building can be analyzed now with added VE damper. We can find damping ratio achieved from the following equation. The equation has been derived from Model Strain Energy Method. If damping ratio is equal to design damping ratio as decided previously then design was complete, else the process was repeated by changing properties or other parameters to get the desired damping ratio.

$$Z_n = \frac{\eta_d}{2}\left(1 - \frac{\omega_n^2}{\omega_{d_n}{}^2}\right) \qquad \text{... (4.21)}$$

Where ω_n and ω_{d_n} were the natural frequency and damped natural frequency of the system and η_d is loss factor.

4.3.6 MODELING THROUGH SAP-2000

In this section the 3-D RC frame defined in Chapter -3 was chosen and viscoelastic dampers were modeled for G+3 storey building and similar procedure of modeling was extended to G+9 storey building. The modeling procedure of viscoelastic damper was similar to viscous damper the only difference was viscoelastic damper increases stiffness and damping of the structure while in viscous damper only damping was enhanced. For getting stiffness and damping of viscoelastic damper, the damper needs to be designed and properties calculated in section 4.3.6.1 are to be feeded to the model made in SAP-2000 to check the response of the structure equipped with viscoelastic damper.

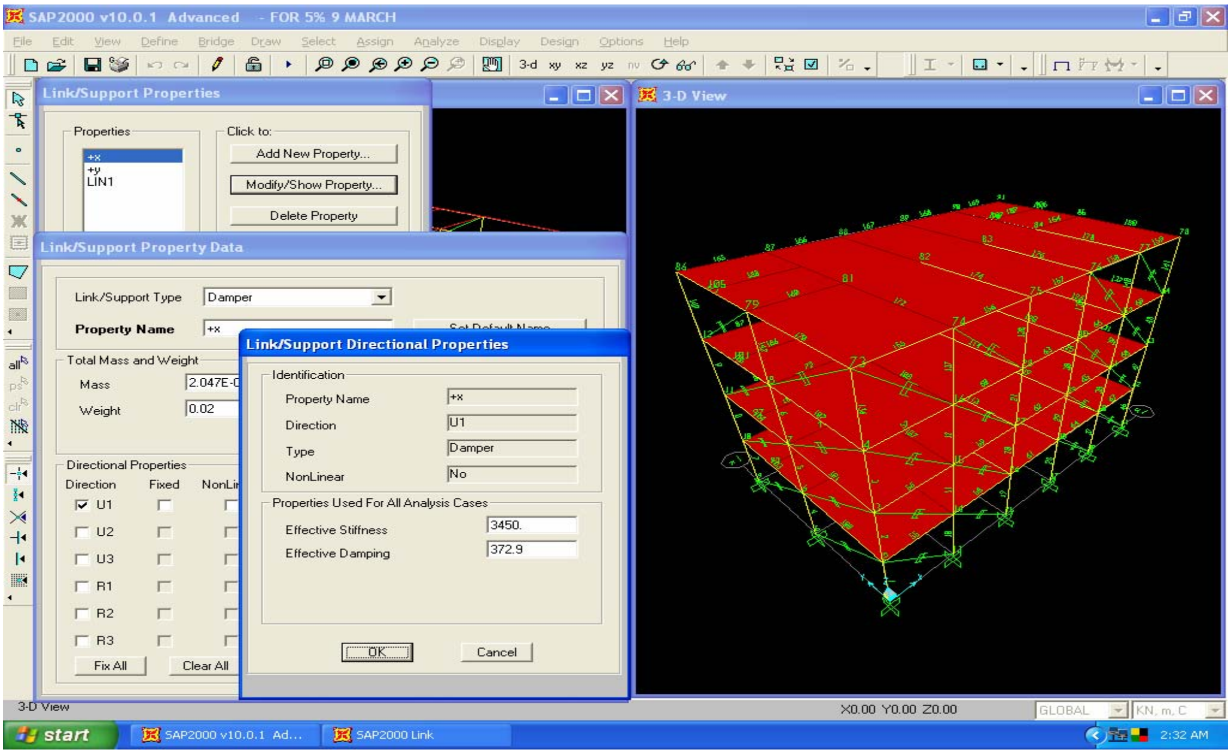


Fig 4.10 Assigning the Viscoelastic Damper to Structure

4.4 ANALYSIS METHODS FOR DAMPERS

This section deals with analysis procedures for damper added structure & discusses various analysis methods specified by FEMA-440.

4.4.1 Methodology

4.4.1.1 Nonlinear Structure / Nonlinear Damper

The maximum displacement of a building generally exceeds its yield displacement in a design earthquake. it is also possible in case of structure equipped with dampers. The damper behavior is generally non linear in local displacement or local velocity as well as in displacement at device, Hence nonlinear dynamic time history analysis in which nonlinearities in structural as well as dampers are accounted for provides most rigorous and complete analysis. There are several approximate methods for analyzing nonlinear damper added structure for example simplified nonlinear static procedures presented in FEMA -440 are available for evaluating the inelastic response of damper added structures subjected to earthquakes.

4.4.1.2 *Nonlinear Structure / Linearized Damper*

The nonlinear procedure can be simplified considerably by using linear characterization of dampers. In this approach the equivalent linear damping and stiffness characteristics of dampers were first integrated with those of the structural elements. This step allows nonlinear analysis of damper-added structures to follow the procedures used with traditional structures with modified damping and stiffness elements.

4.4.1.*3 Linear Structure / Non Linear Damper*

Simplifications also result when damper added structure was expected to behave linearly or can be linearized via one of the equivalent linearization techniques. Although nonlinear behavior of the damper still requires nonlinear modeling of damper added structural system, the use of existing computer programs become simpler when structural elements are represented by linear elements. A good step towards further simplification is to use linear characterization of damper as well.

4.4.1.4 Linear Structure / Linear Damper

When damper added structure was expected to behave linearly or can be linearized, then incorporating the linearized behavior of the damper makes the analysis of damper –added structure linear, for linear structure, the model analysis in time domain and response spectrum analysis are well known, Thus this procedure is attractive because it follows conventional design procedures .Even in situations where these linearized assumptions are not strictly valid, results of this procedure can provide useful preliminary information on damper design and on behavior of damper added structure.

In case of the time history and response spectrum analysis procedures, one possible complication is the mode shapes for structures with significant non proportional damping are complex. However deviation of the exact mode shapes from those assuming proportional damping are usually not significant, this eliminates the added task of dealing with complex mode shapes for the response spectrum analysis.

4.4.2 Response Spectrum Analysis

It has become generally accepted that the mathematical models can be devised to reasonably represent real structures being subjected to strong ground motion and that suitable analytical methods may be employed to simulate and monitor the loading and response of such structures. It was also recognized that the dynamic behavior of any structural system is governed not only by the nature of applied loads but also by dynamic characteristics of the system itself. Because earthquake ground motions are erratic in nature they can not be represented mathematically by a single continuous function for which closed form solution can be obtained. One analytical method of computing dynamic response of a structure, the Modal Superposition Method, recognizes that for a linearly elastic system vibrating with in elastic range, there exists a unique characteristic mode corresponding to each degree of freedom in the system, and that the total response of the system can be represented by the sum of the individual responses from each of the characteristics mode. Since this method is very time consuming as an alternative Response Spectrum analysis can be used to solve the equation of motion .it provides an estimate of maximum response of the structure and does not require the computations of the complete time history of the response.

As illustrated in previous section 4.4 Page no. 41 four cases were undertaken for analysis of building with added dampers. Response Spectrum Method can be used but the basic concept underlying the response spectrum method is that damping is distributed uniformly through out the building and therefore while placing the dampers in a building they should be placed as symmetrically as possible. The reason being Response Spectrum analysis is used for proportionally damped systems.

5. RESULTS AND DISCUSSION

5.1 INTRODUCTION

This Chapter presents the results obtained through analysis of R.C. frame building with Velocity dependent energy dissipation devices (Viscous & Viscoelastic damper). The response of R.C frame building in the form of Displacement, Base shear and Drift were obtained. The analysis method used was Response Spectrum analysis through out. In addition various parameters like time period variation, temperature effect, storey height variation & damper locations were explored critically and same are presented.

5.2 3-D R.C FRAME G+3 STOREY BUILDING WITHOUT DAMPERS

The problem of 3-D R.C. frame has been formulated in chapter– 3(Clause no.3.3 & Page no. 23).This section presents response parameters when a building is analyzed for inherent damping only. The building considered here acts like a bare frame as no brick infills are considered and damping allocated was 5% of critical. Fig 5.1 shows the computational model of G+3 R.C. frame building. Results for base shear & displacement are shown in Table 5.1 & Table 5.2 for various load combinations.

