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RESEARCH ARTICLE

SHAPE FACTOR CORRECTION IN OPTIMUM DESIGN OF ELASTOMERIC LAMINATED SEISMIC ISOLATORS

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ABSTRACT

This study examines the stiffness of different (in terms of diameter and layer thickness) seismic isolators in an effort to compare the vertical stiffness of isolator systems obtained from construction code formulas with that obtained from models simulated via ABAQUS. To this end, 16 different geometric layered (laminated) isolator models were generated. The results showed that increasing the isolator radius at different rubber layer thicknesses, and consequently, increasing the isolator shape factor would lead to an increase in vertical stiffness. In addition, increasing the thickness of the isolation layer increased the slope of the diagram, which emphasized the fact that increasing radius was more effective in isolator systems with greater thickness. The maximum shear stress developed in the rubber layer under vertical pressure was also studied by analyzing a rubber layer which assumed only circular and rectangular shapes. This was done by adjusting the rubber layer dimensions to produce shape factors of 5, 20, and 30. The results showed that it was necessary to introduce another factor for correcting the isolator shape factor. A correction factor of unity works only for rubber layers with lower shape factors. For higher shape factors, the correction factor can be applied to the isolator as a reduction coefficient (factor).

INTRODUCTION

Earthquake is one of the most frequent natural disasters, causing extensive loss of life as well as damages every year. This has made many researchers to investigate this destructive phenomenon. In spite of great advances made in this regard, man has not obtained sufficient knowledge to predict the time of occurrence or the magnitude of earthquakes. For this reason, parallel to the studying how, when, and why earthquakes occur, different studies are under way for designing seismic resistant structures as well as seismic retrofitting of the existing vulnerable structures. In general, relative storey drift (displacement) and the acceleration developed in storeys are the two main mechanisms that contribute to the destruction of a structure under base excitations.

Based on these destructive mechanisms, two methods have been devised for seismic design of structures:

- Designing buildings with high stiffness to prevent drifts arising from base excitations. The disadvantage of this method is that increasing stiffness also imposes increased acceleration on the storeys.
- Designing highly ductile (flexible) structures to reduce their storey acceleration as well as the acceleration transferred to diaphragms, which in turn would lead to increased storey drift.

Due to the disadvantages of both the above methods, a suitable method which can reduce the force applied to the structure while controlling the relative storey drift would be desirable. To control structural vibrations against seismic forces, many researchers around the world today have turned to “energy damping systems” so as to facilitate structural restoration and retrofitting while concentrating the nonlinear deformations arising earthquakes on these systems at the same time. From an energy perspective, a structure acts as an energy filter in seismic design problems. The energy entering a structure is not only dependent on ground motion characteristics, but also on structural characteristics. From an energy perspective, a suitable seismic design entails minimizing the hysteretic energy dissipation in the structure. In reality, there are two important viewpoints in this regard. The first includes designs where the input energy to the structure is reduced (via installing seismic isolators), and the second focuses on energy dissipation mechanisms within the structure. The energy dissipation equipment is designed to dissipate part of the input energy, thus reducing the damage to the main structure arising from hysteretic energy dissipation. Seismic isolators are deployed at the base level in a building and, through reducing the acceleration acting on the building as well as the relative

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drift between storeys, they greatly reduce structural damages caused under base excitations during seismic activities.

Structural Vibration Control

The extensive damages resulting from recent earthquakes. Extensive damage to infrastructural facilities during recent earthquakes as well as public demand for nonstop performance on the part of such facilities has led to widespread research for satisfying this demand. One method considered in recent decades for increasing structural performance is structural control. Structural control is modifying structural characteristics for achieving the desired structural response against external loads. Modifying structural characteristics includes changing structural stiffness and damping for acquiring the desired response. Structural control is often applied in the case of dynamic loading, whereas modifying structural characteristics is aimed at reducing the excitation applied to the structure. Though structural control seems an appealing subject today, the fundamental concepts of control are not new. These concepts have been – in recent decades – among the fundamental concepts of Electronic Engineering and Control Engineering disciplines in the Electrical Engineering Departments, and have found applications in different fields including Aerospace Engineering. Nevertheless, structural control in Civil Engineering, particularly with regard to reducing seismic effects on structures, is a relatively new discipline. The techniques used in structural design are divided into four main groups: 1) passive control, 2) active control, 3) semi-active control, and 4) hybrid control. These are briefly discussed in the following sections.