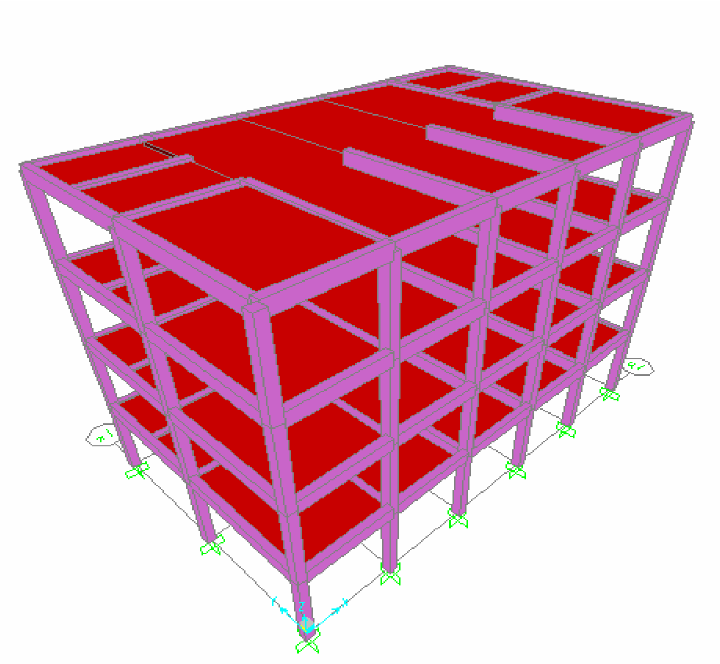


Fig 5.1 3-D RC Frame Building without Dampers

Table 5.1 Base Shear Results for Bare Frame

Load Combination	Base Shear(+X) (kN)	Base Shear(+Y) (kN)
1.5DL+1.5EQ+X/1.5DL+EQ+Y	360	354

Table 5.2 Displacement Results for Bare Frame

Storey No.	Load Combination	Displacement(+X) (mm)	Displacement(+Y) (mm)
4	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	12	13.3
3	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	10.4	11.5
2	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	7.4	8.1
1	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	3.5	3.8

It is quiet evident from Table 5.1 & Table 5.2 that displacement at top storey is maximum. Also, note that the displacement & base shear in both directions are almost same, as building was symmetric & properties of all structural elements were same.

5.3 3-D R.C FRAME G+3 STOREY BUILDING WITH VISCOUS DAMPERS

After designing viscous dampers for four storey building they were modeled in SAP-2000. This section provides the response of structure when 5% additional damping has been provided through viscous damper. Results for base shear & displacement are shown in Table 5.3 & Table 5.4.

Table 5.3 Base Shear Results for Frame with Viscous dampers (5% Added Damping)

Load Combination	Base Shear(+X) (kN)	Base Shear(+Y) (kN)
1.5DL+1.5EQ+X/1.5DL+EQ+Y	251	230.52

Table 5.4 Displacement Results for Frame with Viscous dampers (5% Added Damping)

Storey No.	Load Combination	Displacement(+X) (mm)	Displacement(+Y) (mm)
4	1.5DL+1.5EQ+X/1.5DL+EQ+Y	8.5	8.5
3	1.5DL+1.5EQ+X/1.5DL+EQ+Y	7.1	7.4
2	1.5DL+1.5EQ+X/1.5DL+EQ+Y	5.1	5.3
1	1.5DL+1.5EQ+X/1.5DL+EQ+Y	2.4	2.5

From results obtained through dynamic analysis is as shown in Table 5.3 & Table 5.4.It is evident that there is reduction in displacement of 29.16% in +X direction and 36.09% in +Y direction. Also, there is substantial reduction in base shear i.e. about 30% in both the direction (+X & +Y) for 5% additional damping.

5.4 3-D R.C FRAME G+3 STOREY BUILDING WITH VISCOELASTIC DAMPERS

The design of Viscoelastic dampers were done as explained in Chapter Clause 4.3.4 subsection 4.3.4.2 Page No. 34. This section represents results of analysis obtained for R.C. frame building with Viscoelastic dampers as shown in Table 5.5 & Table 5.6

Table 5.5 Base Shear Results for Frame with VE damper (5% Added damping)

Load Combination	Base Shear(+X) (kN)	Base Shear(+Y) (kN)
1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	237	223

Table 5.6 Displacement Results for Frame with VE damper (5% Added damping)

Storey No.	Load Combination	Displacement(+X) (mm)	Displacement(+Y) (mm)
4	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	6.8	8.2
3	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	5.9	7.1
2	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	4.3	5.1
1	1.5DL+1.5EQ+X/ 1.5DL+EQ+Y	2.1	2.4

From the results shown in Table 5.5 & Table 5.6, it is clear that substantial reduction in displacement of 43% in +X direction and 38.3% in +Y direction took place. The reduction in base shear is more than 35% in both directions (+X &+Y), which is more than viscous damper results. Since in case of Viscoelastic damper there is addition of both Stiffness and damping and in viscous damper there is only addition of damping, so the results seems quiet logical.

5.5 PARAMETRIC COMPARISION OF VISCOUS & VISCOELASTIC DAMPERS

This section provides the results for the parametric studies that have been carried out on Viscous & Viscoelastic dampers.

5.5.1 Response of Structure for Higher Levels of Damping

In order to calculate response of structure to higher level of damping both Viscous and Viscoelastic dampers were designed up to 30% additional damping which a feasible option as explained in FEMA-273. Also, reference can be made through literature where damping upto 30% had been used. Results obtained are compared and discussed here Table 5.7 gives the comparison of model period for the frame equipped with Viscous and Viscoelastic Damper.

Table 5.7 Comparison of Time Period for various models

Additional Damping	Time Period (For Bare Frame in secs)	Time Period (Frame with Viscous Damper in secs)	Time Period (Frame with Viscoelastic Damper in secs)
0	0.64	0.64	0.64
5	0.64	0.64	0.58
10	0.64	0.64	0.56
15	0.64	0.64	0.54
20	0.64	0.64	0.51
25	0.64	0.64	0.49
30	0.64	0.64	0.46

From Table 5.7 it can be said that there is no change in time period when viscous dampers were used in the building which is quiet true since Viscous damper only imparts damping to the structure. However, in case of Viscoelastic damper there is reduction in modal time period as amount of additional damping increases because Viscoelastic Damper imparts both Stiffness and Damping to the Building.

Following tables shows the results obtained for various response parameters in case of Viscous Damper

Table 5.8 Base Shear at Various Levels of Damping for Viscous Damper

Additional Damping (%)	Base Shear(kN) (+X direction)	Base Shear(kN) (+Y direction)
0	360	354
5	251	230
10	206	184
15	168	147
20	147	125
25	128	106
30	110	89

Table 5.9 Joint Displacements at Various Levels of Damping for Viscous Damper (+X Direction)

Storey No.	Displacement (in mm)						
Additional Damping	0%	5%	10%	15%	20%	25%	30%
4	12	8.5	6.6	5.2	4.5	3.9	3.4
3	10.4	7.1	5.7	4.6	4	3.4	3
2	7.4	5.1	4.1	3.3	2.9	2.5	2.2
1	3.5	2.4	2	1.6	1.4	1.2	1.1

Table 5.10 Joint Displacements at Various Levels of Damping for Viscous Damper (+Y Direction)

Storey No.	Displacement(in mm)						
Additional Damping	0%	5%	10%	15%	20%	25%	30%
4	13.3	8.5	6.7	5.3	4.5	3.8	3.2
3	11.5	7.4	5.8	4.6	3.9	3.3	2.7
2	8.1	5.3	4.2	3.3	2.8	2.4	2
1	3.8	2.5	2	1.6	1.3	1.1	1

The above listed results can be graphically represented as shown in Fig 5.2 and Fig 5.3 for 3-D frame building with viscous damper.

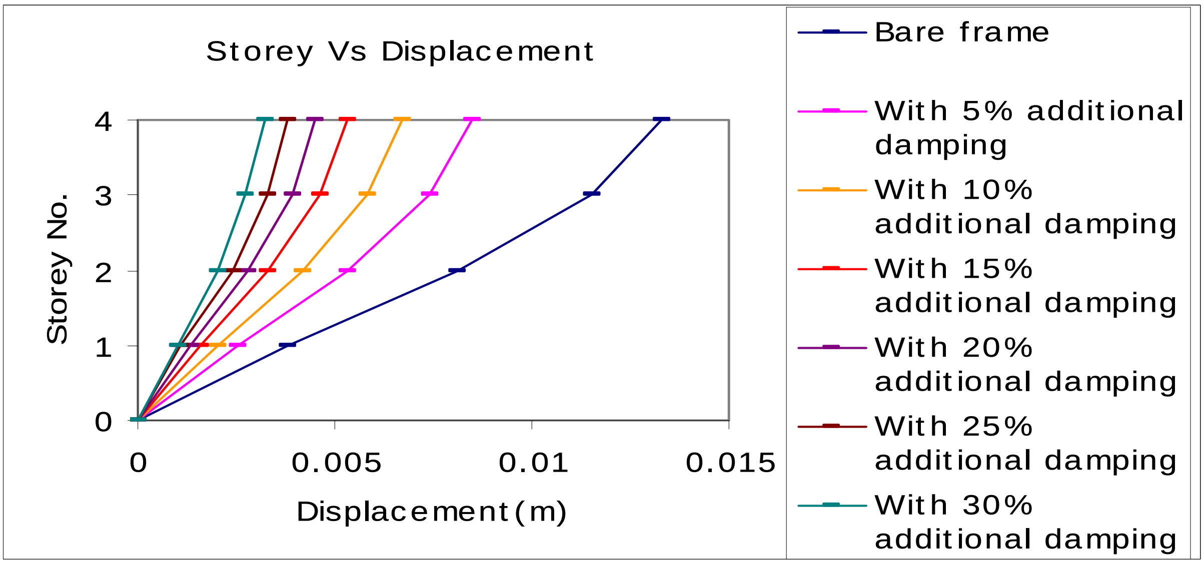


Fig 5.2 Displacements at Various Levels of Damping for Viscous Damper

(+ X direction)