Seismic Isolators

Structural damage arising from seismic activity is generally due to two basic factors:

- Relative storey drift
- Accelerations induced at building floors

Storey drift causes relative thrust at different heights. However, since storeys do not move simultaneously and at the same velocity, a relative drift is created between them. Sometimes, the change in the direction of the force applied to the building even causes the storeys to move in different directions (due to the uneven force transfer among the storeys) resulting in destruction of the internal isolator walls, breaking of windows, and collapse of service installations, as a result of which the building stops being operational and sustains considerable damage. In addition, the acceleration arising from earthquake is transferred to the building floors where the structural mass is concentrated. At each floor, an acceleration proportional to the floor mass is created. This storey acceleration would damage the building inhabitants as well as the instruments installed therein, thus inflicting extensive damage. Where the main purpose of establishing the building is to utilize the equipment installed therein, the damage to the equipment is far greater than that inflicted on the main structure. Therefore, the main problem in seismic design of a building is to find ways of minimizing relative storey drift as well as storey accelerations. Large relative storey drifts cause damage to nonstructural elements as well as the equipment connecting the storeys. Such damages can be reduced by increasing stiffness. However, this would strengthen ground motions which in turn increase acceleration of stories, leading to the sensitive internal equipment being damaged. Storey accelerations can be reduced by increasing the ductility of the system. On the other hand, excessive ductility has its own disadvantages such as introducing significant drift at storey level leading to extensive damage, causing unfavorable structural performance under strong winds as well as lower-magnitude earthquakes, and requiring additional design efforts as well as costs for creating the required ductility in structural members and connections/joints.

The above limitations clearly show that the existing seismic design methods do not provide favorable or ideal structures. This is particularly true about special structures which are expected to provide high serviceability under (emergency) conditions after the occurrence of an earthquake. Other methods that have been practiced since the start of the previous century include increasing the energy absorption capability and reducing seismic requirements by implementing such methods as isolating the structure from its foundation, reducing structural mass, and using energy dissipation systems. Isolating buildings from ground vibrations is a new method considered in the past few decades and is the only practical way of simultaneous reduction of relative storey drift and storey acceleration.

This method (considered to be a passive structural seismic response control method against earthquakes) targets seismic requirements rather than increasing structural capacities; therefore, it uses isolators as tools for reducing seismic forces and providing better distribution of lateral forces among structural supports. This method is particularly useful in buildings containing sensitive and important equipment, or buildings that are to remain serviceable immediately after occurrence of an earthquake. In this method, systems of different forms are placed – usually at the level of a load carrying system close to the foundation - to isolate the superstructure from the foundation. Concentrating the resultant drifts at the isolator level, such a system would provide the required ductility for the structure and isolate the building from the horizontal components of ground motion. Thus, the fundamental frequency of the resulting system would be much lower than that of the dominant seismic motions, being equal to the fundamental frequency of the same building with a fixed joint.

Fig. 1.1 shows the schematic of a seismic isolator at the foundation level of a building and the effect of the isolator system in reducing superstructure drift and acceleration. The behavior of an isolated structure compared to an ordinary system is also shown. The superstructure is similar in both the systems and both systems are exposed to the same seismic loading (earthquake). However, in the ordinary structure, ground motions transferred to the superstructure induce complicated inertias in structural members. As a result, seismic acceleration resonance occurs at upper storeys, leading to failure in the lower members. In contrast, the major lateral drift in the seismic isolator system occurs at the isolator level and the acceleration transferred to upper floors as well as relative storey drift is significantly reduced. In this way, structural and nonstructural failure in members arising from seismic loads can be simultaneously prevented.