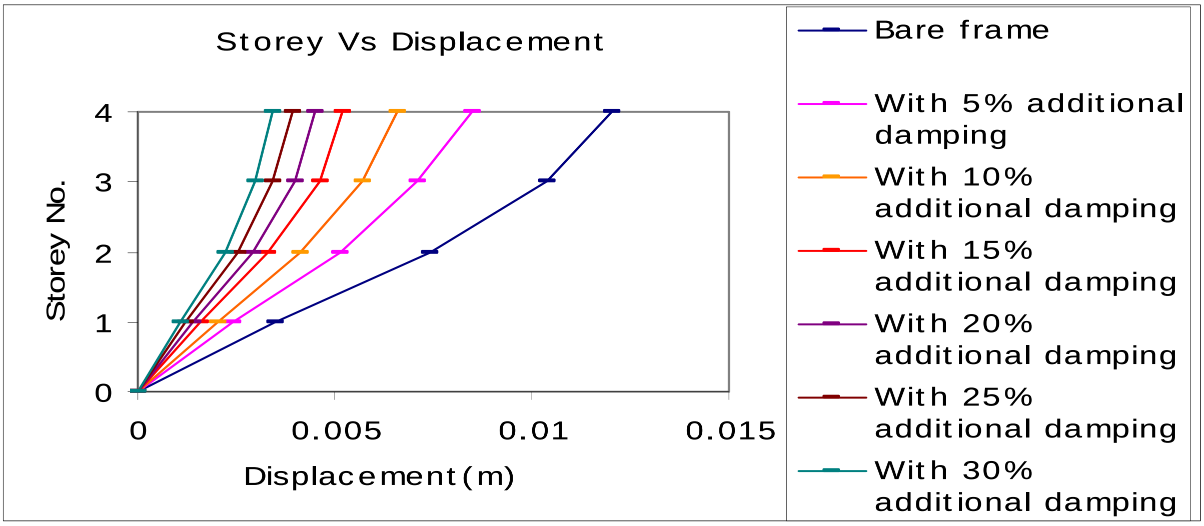


Fig 5.3 Displacements at Various Levels of Damping for Viscous Damper (+ Y Direction)

Above results for Viscous damper shows the influence of damping on response of the structure. As percentage of damping increases there is substantial reduction in displacement and for additional 30% damping the reduction in displacement is approximately 70% in both directions also reduction in base shear is approximately 70% in both directions.

Fig 5.4 & Fig 5.5 shows the graphical representation of drift for various levels of damping.

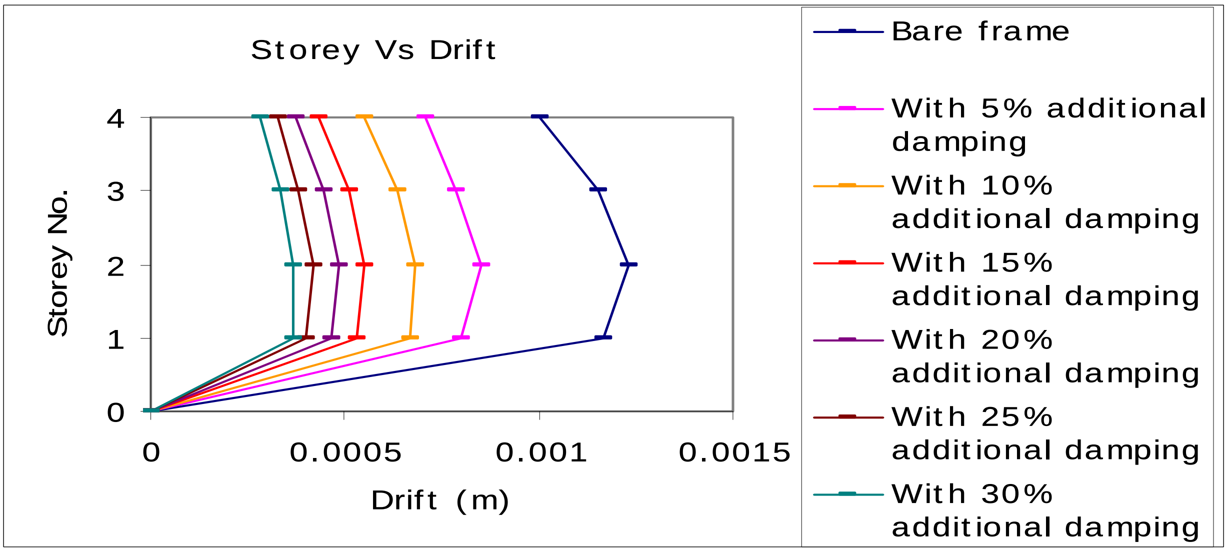


Fig 5.4 Drift at Various Levels of Damping for Viscous Damper (+X Direction)

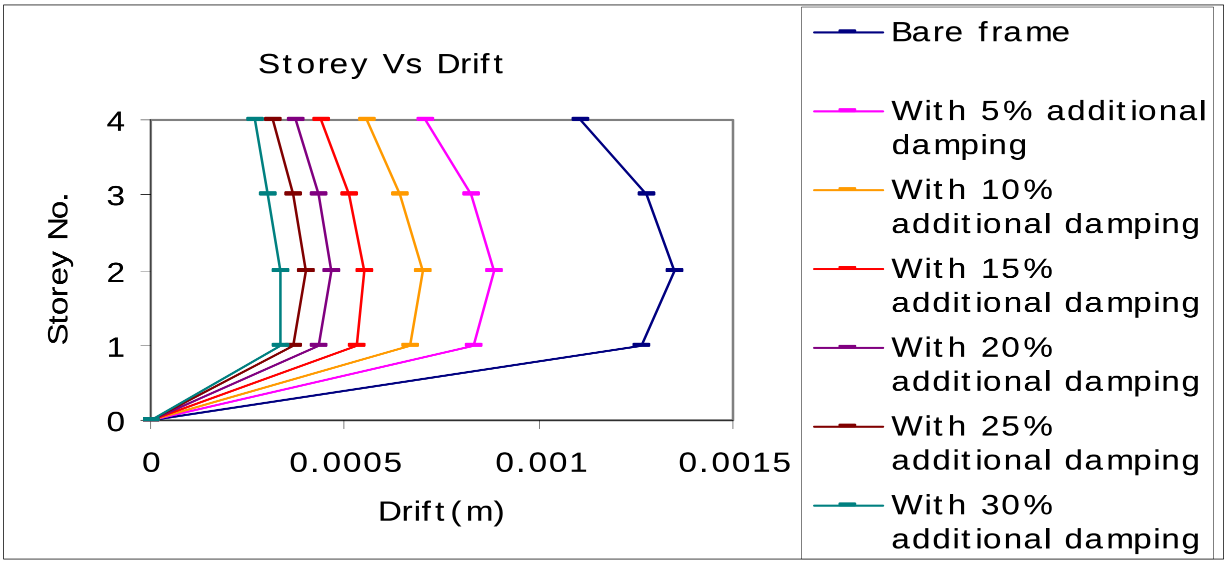


Fig 5.5 Drift at Various Levels of Damping for Viscous Damper (+Y Direction)

It is clear from the above graphs that there is continuous reduction in drift as amount of damping increases. However, there are some provisions given in IS-

1893-2002(Part-I) Clause no.7.11 Page no. 27 [11] about the limiting drift. It can be said by use of dampers there is substantial reduction in drift.

Following tables shows the results obtained for various response quantities in case of Viscoelastic Damper

Table 5.11 Base Shear at Various Levels of Damping for Viscoelastic Damper

Additional Damping (%)	Base Shear in kN (+X direction)	Base Shear in kN (+Y direction)
0	360	354
5	236	247
10	210	210
15	177	174
20	152	152
25	138	134
30	119	121

Table 5.12 Joint Displacements at Various Levels of Damping for Viscoelastic Damper (+ X direction)

Storey No.	Displacement(in mm)						
Additional Damping	0%	5%	10%	15%	20%	25%	30%
4	12	6.8	5.9	3.8	3.5	2.9	2.4
3	10.4	5.9	5.1	3.3	3.1	2.6	2
2	7.4	4.3	3.7	2.4	2.3	1.9	1.5
1	3.5	2.1	1.9	1.2	1.1	1	.8

Table 5.13 Joint Displacements at Various Levels of Damping for Viscoelastic Damper (+Y direction)

Storey No.	Displacement(in mm)						
Additional Damping	0%	5%	10%	15%	20%	25%	30%
4	13.3	8.2	6.6	4.9	3.9	3.1	2.5
3	11.5	7.1	5.7	4.2	3.4	2.7	2.2
2	8.1	5.1	4.1	3.1	2.5	2	1.6
1	3.8	2.4	2	1.5	1.2	1	0.8

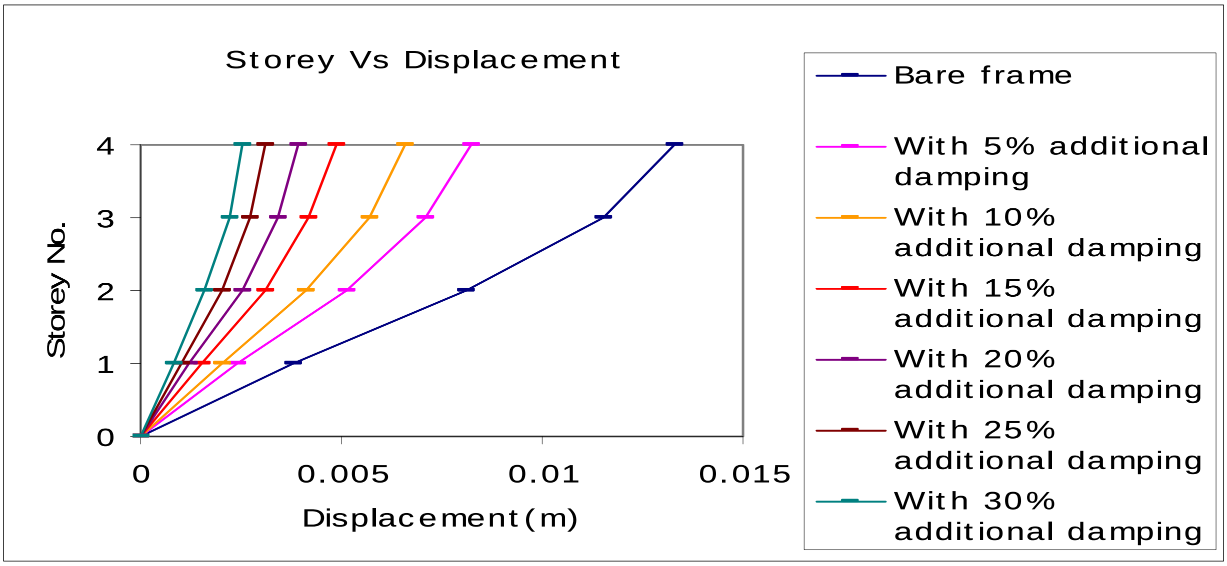


Fig 5.6 Displacements at Various Levels of Damping for Viscoelastic Damper (+X direction)