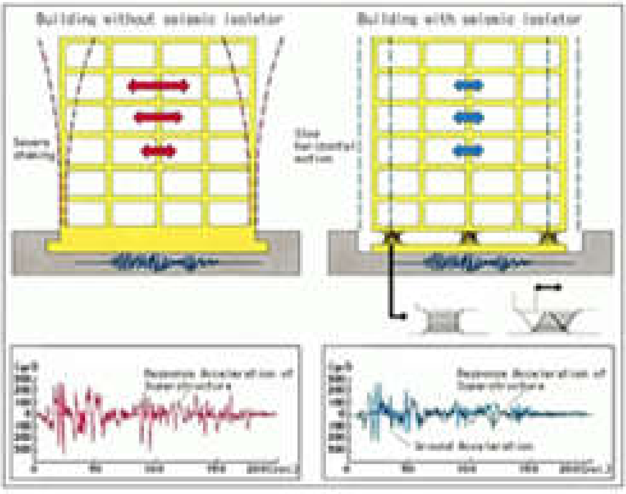


Fig. 1. Application of the seismic isolator system in a building

Although the vibration isolator technology is relatively new, numerous studies have been conducted about it. This method has, due to availability in recent years of various resources regarding construction technology and knowledge of engineering analytics, been implemented for retrofitting structures and is currently being developed rapidly while acquiring increasing acceptability. In this method, the seismic response of a structure is isolated from ground vibrations via a flexible surface, and as a result, seismic requirements of the structure are significantly reduced, leading to a better seismic behavior on the part of the structure than that exhibited by structures with fixed foundations. As a result, one of the most important effects of seismic isolators is reducing the seismic forces (loads) applied to the structure as well as reducing the seismic response of the structure (created by increasing the period of vibrations in the structure as well as damping of the isolator layer). In the best condition, the first vibration mode expresses the dominant behavior of isolated structures and the effect of other modes which lead to application of higher accelerations to the structure are reduced. As a result, these isolators would produce a new vibration mode in the structure which increases the fundamental period of the structure while keeping a distance between it and the fundamental period of the input content (Fig. 1.2). the other important effect of these isolators is reducing sytem response through increased damping (Fig. 1.2).

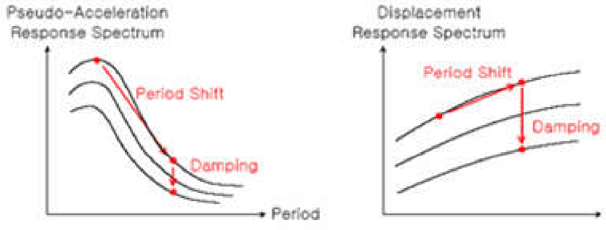


Fig. 1.2. Seismic Isolator performance in reducing structural response to vibrations

In addition to absorbing part of the input seismic energy via shifting the fundamental period of vibration, the isolator system increases its distance from the high seismic energy frequencies, thus avoiding resonance and reducing structural seismic response. In addition, in the first vibration mode of the isolated structure, deformation occurs only in the isolator system and the vertical displacements as well as horizontal accelerations are the same for all structural masses, so that the superstructure acts almost as a rigid body. The higher modes which are perpendicular to the first mode (and therefore, to the ground motion) shall have no effect on the transferred motion and, consequently, the input seismic energy shall not be transferred to the structure. As a result, in their first vibration mode of such structures, the period and damping would depend on the isolator characteristics alone and are independent of structural features. To study the general effect of the isolator on structural response, see Fig. 1.3. As can be observed in this figure, the isolators have caused the structural vibration period to shift from 0.1-0.6 seconds (for ordinary structures) to about 2-3 seconds, thus considerably reducing the acceleration applied to the structure.