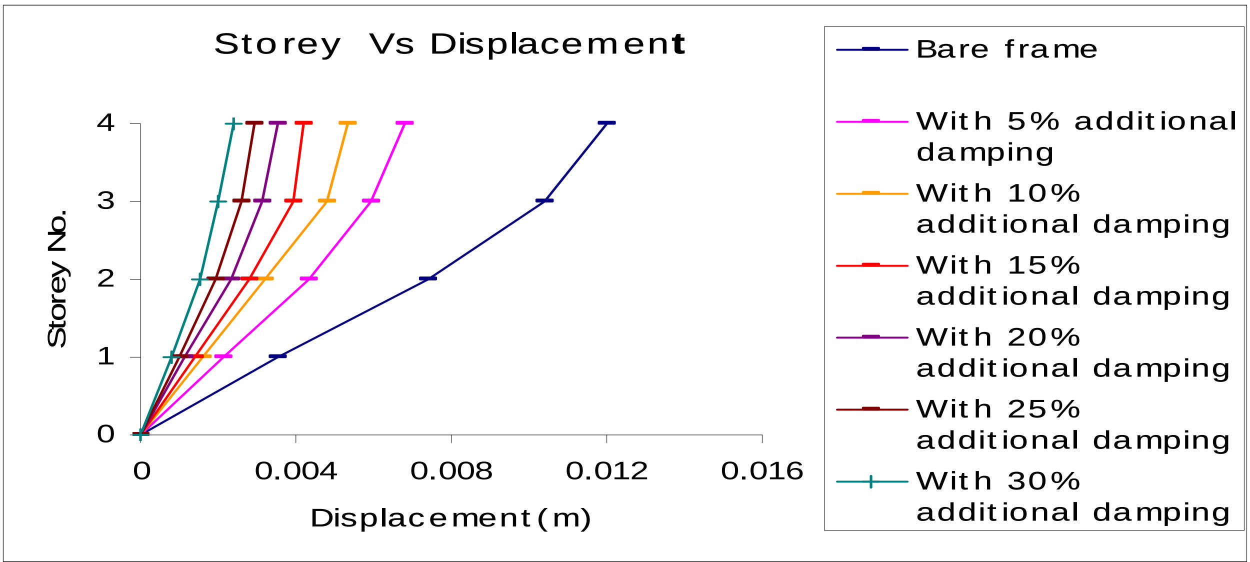


Fig 5.7 Displacements at Various Levels of Damping for Viscoelastic Damper (+Y direction)

As per results shown in Table 5.10 & Table 5.12 it can be interpreted that there is substantial reductions of displacement in both X and Y direction that is approximately 80%. It is seen that displacement reduction in case of Viscoelastic damper is more than in case of viscous damper due to additional Stiffness contributed by Viscoelastic damper. It is also interesting to note that major reduction in response parameters occurs for additional 5% damping that shows even 5% additional may be good enough for some buildings which will definitely lead to overall economy. The reduction is base shear is approximately 67% for both direction which is less than in case of Viscous damper since Viscous damper imparts more flexibility to the structure Graphical representation of response parameters have been shown from Fig 5.6 to Fig 5.7

The graphical representation of drift in +X & +Y direction for Viscoelastic dampers are as shown in Fig5.8 & Fig 5.9

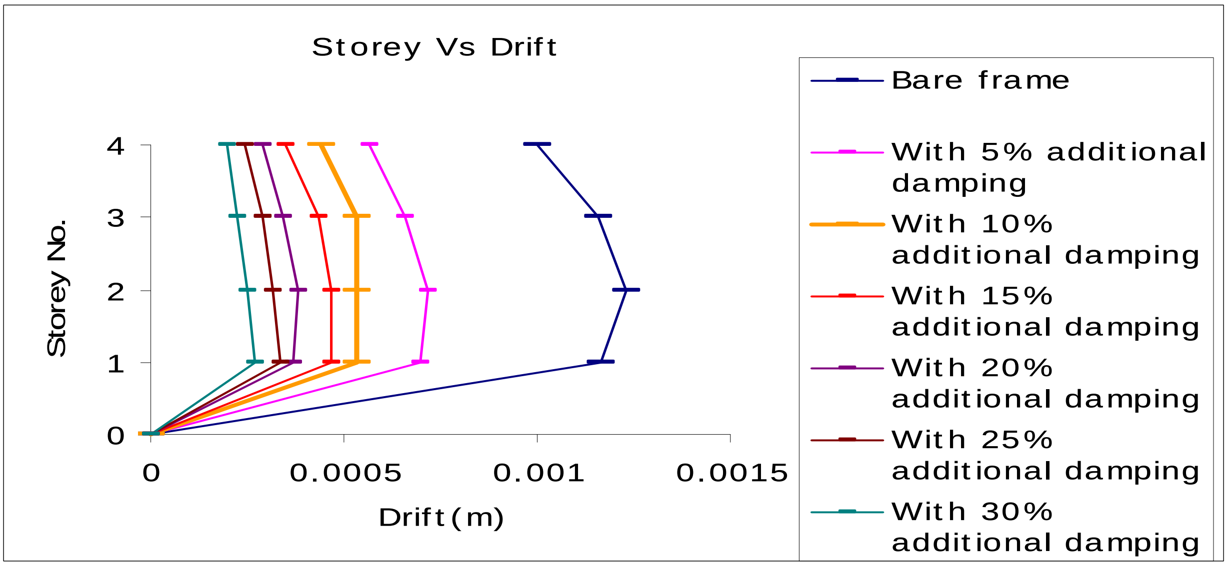


Fig 5.8 Drift at Various Levels of Damping for Viscoelastic Damper (+X Direction)

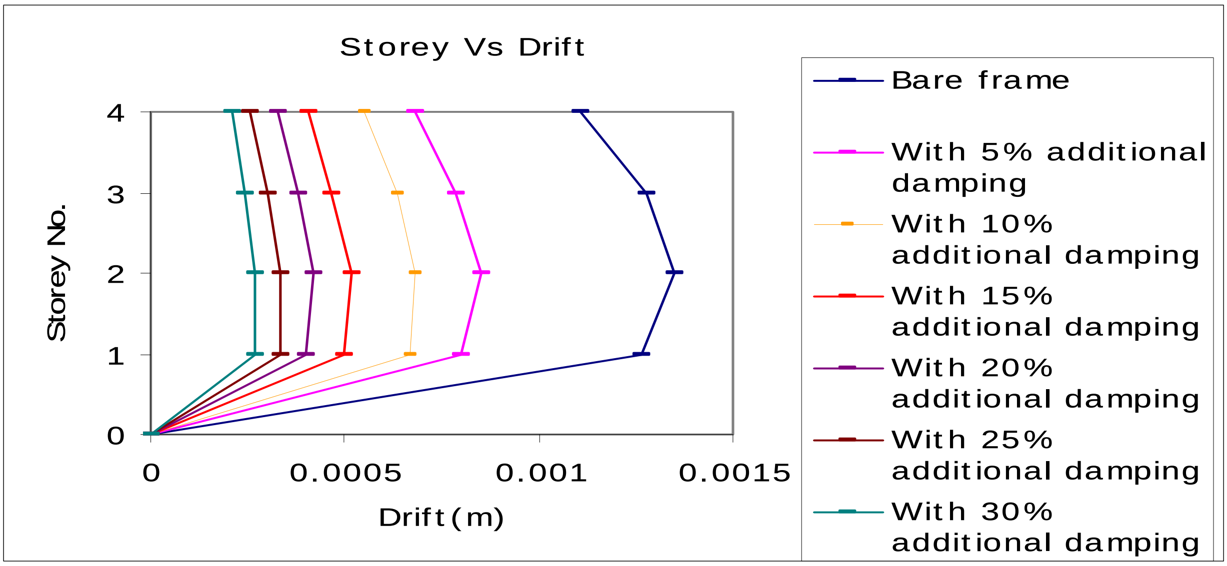


Fig 5.9 Drift at Various Levels of Damping for Viscoelastic Damper (+Y direction)

From the Fig 5.8 & Fig 5.9 it is clear that there is continuous reduction in drift for Viscoelastic damper also. It is interesting to note that drift reduction in case of Viscoelastic damper is more as compared to viscous damper.

5.5.2 Effect of Variation of Storey Height

In some buildings it has been seen that there is increase in height of a particular storey. It is usually in case of ground storey that is used for parking purposes, but there may be change in storey height at any level. This ultimately leads to soft storey problem. In this study height of every storey is enhanced one by one and response of structure is compared when the same building is equipped with Viscoelastic damper of 15% additional damping.