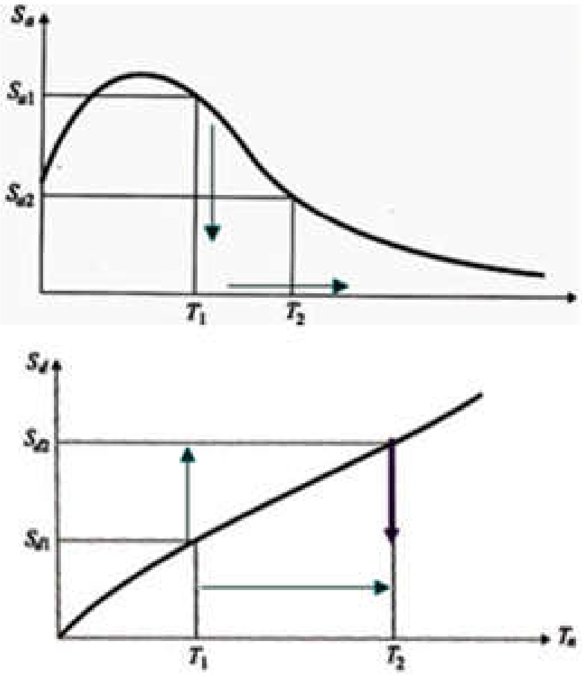


Fig. 1.3. Reduced acceleration and increased displacement in isolated structures

In the meantime, considering the abovementioned performance for isolator systems, we conclude that using these systems to improve the seismic behavior of high buildings (the periods of which are inherently long) that are safe from seismic wave accelerations that transfer significant energy to the structure at high frequencies would be unsuitable as well as unjustifiable. In addition, the geotechnical texture of soil in certain cases can put obstacles in the way of using isolator systems. To improve the efficiency of the isolated system, soil at the site of the structure must be hard; otherwise, seismic isolation might cause the accelerations transferred to the structure to increase rather than decrease. On the other hand, increasing period of the structure can largely increase structural drift. This drift is, of course, due to the isolator system itself and relative drifts are greatly reduced at the superstructure. This is contrary to fixed-foundation structures where drift increases with altitude. Isolator layer drift has a significant effect on isolator system costs, posing yet another limitation in the application of these systems due to the fact that considerable drift would occur at the isolator level if the structure cannot be fully isolated from the ground and surrounding soil. Of course, we must consider that this large drift would create better conditions for using dampers since it provides more work at the dampers. In structures not fitted with seismic isolators, drift increases along the height of the building, whereas in isolated structures, drift is mostly due to the isolator system displacement itself and structural drift above the isolator level is slight (the drift curve in the first mode is almost rectangular). Fig. 1.4 shows structural drift caused by seismic force in an isolated and an unisolated structure. As can be observed, in the isolated structure, a large drift is created at the isolator, whereas the structure does not sustain significant relative drift and acts basically as a rigid system. This is contrary to the unisolated structure where a relatively uniform drift can be observed at different heights along the building.

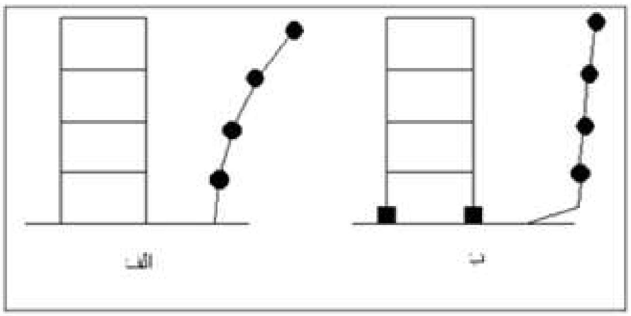


Fig 1.4. Comparison of seismic drifts in structures: a) an unisolated building; b) an isolated building

From the above discussion, we conclude that the horizontal acceleration resulting from isolating the building is controlled by the first vibration mode and that the role of higher modes in this regard is insignificant. We know that drift in unisolated buildings with periods of 1 s and less is also predominantly ruled by the first vibration mode,, and this is more pronounced after the building is isolated. Therefore, the seismic behavior of structures with linear isolators can be expressed – except under certain circumstances – based on the seismic response spectrum and the first vibration mode. If the isolator system is fully nonlinear, then the seismic response can also be approximated via the first vibration mode, but in this case, considering higher vibration modes would increase the accuracy of the solution. Ultimately, we can say that the high costs of seismic isolators are in contrast with the goal of achieving an economic solution system via reducing the forces transmitted to the substructure. This stresses the fact that further research must be conducted for developing isolator systems which act effectively across a wide range of ground motions. This has led many researchers to work on hybrid isolator systems for reducing vibration, systems capable of adapting themselves with different loading conditions, and systems where vibration mode control is possible. In the meantime, we can generally conclude that if the following conditions exist in a structure, then that structure would qualify for seismic isolation:

- Since base isolation exhibits the highest efficiency in structures with short periods (less than 1 s), isolation is mostly suitable for buildings with low or medium heights, not for high-rise buildings. The effective maximum building height for seismic isolation also depends on the structural system in use. In braced frames or framed wall systems, this maximum height would be between 12 and 15 storeys, whereas in moment frame systems (which have higher flexibility), isolator systems would not be suitable for buildings with more than 8-10 storeys. There are exceptions to this rule, however. For example, in the Los Angeles Auditorium Retrofitting Project, a 28-storey building was retrofitted via base isolation.
- Seismic isolation design must be such that the structure would maintain its initial rigidity and stiffness against lateral non-seismic loads so that unfavorable vibrations and drifts resulting from service loads can be prevented. Therefore, isolators must be designed in such a way that they would not yield under nonseismic loads. For this reason, seismic isolators must not be deployed where nonseismic lateral loads exceed 15% of the structural weight.
- The other problem to be considered is related to the soil conditions of the site and geological considerations to be observed. In general, the harder the soil, the lower would be the dominant period of seismic vibration. This provides suitable conditions for implementing base isolation systems. However, in loose soil (like that in Mexico City) implementing seismic isolators would increase the structure's period, thus increasing the risk of resonance which results from the period of the structure coinciding with the dominant seismic period.