Table 5.14 Displacement Results for Changing First Storey Height (+X &+Y Direction)

Storey Height	Displacement in mm (bare frame)		Displacement in mm (with dampers)	
	(+X Direction)	(+Y Direction)	(+X Direction)	(+Y Direction)
13.5	16	16.7	6.7	6.6
10.5	14.8	15.4	6.1	6
7.5	12.5	12.9	5.1	5
4.5	9.1	9.2	3.7	3.5
0	0	0	0	0

Table 5.15 Displacement Results for Changing Second Storey Height (+X &+Y Direction)

Storey Height	Displacement in mm (bare frame)		Displacement in mm (with dampers)	
	(+X Direction)	(+Y Direction)	(+X Direction)	(+Y Direction)
13.5	15.6	16.2	6.3	6.1
10.5	14.1	14.9	5.7	5.6
7.5	11.7	12.2	4.7	4.5
3	3	3.1	1.3	1.3
0	0	0	0	0

Table 5.16 Displacement Results for Changing Third Storey Height (+X Direction)

Storey Height	Displacement in mm (bare frame)		Displacement in mm (with dampers)	
	(+X Direction)	(+Y Direction)	(+X Direction)	(+Y Direction)
13.5	15	15.5	5.7	5.7
10.5	13.1	13.9	5.2	5.1
6	6.1	6.4	2.6	2.7
3	2.7	2.8	1.2	1.3
0	0	0	0	0

Table 5.17 Displacement Results for Changing Forth Storey Height (+X &+Y Direction)

Storey Height	Displacement in mm (bare frame)		Displacement in mm (with dampers)	
	(+X Direction)	(+Y Direction)	(+X Direction)	(+Y Direction)
13.5	15.1	15.7	5.5	5.6
9	10.2	10.7	4.1	4.2
6	7.2	7.5	3	3
3	3.4	3.5	1.5	1.5
0	0	0	0	0

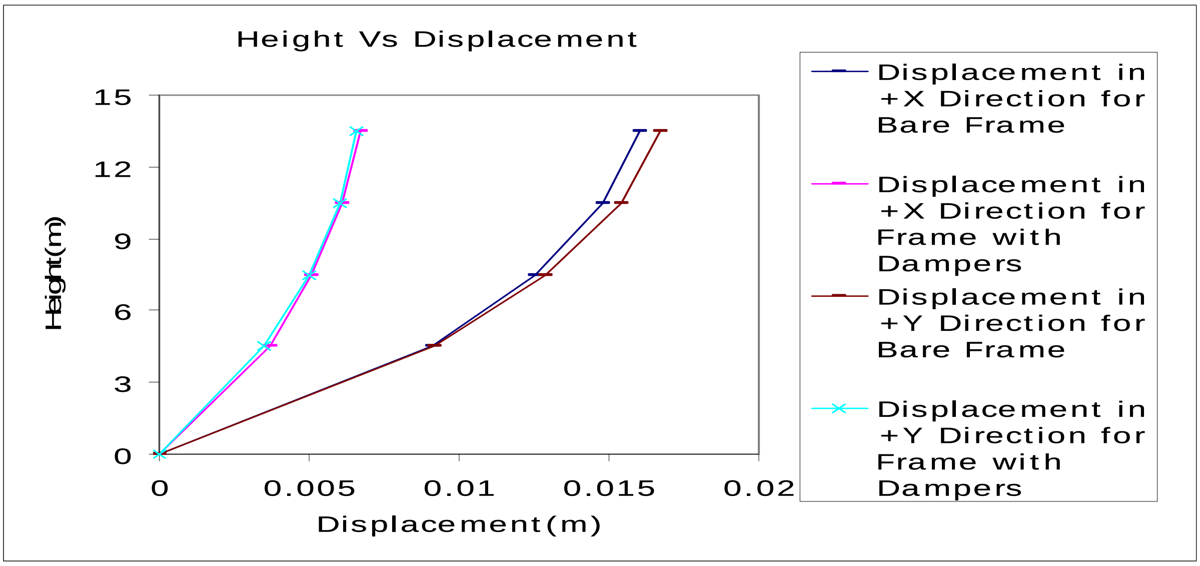


Fig 5.10 Graph Showing Increase in Displacement by changing first Storey ht

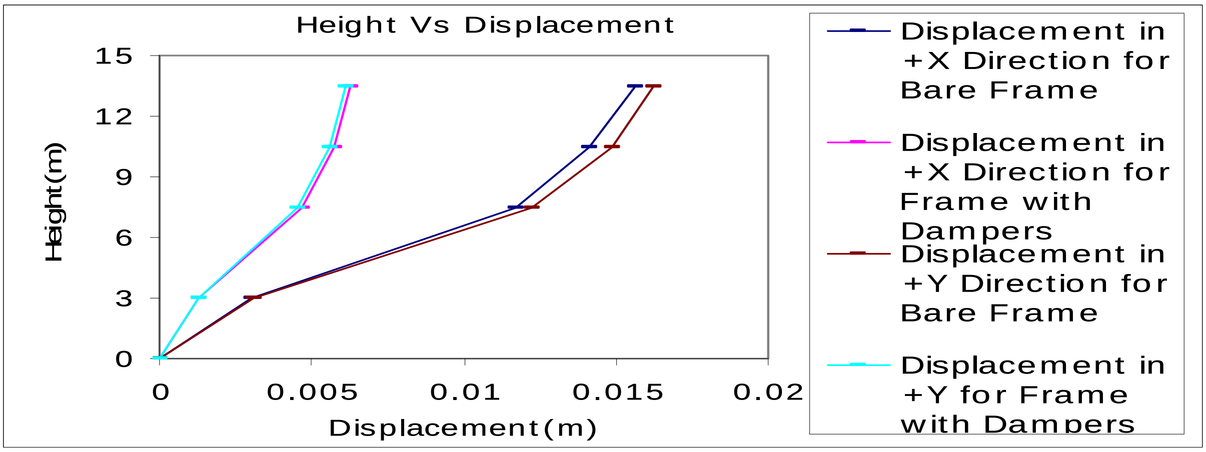


Fig 5.11 Graph Showing Increase in Displacement by changing second Storey ht

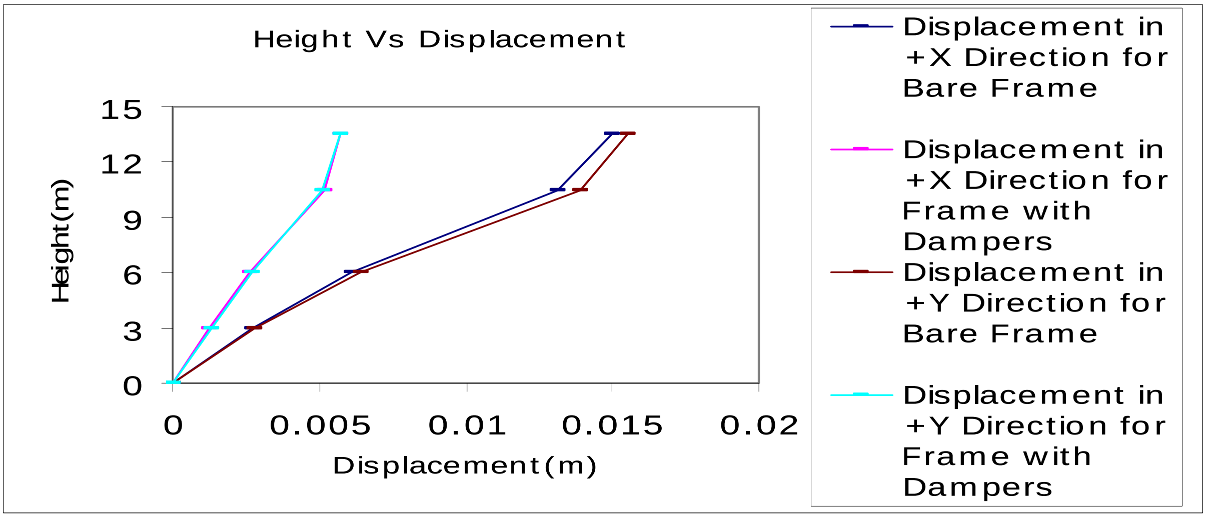


Fig 5.12 Graph Showing Increase in Displacement by changing third Storey ht

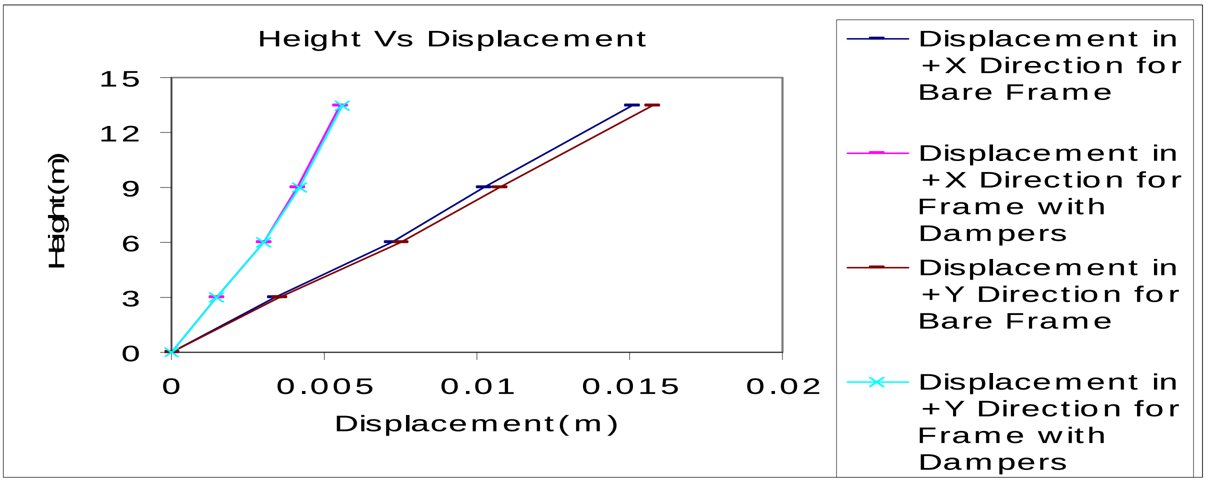


Fig 5.13 Graph Showing Increase in Displacement by changing forth Storey ht

In the above study whenever there is increase in a particular storey height sharp increase in displacement have been observed. However, when the same building is equipped with dampers there is considerable reduction in displacement were seen. For example, in case of increasing first storey height there was sharp increase in displacement but by use of Viscoelastic damper almost 60% reduction in displacement for that particular storey was found.

5.5.3 Effect of Variation of Temperature on Performance of Viscoelastic Damper

In Viscoelastic damper energy is dissipated through Viscoelastic materials. However, performance of Viscoelastic damper is highly dependent on Viscoelatic material which in turn depends on temperature. As temperature increases there is change in behavior of material and therefore, in this study material properties of Viscoelastic damper have been calculated at different temperatures and stiffness of damper requires to cope up with the temperature has also been calculated.

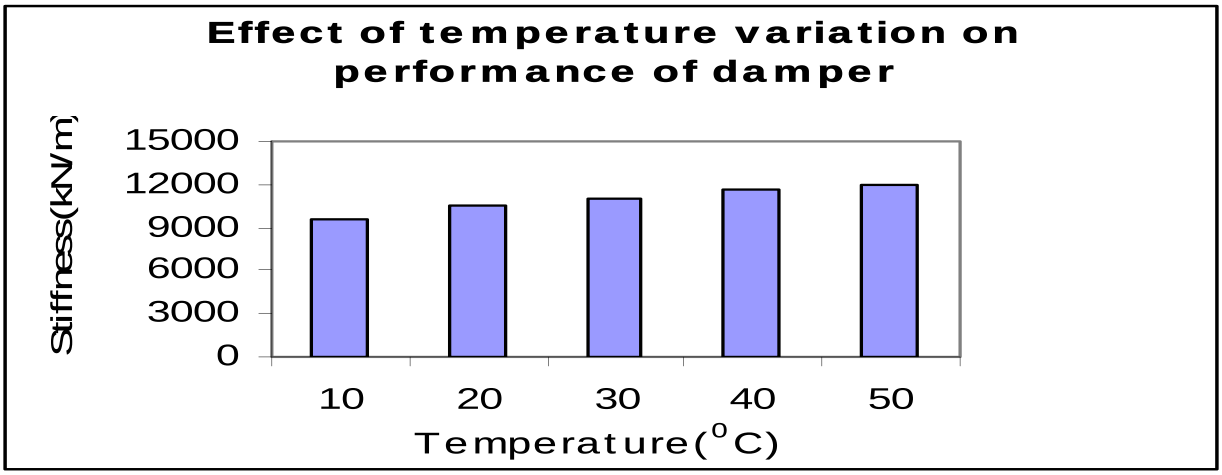


Fig 5.14 Increase in Stiffness with Increase in temperature

From Fig 5.22 it can be seen that as temperature increases there is increase in stiffness of the material. It can be understood that, if Viscoelastic damper designed for 20^{o}C may not perform well at 50 ^{o}C. For the purpose of analysis a temperature of 33^{0}C was adopted considering average temperature in this part of country.

5.5.3 Effect of Various Placements

In this study dampers were placed at different locations symmetrically in the building and response of the structure has been calculated. Additional damping imparted to the structure was 15% along with inherent 5% damping.

Table 5.18 Displacement for viscous dampers placed at various locations (+X Direction)

Storey No.	Displacement (in mm)		
	Location of dampers		
	central bay	alternate bays	corners
4	3.96	3.8	3.77
3	3.4	3.3	3.2
2	2.83	2.4	2.3
1	1.3	1.2	1.34

Fig 5.19 Displacement for Viscoelastic dampers placed at various locations (+X Direction)

Storey No.	Displacement (in mm)		
	Location of dampers		
	central bay	alternate bays	corners
4	5.25	5.2	5.2
3	4.71	4.5	4.4
2	3.38	3.3	3.2
1	1.64	1.6	1.5

It has been seen that there is definite influence of location of damper on response of the building. It can be interpreted that when dampers were placed in corners locations their effect becomes maximum, which is also supported by guidelines specified in FEMA-273. It is important to note that, this study helps to get quantitative idea of location for dampers. The optimal solution for the problem can be done applying optimization techniques.

5.5.4 Force Carried by dampers

As per guidelines of FEMA-273 emphasis has been given to calculate the force carried by a single damper. This calculation of force carried per damper ultimately gives an idea that how many numbers of dampers are required for a particular building. It also helps in calculating total cost of damper equipped into building. Later on classification of force carried by building and force carried by damper was also brought out.

Table 5.20 Force carried by viscous dampers in +X direction

Storey No.	No. Of dampers(per floor)	Force (kN)	Horizontal Force (kN)
4	4	11.69	8.27
3		21.02	14.86
2		28.13	19.89
1		25.76	18.21

Table 5.21 Force carried by viscoelastic dampers in +X direction

Storey No.	No. Of dampers(per floor)	Force (kN)	Horizontal Force (kN)
4	8	14.95	10.57
3		35.40	25.03
2		48.61	34.37
1		48.61	34.37

From the above study it is easy to find force carried by dampers. It can be concluded from the above results that even the 15% additional damping is good enough to change the response of the structure. However similar procedure can be adopted for force estimation of dampers up to 30% damping. It is also clear from the table that force carrying capacity of Viscoelastic damper is more then viscous damper since viscous damper provides additional stiffness. The actual lateral force carried by Viscous and Viscoelastic damper was 21% and 44% of the total lateral force. The detailed calculation of above mentioned results are presented in Appendix-E.

5.5.5 Comparison of Column reinforcement

After carrying out Dynamic analysis of the building members were designed using SAP-2000 (v9.19) as per IS-456[14].Following table shows the comparison of Column reinforcement for bare frame and damper equipped Building

Table 5.22 Comparative study of column reinforcement for G+3 Storey Building

Column No.	Storey No. 1 Area of Steel (mm^2)			Storey No. 2 Area of Steel (mm^2)			Storey No. 3 Area of Steel (mm^2)			Storey No. 3 Area of Steel (mm^2)		
F_1	A	B	C	A	B	C	A	B	C	A	B	C
C_1	797	720	720	727	720	720	720	720	720	720	720	720
C_2	724	720	720	763	720	720	720	720	720	720	720	720
C_3	720	720	720	720	720	720	720	720	720	720	720	720
C_4	720	720	720	720	720	720	720	720	720	720	720	720
C_5	731	720	720	757	720	720	720	720	720	720	720	720
C_6	797	720	720	727	720	720	720	720	720	720	720	720
C_7	774	720	720	776	720	720	720	720	720	720	720	720
C_8	765	720	720	768	720	720	720	720	720	720	720	720
C_9	791	720	720	779	720	720	720	720	720	720	720	720
C_{10}	791	720	720	779	720	720	720	720	720	720	720	720
C_{11}	761	720	720	768	720	720	720	720	720	720	720	720
C_{12}	773	720	720	776	720	720	720	720	720	720	720	720
C_{13}	800	720	720	731	720	720	720	720	720	720	720	720
C_{14}	738	720	720	774	720	720	720	720	720	720	720	720
C_{15}	720	720	720	743	720	720	720	720	720	720	720	720
C_{16}	720	720	720	735	720	720	720	720	720	720	720	720
C_{17}	741	720	720	770	720	720	720	720	720	720	720	720
C_{18}	800	720	720	731	720	720	720	720	720	720	720	720

A Bare Frame

B Frame With Viscous damper (5% additional damping)

C Frame with Viscoelastic damper (5% additional damping)

As per above results shown in table 5.22 there is marginal difference in reinforcement of bare frame as compared with damper equipped frame. It is also clear that saving in reinforcement is more in case of Viscoelastic damper. However for getting more clear idea about the percentage saving in reinforcement a G+9 Building has been designed and reinforcement were compared.

5.6 RESULTS FOR G+9 STOREY BUILDING

This section deals with the comparison of reinforcement in columns for G+9 storey Building. From the results obtained there is 14% saving in column reinforcement which is quiet a big amount of saving. It can also be understood here that for high rise buildings there is more saving in reinforcement which may lead to overall economy and damper cost will be overcomed. Table 5.23 shows the comparison of Column reinforcement for bare frame and frame with Viscous Damper.