A review of Seismic Isolators Applications

Although the concept of seismic isolators goes back to the final years of the 19th and the beginning of the 20th century, it can still be considered a new and widely researched concept with particular applications since the 1970's. Research on seismic isolators started in 1976 at EERC and, later, in other seismic zones throughout the world, and rapidly found its way to the United States and Japan. Upon further developments and lowering its costs, this technology was also used in other countries including Italy, New Zealand, China, and Armenia, particularly since the isolated buildings showed favorable behaviors when exposed to actual earthquakes that occurred in the region. Of course, using the seismic isolation method has its own particular concerns since structures using this technology have not exhibited the expected performance in practice. The unfavorable performance of certain isolated structures in Luma Pritta and Northridge (Silmar) are examples of such a case. The accelerations recorded for these buildings were many times those of earth's acceleration of gravity.

Application of this method in structures with soft bedding or structures exposed to near field excitations is limited due to inefficiencies resulting from the occurrence of seismic activities with long periods with the same frequency range as that of the isolated structures. In addition, application of this method in more ductile structures would reduce the efficiency of the isolators due to the reduced structure-to-isolator stiffness ratio although advances in isolator construction technology as well as production of high resistance rubbers in elastomeric isolators have somehow increased the applications of this method in high-ris buildings. Simultaneously with the development of isolators, different codes have been provided for design and examination of isolated structures including UBC, FEMA, NEHRP, and other codes developed in New Zealand, Italy, and Japan. A brief study of the codes on isolated structures shows that two risk levels are considered in these structures: severe seismic risk and medium seismic risk.

The philosophy behind designing isolated structures is to improve the performance of these structures as compared with fixed-base (fixed-foundation) structures, provide the possibility of nonstop use of these structures after occurrence of earthquakes, and make these structures more resistant against severe seismic loads. These codes provide the possibility of making the superstructure elastic, and prevent formation of elastic hinges through controlling the damages incurred to the structure.

Applying an R coefficient between 1.5 and 2 as well as reduced acceleration transfer to these structures confirms the assumption that these structures are nonductile at the design phase. It is noteworthy that, under certain conditions, this coefficient increases up to six times the above value in fixed-base structures, whereas the lateral load exerted on the structure is reduced by 12 times die to the increased structural ductility. In general, in the codes published for designing seismically isolated structures, parameter of cost is not a determinant and the main purpose is only improving structural performance. On the other hand, these codes entail large drifts at isolator layers as well as severe regulations for ensuring suitable behavior in isolators. Te near field coefficients are particularly large in some codes where large drifts are predicted for isolators under base excitations. In addition, the isolators are required to tolerate the even larger drifts resulting from twisting of the structure or drifts related to higher level risks so that the stability of these isolators can be maintained consistently and separation of the structure and the isolator can be prevented. This leads to designing large-scale isolators capable of tolerating the large drifts that are produced during earthquakes. A review of seismically isolated structures shows that the main application of these isolators is in strategically important institutes, fire suppression buildings, hospitals, and other similar buildings where nonstop serviceability after the occurrence of earthquakes is required. As a result, these isolators are rarely used in ordinary buildings where nonstop serviceability is not required.

Statistics regarding application of such structures in recent years prove that the seismic isolation method has had limited use in recent years. It can be claimed with certainty that no seismically isolated buildings have so far been constructed in Iran.

Main Components of Seismic Isolators Systems

Seismic isolator systems generally comprise three parts:

- A ductile base (suppot) for increasing the period of natural structural vibrations and reducing seismic loads
- A damper or energy dissipater for limiting the drift between the ground and the structure to an acceptable level
- An element for creating suitable lateral stability in the structure for tolerating small-scale loads including service loads, insignificant earthquakes, or wind loads.

Seismic Isolator Types

As already mentioned, isolators are devices which tolerate vertical loads and, at the same time, provide the possibility of withstanding large drifts resulting from lateral loading. Isolators increase structural period to a range above the dominant seismic periods where the most seismic energy lies, thus decreasing the energy transferred from the ground to the structure. The energy dissipation mechanism in these isolators is of the hysteretic energy dissipation type and causes part of the energy transferred to the structure to be dissipated. Therefore, deploying an isolator system at the foundation level (along the length of the structure) becomes largely independent of ground motions. Different isolator systems have so far been constructed and patented, with many more being added to the previous ones annually. In general, these isolators can be divided into two groups, namely, elastomeric and sliding isolators. Energy dissipation, restoring the isolator to its equilibrium position upon lateral excitation, and providing restraints against movement under service loads are among the important functions of seismic isolators. Several parameters must be considered in selecting seismic isolator systems in addition to their ability to change structural period and increase structural damping:

- Ductility under alternating semi-static loads (i.e., initial stiffness)
- Yield force and deformation
- Ultimate drift (displacement) and the behavior of the structure thereupon
- Ability to be restored to pre-deformation state (resistant force)
- Vertical stiffness

Seismic Isolator Systems

Introduction

In the history of mankind, occurrence of earthquakes has been forever associated with extensive loss of life as well as material damage. Before the Industrial Revolution (several centuries ago), man did not know how to cope with the destructive effects of earthquakes. Today, however, technological advances have enabled man to develop suitable techniques for preventing seismic damage. In line with this, many methods have been devised for making structures more seismic resistant. Some of these methods like installing bracing elements in frames, moment frames, and shear walls have been more commonly used than the others. These methods are mostly based on the fact that seismic forces are transferred to a structure via its foundation. Then, these forces are distributed among special members specifically placed for this purpose in the structure and subsequently absorbed by these members. In this method, the structure is fully influenced by seismic forces. In spite of placing such members in the structure, sometimes an earthquake is so severe that even the reinforced buildings sustain heavy damage and are destroyed as a result. To make structures resistant against the most severe earthquakes, we must use stronger, more ductile materials and this would be associated with increased, sometimes unacceptable, costs. It is desirable to build certain structures which – due to their application - can be fully isolated from ground motions. These include the sensitive parts of nuclear reactors, sensitive parts of electrical power plants, and buildings where sensitive computer equipment is kept. Or, in other cases, we might wish to safeguard from earthquakes a certain historically/culturally valuable building or statue which is not equipped with seismic resistance mechanisms.

In response to these needs, a different method was devised at the start of the present century for making structures seismic resistant. This method, known as "seismic isolation method", has seen many advances in recent years due to availability of many facilities including construction technologies and engineering analytics know-how. The main purpose in this method is preventing direct transfer of seismic forces from the foundation to the structure. For this reason, this method is also called "the base isolation method" where special isolator systems are used as obstacles at the junction of foundation to the structure to prevent seismic forces/energy from being transferred to the structure. As a result of the small forces being transferred to the structure in this method, the following results are obtained:

- Significant reduction in the acceleration applied to the storeys,
- Tangible reduction of structural and nonstructural damage,
- Reduced architectural problems in buildings, and
- Reduced relative storey drifts.

As a result of seismic isolation, the lateral stiffness of the structure is reduced, resulting in the natural period of the structure to increase. Consequently, the acceleration induced in the structure due to ground motions is reduced. In certain cases (including occurrence of earthquakes with long periods or when the soil at the site of the structure is loose/soft), the seismic isolation system might not exhibit a favorable performance and even cause resonance to occur within the structure. Therefore, such exceptions must be duly considered in the design period. In this chapter, we discuss seismic isolators in greater detail.

Research Background

Introduction

Though the seismic isolator technology is relatively new, much research has so far been conducted on this subject. In recent years, due to availability of various facilities (in terms of construction technology and engineering know-how) for design, analysis, and implementation of seismic retrofitting projects, this method has been widely applied to practical situations and is experiencing rapid progress, becoming more and more acceptable in the process. In this section, we present a brief history of seismic isolators as well as the research conducted in this regard.

History of Isolators in Iran

The first instances of seismic isolators in Iran are related to olden times when structures used to be built on rocks with smooth surfaces. The smooth surface of the rock would cause the structure to slide relative to its foundation during earthquakes, and increased the period of the system for the purpose of reducing the forces applied to the structure. Some regard Cyrus the Great's Tomb in Pasargad, Iran, as the first seismic isolator built in the world. Another example of a seismic isolator is using wooden lumbers under the bearing walls in a building (Fig. 3.1). An example of this system can be found in Masouleh in northern Iran. Due to its environmental conditions, Masouleh's architecture is based on preserving the buildings against earthquakes and moisture. The lumbers would prevent moisture from penetrating the building and, during earthquakes, would isolate the building from its foundation through rolling theses lumbers.

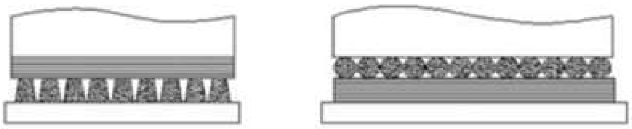


Fig. 3.1. Using lumbers under bearing walls

Another positive point in the design of structures in Masouleh is using wooden frames with vertical and horizontal yokes in construction of wind braces. Such a frame would cause the building to act as an integral structure during an earthquake and is an essential component n the isolator system (Fig. 2.3).