Table 5.23 Comparison of Column Reinforcement for G+9 Storey Building

Column No.	Storey No. 1 Area of Steel (mm^2)		Storey No. 2 Area of Steel (mm^2)		Storey No. 3 Area of Steel (mm^2)		Storey No. 4 Area of Steel (mm^2)		Storey No. 5 Area of Steel (mm^2)		Storey No. 6 Area of Steel (mm^2)		Storey No.7 Area of Steel (mm^2)		Storey No.8 Area of Steel (mm^2)		Storey No.9 Area of Steel (mm^2)		Storey No.10 Area of Steel (mm^2)	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
F_1																				
C_1	889	828	934	828	828	828	828	828	828	828	828	828	828	828	828	828	828	828	828	828
C_2	2360	1734	2050	1511	1686	1177	1336	1128	923	828	828	828	828	828	828	828	828	828	831	828
C_5	4053	3286	3235	2548	2607	2034	1895	1556	1319	828	828	828	828	828	828	828	828	828	919	828
C_6	1811	1223	1617	828	1348	1528	1072	1128	828	828	1126	828	828	828	828	828	832	828	924	828
C_8	4653	3165	3894	3226	3039	2519	2320	1734	1566	1128	1185	828	828	828	828	828	847	828	959	828
C_{11}	4830	3491	3992	2726	3090	2436	2358	2034	1580	1128	1340	828	828	828	828	828	828	828	1022	828
C_{13}	1805	1256	1813	956	1353	1328	1082	828	828	828	828	828	828	828	828	828	828	828	828	828
C_{14}	4188	3386	3413	2724	2743	2056	2055	1911	1443	828	828	828	828	828	828	828	828	828	828	828
C_4	1787	1228	1585	1411	1308	1128	1024	828	828	828	828	828	828	828	828	828	828	828	828	828
C_{17}	2523	1234	2205	1234	1788	1428	1426	1028	1009	828	828	828	828	828	828	828	828	828	828	828
C_{18}	1076	828	1144	877	877	828	828	828	828	828	828	828	828	828	828	828	828	828	828	828
F_2																				
C_3	899	1228	956	928	828	828	828	828	828	828	828	828	828	828	828	828	828	828	911	828
C_4	1787	1477	1585	1211	1308	1128	1024	1128	828	828	828	828	828	828	828	828	828	828	828	828
C_7	2402	1934	2331	1911	2048	1623	1768	1128	1480	1028	828	828	866	828	828	828	828	828	828	828
C_9	2477	1656	2409	1811	2132	1623	1824	1211	1540	828	1159	828	894	828	828	828	846	828	935	828
C_{10}	2406	1834	2341	1934	2068	1823	1785	1328	1500	1228	828	828	884	828	828	828	828	828	826	828
C_{12}	2676	2056	2625	2034	2343	1923	1991	1677	1678	1328	828	828	1025	828	850	828	872	828	828	828
C_{15}	1968	1377	1765	1428	1508	1228	1242	1028	923	828	828	828	828	828	828	828	828	828	828	828
C_{16}	922	828	990	928	828	828	828	828	828	828	828	828	828	828	828	828	828	828	828	828

A- Bare Frame

B- Frame With Viscous damper (15% additional damping)

6. CONCLUSION AND FURTHER SCOPE OF WORK

The main aim of the work was to understand the behavior of the building equipped with passive energy dissipation devices. It is important to note that results obtained by this work were based on the models specified by FEMA-273 i.e. Maxwell Model for Viscous damper and Kelvin Model for Viscoelastic damper. Based on the work carried out following conclusions are made.

- The fundamental time period of 3-D R.C framed building act as bare frame building and viscous damper equipped building remained same (0.645 sec). However, time period for building equipped with Viscoelastic damper was decreased by 30% compared to previous two models for 30% additional damping.
- The displacement response of 3-D R.C frame building in x & y direction with Viscous damper in Chapter 5 Page No. & Fig No. Indicates 30% reduction compared to bare frame model. Similarly, base shear has also reduced to 30% for model with 5% additional damping. The reduction into displacement & base shear were increased as level of damping increased from 5% to 30% with an increment of 5%.
- The displacement response of 3-D R.C frame building in x & y direction with Viscoelastic damper in Chapter 5 Page No. & Fig No. Indicates 43% reduction compared to bare frame model similarly, base shear has also reduced to 34% for model with 5% additional damping. The reduction into displacement & base shear were increased as level of damping increased from 5% to 30% with an increment of 5%.
- As higher level of damping is not feasible in all types of building. It was found from the study that, even 15% of additional damping achieved had great influence on response reduction. For Viscous damper equipped building reduction in displacement & base shear are 56.6% & 53.36%, respectively, similarly for Viscoelastic damper equipped building reduction in displacement & base shear are 68.3% & 50.86% respectively.
- The Drift obtained for viscous damper equipped was 56.6%.However for Viscoelastic damper equipped building it was 68.3% for 30% additional damping. This result indicates that amount of damping directly influence the drift by reducing it.

- In case of a building with dissimilar storey height, inherent damping does not help in controlling the response. But, study undertaken shown that, presence of additional damping through dampers helps in controlling displacement and also avoid soft storey kind of phenomenon.
- The locations of damper placement are most important aspect of controlling response. It was found through study that dampers located symmetrically at corners of building gives maximum response reduction compared to other locations of symmetry. However, unsymmetrical placements of dampers make the problem complex because of additional torsional response.
- It is important to note that, for G+ 3 storeys R.C frame building addition of dampers does not help in saving amount of reinforcement into structural element specifically column. Because of minimum steel reinforcement as per codal provisions of Indian standards but study on G+9 storey R.C. frame building has shown 14% of reinforcement saving compared to G+3 storey R.C frame building. It may therefore understood that, for medium height building provision of additional damping in form of dampers does not help in achieving economy of steel reinforcement, but displacement, base shear and drift response are influenced most, Which is essential for buildings in high seismic zones.
- As per guidelines of FEMA-273 Lateral force carried by Viscous & Viscoelastic damper was calculated. It was found that about 21% & 44% of lateral load was carried by Viscous & Viscoelastic damper respectively. However these results are for 15% additional damping. For higher level of damping force carried by dampers proportionally increases with amount of additional damping.
- Estimation of cost of damper (Viscous & Viscoelastic) depends on so many parameters, also manufacturing techniques may also influence the cost. However, cost of viscous damper was estimated as 150 per square feet. Based on information collected from various sources.
- In case of Viscoelastic damper, temperature variation has direct impact on performance of dampers. It was clear from the work that higher temperature needs higher value of stiffness & therefore area of Viscoelastic pad turned out bigger in size. It was understood that use of

Viscoelastic damper for higher temperature locations restricts its use and other alternative to be adopted.

FURTHER SCOPE OF WORK

The present work can be used as an input for further work explained as follows

- Present study has considered only Maxwell and Kelvin Model. However more précised mathematical model can be taken up for analysis.
- This work considered Response Spectrum Method for analysis of damper equipped structure but to get more detailed understanding nonlinear procedures like Push over Analysis and Time History analysis can be undertaken.
- The optimal locations of damper placement can be obtained through various optimization techniques.
- Other types of passive energy devices like Friction damper, Metallic damper, Sliding damper can be studied.
- Comparative study of base isolation and passive energy dissipation devices can help in appropriate selection for the various buildings in various seismic zones.

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LIST OF USEFUL WEBSITES

S.NO	Name of Website
1	www.vivisimo.com
2	www.nicee.org
3	http://mceer.buffalo.edu
4	http://www.eeri.org
5	http://ndparking.com/carsonbooks.com
6	http://www.%20fema.gov/pte/prep.htm
7	http://www.peer.berkeley.edu
8	http://www.taylordevices.com
9	http://www.3m.com
10	http://www.sciencedirect.com

APPENDIX- B

As Indian Standards related to Earthquake Engineering have not included any guidelines for Supplementary damping devices, the design procedure for Viscous damper was done according to guidelines given in FEMA-273. It is important to note that Viscous dampers are Velocity dependent dampers and it only imparts damping to the building.

Floor No.	Mass(kg)	Cos θ	First mode time period	Mode shapes
4	76962	0.7071	0.645(sec)	1
3	110703	0.7071		0.86
2	110703	0.7071		0.61
1	110703	0.7071		0.28

Modal drift between floors

	0.136
$\{\phi_r\}$	0.251
	0.329

Effective damping ratio calculated as per formula explained in Chapter 4 Clause No.4.1 Page No.28

C = 551.43 kN-sec/m (for single damper)

Number of dampers used was four in number and each damper contributed the above calculated damping. Similar procedure can be adopted for any level of damping.

APPENDIX- C

The design of Viscoelatic damper is an iterative process. Many iteration were performed to achieve the exact area of Viscoelastic material pad. The design is performed according to FEMA-273. which recommends **Kelvin Model** for analysis. To support the iterative calculations Microsoft Excel Sheet was used. The procedure for design was given in chapter 4 Clause No.4.3.5 Page No.38 with various equations. Calculation usually comprise of estimating additional stiffness and damping provided by the damper which were calculated by equations 4.6 and 4.7 explained in Chapter 4. The properties calculated were assigned to the damper that has been modeled in SAP-2000 using Nonlinear Link Element. The following calculations were used as an input for Modeling Damper in SAP-2000 calculations shown are preliminary calculations for targeted 5% damping. The similar worksheet can calculate the damping co-efficient & other properties for various levels of damping.

DESIGN OF VISCOELASTIC DAMPER

Grade of Concrete	M 20
Grade of Steel	Fe 415
Column Size	300 x 300 mm
Primary Beam Size	230 x 450 mm
Secondary Beam Size	230 x 350mm
Damping to be achieved	5%
Length of Column	3m
Total No. of columns(per storey)	18
Inclination of device	45^{0}
DESIGN CALCULATIONS	
Storey Stiffness	120747 kN/m
Stiffness of damper required(per floor)	9737.8 kN/m
No. of dampers per floor	8
Stiffness per damper	1217.23 kN/m

Above calculated Stiffness was used in modeling of damper and the damping achieved using calculated stiffness was obtained by Model Strain Energy Method as per Equation 4.21 of Chapter 4. As, in first iteration damping achieved was not equal to 5% as expected, Stiffness of damper needs to increased till expected damping achieved, the dimensions of Viscoelastic pad were Calculated.
The material used for Viscoelastic damper is manufactured by 3M company and properties adopted accordingly. It is clear from the present Excel worksheet that the calculations for any level of damping for +X & +Y direction can be obtained quickly.The loss modulus and Storage modulus were calculated from the equation 4.3 to equation 4.5 as explained in Chapter 4.