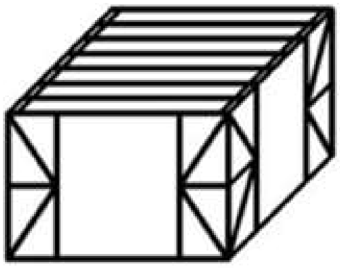


Fig. 3.2. Using wooden frames to reinforce houses in Masouleh

Another example of this system can be found in Lahijan Village. Observational evidence shows that this method originated thousands of years ago. These structures exhibited an acceptable performance during the deadly Menjil Earthquake in 1990. Some of these structures withstood approximate permanent displacements of 15-20 centimeters.

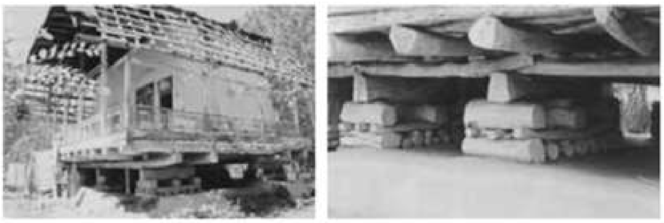


Fig. 3.3. Using the roller system in houses in Lahijan

The first effort in modern times to use seismic isolators in Iranian buildings was accomplished in 1970 in Tehran Communications Center. The isolator used in this building consists of two Teflon layers separated by a rubber layer. This isolator is placed within the gap between the basement ceiling and the ground floor columns. However, there are no available plans of the details of this system.

The most recent use of isolator systems is related to a recent contract concluded between Iran's Housing and Urban Planning Ministry and the Malaysian government. According to this contract, the Malaysian side of the contract undertakes to build several residential blocks in the newly founded Parand and Hashtgerd towns. Using seismic isolators is compulsory in this contract. This is actually the first project where seismic isolators are implemented in Iran in accordance with modern construction codes.

Fig. 3.4. Tehran Communications Center

Fig. 3.5. Seismic isolators used in Parand

METHODS AND MATERIALS

Introduction

Increasing human needs and efforts for satisfying them have created new and complex problems in all scientific and technical fields in general, and the field of Mechanical Engineering is no exception in this regard. In most cases, it is necessary to design and analyze parts with complicated geometries and (more recently) complicated materials properties under irregular loadings. Applying classical methods (e.g., theory of elasticity for stress distribution) would lead to very complicated governing equations with various boundary and initial conditions which render their analytical solution impossible. For this reason, a variety of numerical methods have been proposed for solving the governing equations of different systems. These methods are widely used in present applications. Depending on the numerical method used and the elements chosen for the meshing, various methods exist for solving the governing equations, including the finite volume, the finite element, and the finite difference method. Of these, the finite element method is the most widespread method used – in the form of software including ANSYS, ABAQUS, and NASTRAN - in the majority of Solid Mechanics problems. In this chapter, we address the general problems encountered in modeling isolator systems and introduce the existing methods and software that are in use today.

The Finite Element Method

Engineers and physicists often describe a physical phenomenon via a system of ordinary or partial differential equations which hold under certain conditions and satisfy the relevant initial as well as boundary conditions. In fact, a differential equation with its proper initial and boundary conditions represents a complete mathematical model of a physical phenomenon. To find the desired distributions for the variables of this differential equation, the equation must be solved and the numerical values of the relevant variables obtained at the desired points. However, due to the fact that only very simple forms of these equations (within very simple geometrical regions) can be solved via analytical methods, we confront a huge problem when solving these equations. To overcome such difficulties and to use the most powerful machine made by man in the 20th century, namely, computers, it is essential to design the desired problem in the form of a fully algebraic problem so that we can solve it through algebraic operations alone. To this end, we can apply different discretionizing techniques to a continuous problem defined by the differential equations. In these methods, the known and unknown functions represented by an infinite set of numbers are represented instead via a finite set of unknown parameters. Naturally, these methods generally involve a certain degree of approximation.

The finite element method is a numerical procedure for solving physical problems described by the relevant differential equations. This method has two characteristics which separate it from other methods:

- It uses an integral formulation for forming a set of algebraic equations, and
- It uses smooth piecewise continuous functions for approximating the unknown quantities.

The latter characteristic is the distinctive feature of the finite element method and does not exist in other numerical methods using integral formulations.