K	3450 kN/m
C_d	372.9 kN -sec/m
Mass of material	2.04E-03
Weight of material	0.02
Damping achieved	4.96%
Area of single pad required	150mm $\times$450mm
Thickness of pad required	17mm

APPENDIX- D

This section deals with verification of results obtained through commercially available software SAP (V 9.19) with manual calculations done using fundamental equations of dynamics.

Static analysis as per IS:1893-2002 (Part - I)

Design Seismic Base Shear for +X & +Y direction

Z (zone factor)	0.36
I (importance factor)	1
R (response reduction factor)	5
T_a (time period IS-1893 clause 6.4.5)	0.4835
S_a/g	2.5
Factor for 5% additional damping	0.8
A_h	0.072
V_b(+X direction)	288.936 kN
Base Shear in SAP-2000(+X direction)	288.97 kN
Percentage Difference	0.0117%
V_b(+Y direction)	288.936 kN
Base Shear in SAP-2000(+X direction)	277.141 kN
Percentage Difference	4.08%

Dynamic analysis (for +Y direction as per IS-1893)

Floor No.	Mass(kg)	Cosθ	First mode time period	Mode shapes
4	76962	0.7071	0.645	1
3	110703	0.7071		0.86
2	110703	0.7071		0.61
1	110703	0.7071		0.28

Ah	0.0765

Modal Participation Factor	1.294

Floor Acceleration	0.099
	0.085
	0.060
	0.028

Design Lateral Force	74.77 kN
	92.86 kN
	65.87 kN
	30.49 kN

Base Shear	264 kN

SAP-2000 result	240.886 kN

Percentage difference in result	8.75%

Design Storey Shear	74.77 kN
	167.64 kN
	233.51 kN
	264 kN

Floor Displacement	10.24mm
	8.84mm
	6.27mm
	2.90mm

SAP-2000 results for Floor Displacement	8.93mm
	7.7mm
	5.47mm
	2.54mm

Percentage Difference in results	12.86%
	12.97%
	12.84%
	12.55 %

Dynamic analysis (for +X direction as per IS-1893)

Floor No.	Mass(kg)	Cosθ	First mode time period	Mode shapes
4	76962	0.7071	0.62	1
3	110703	0.7071		0.86
2	110703	0.7071		0.61
1	110703	0.7071		0.27

Ah	0.077

Modal Participation Factor	1.293

Floor Acceleration	0.099
	0.085
	0.061
	0.027

Design Lateral Force	75.30 kN
	93.38 kN
	66.65 kN
	30.26 kN

Base Shear	265.60 kN

SAP-2000 result	241.986 kN

Percentage difference in result	8.89%

Design Storey Shear	75.30 kN
	168.68 kN
	235.34 kN
	265.60 kN

Floor Displacement	9.47mm
	8.16mm
	5.82mm
	2.64 mm
SAP-2000 results for Floor Displacement	8.2mm
	7.1mm
	5.1mm
	2.6mm

Percentage Difference in results	13.45%
	13.08%
	12.51%
	12.55 %

It was seen from above calculations that for static analysis the difference in results obtained through SAP-2000 & manual calculations was 4% for base shear However, for dynamic analysis maximum difference of base shear & displacement were 8.9% & 13.45% respectively.

APPENDIX- E

This section deals with manual calculation to estimate the force carried by a damper for 15% additional damping. The equations used are defined in Chapter 2 Page No.17. The procedure followed is as per FEMA-273. The input data were taken from SAP result output.

Force Carried by Viscous Dampers (+X direction)

Floor Displacement	3.8 mm
	3.3 mm
	2.4 mm
	1.2 mm

Floor Drift	0.5 mm
	0.9 mm
	1.2 mm
	1.2 mm

Velocity between ends of the damper	3.63 kN
	6.55 kN
	8.73 kN
	8.73 kN

Damper force per floor	9.59 kN
	17.27 kN
	23.02 kN
	23.02 kN

Horizontal Component of Damper Force	6.78 kN
	12.21 kN
	16.28 kN
	16.28 kN
Total horizontal force resisted	51.56 kN

Force Carried by Viscoelastic Dampers (+X direction)

Damper force per floor	14.95 kN
	35.40 kN
	48.61 kN
	48.61 kN

Horizontal Component of Damper Force	10.57 kN
	25.03 kN
	34.37 kN
	34.37 kN

Total horizontal force resisted	104 .34 kN

Fig 5.24 & 5.25 shows the Lateral Force Distribution in G+3 R.C Frame Building for Viscoelastic damper in +X direction with 15% additional damping.

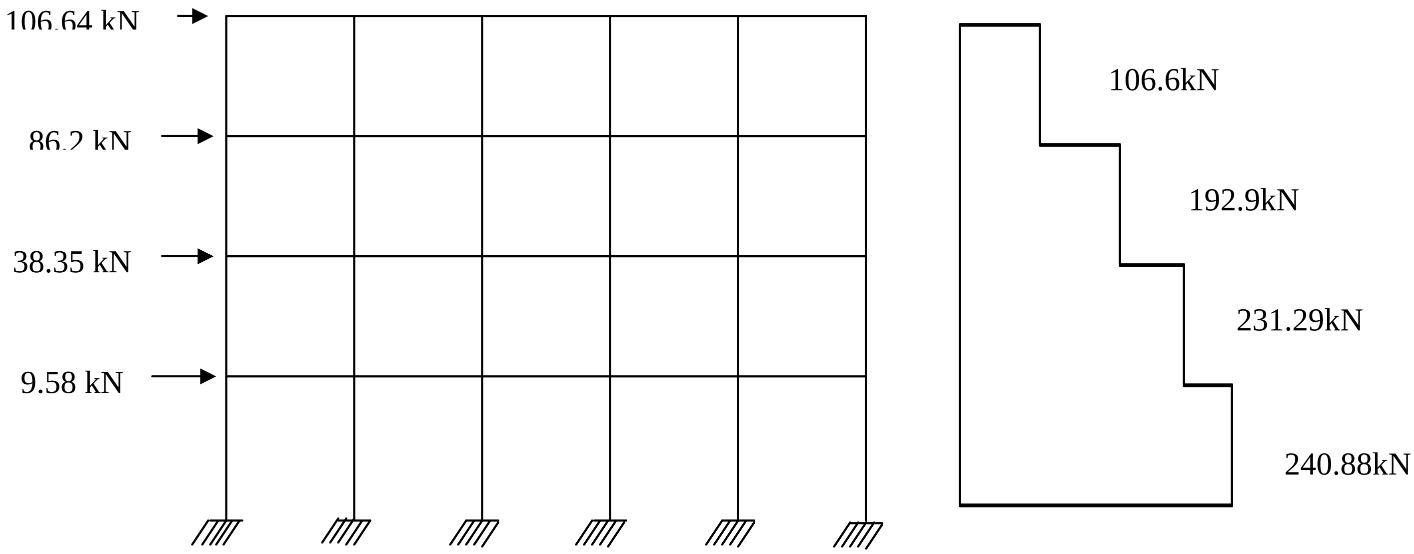

Fig 5.15 Distribution of Lateral forces at Each Storey Level

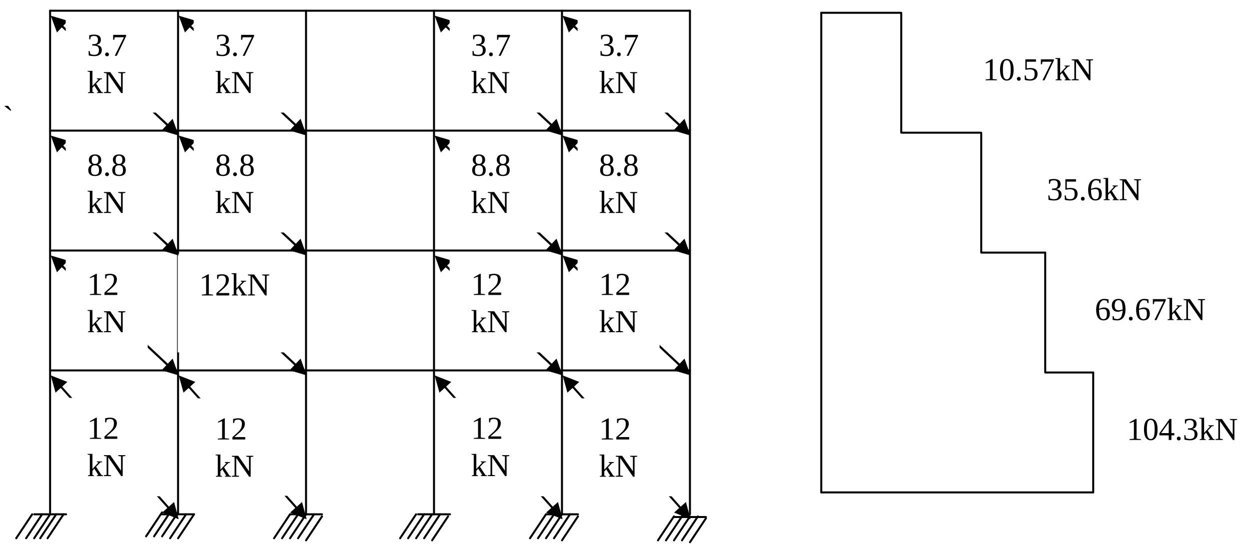

Fig 5.16 Force Carried by Viscoelastic Damper in +X direction

PAPER PUBLISHED & COMMUNICATED

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