The finite element method can be divided into five main stages:

- Dividing the studied region into many small subregions called “elements”. These elements are joined by points referred to as “nodes”.
- Setting an initial solution approximation in the form of a function with constant unknown coefficients. This function is either linear of the third degree or quadratic of the fourth degree. Upon determining the order of the initial approximation, the governing equation at each node can be written.
- Extracting the system of akgebraic equations. If the Galerkin method is used, the seiht function for each node is specified and then, the residual weighted integral is formed. Upon integration, an algebraic equation is obtained for each node. After obtaining

similar algebraic equations for all the nodes, a system of algebraic equations is obtained.

- Solving the system of algebraic equations
- Computing the other unknown quantities from the node values

As already mentioned, in the first stage, the problem geometry is divided into small elements. Nodes are the common points between adjoining elements. A group of elements with their associated nodes are called a "mesh" (meshing). Elements can be one, two, or three dimensional. In addition, depending on the element dimension, different shapes can be selected for an element. A 2D element can be in the form of a triangle, square, or any other arbitrary shape. A 3D element can be tetrahedral, prismatic, or cubic. Meshing is an important stage in modeling and requires special care as well as skill. In the second stage, an initial approximation is considered for the solution in the form of a function with constant unknown coefficients. This approximation is performed within one element for the entire problem. For the problems solved via software, the approximation never goes beyond a second degree function since the selected element dimensions can be very small. In other words, the initial approximation for the software solution is either linear or parabolic. In the next stage, the governing equation for each node is written and converted into an algebraic equation upon performing the necessary integrations. As each equation involves more than one unknown, it cannot be individually solved. Rather, we must first extract the equations for all the nodes to obtain a system of equations which can be subsequently solved to find all the unknown quantities. Upon extracting the equations, we must solve them. There are various methods for solving these equations. In the next step, upon determining the node values, other quantities such as strains, stresses, forces and moments are calculated with due regard of the initial dimensions and geometric properties of the described materials.

ABAQUS

General: ABAQUS is powerful finite element tool presented in the market. The name of this software is derived from the Greek word "abacus" (meaning "an old computing tool" in English and "a wooden board covered with sand" in Greek). In spite of its vast capabilities, ABAQUS is very easy to learn.

The main idea for developing this software was presented in Dr. David Hibbit's (1972) doctoral dissertation at Brown University entitled "Computational Mechanics based on the Finite Element Method". In 1978, Mr. Hibbit, accompanied by his two partners Karlson and Soreson, founded a company called HKS and published the first version of ABAQUS. In 1991, the same company added the ABAQUS/Explicit Solution to the software, thus publishing its main software. Finally, in 1999, the first graphical version called ABAQUS/CAE was presented to the market. The first graphic version (ABAQUS 6.3) included 9 modules for modeling, solving the problem, and extracting the results. The finite element method (FEM) is a numerical method for approximate solution of partial differential equations as well as integration. This method is based on either complete elimination of differential equations or converting them into simpler ordinary differential equations which can be subsequently solved via numerical methods such as Euler's Method. The important thing in solving partial differential equations is reaching a simple, numerically stable equation (i.e., the obtained error in the initial data and during the solution process must not be so large as to produce unrealistic results). Different methods – each having its own specific advantages as well as disadvantages – can be used for achieving this result, with the finite element method being one of the best. FEM is particularly useful for solving partial differential equations in complicated domains (e.g., vehicles and oil pipelines), variable domains, when high precision is not required at all points of the domain, and when the obtained results lack the required correlation or consistency.

ABAQUS is capable of simulating complicated problems in Mechanical Engineering, Civil engineering, and other engineering field. Due to the high cost of experiments, FEM simulation can be used as a substitute for practical tests. The point to be considered here is that using FEM packages without sufficient knowledge of the finite element method can produce erroneous simulations as well as misleading results. Therefore, relative familiarity with the FEM is essential before using such software. The simple graphical environment in ABAQUS might lead the user into thinking that he can learn how to model via this software via trial and error without the required training. Nevertheless, using this site would help the user to find the best and fastest tool during modeling. In this site, an effort is made towards step-by-step teaching of ABAQUS through different examples. Advantages of ABAQUS include:

- Advanced capabilities for analyzing nonlinear problems including plastic behavior and large deformations
- Analysis of part failure and crack development (in addition to crack germination), thus providing the possibility of predicting dynamic development of cracking in isotropic and compound materials
- Possessing special capabilities in the field of composite materials
- Capability of providing explicit as well as implicit solutions for problems
- Possessing different easily accessible subroutines for the user so that he can find what theories are used for solving individual problems.

ABAQUS is able to solve a variety of problems, ranging from simple linear analyses to the most complex nonlinear modeling instances. This software presents a wide set of different elements for modeling any kind of geometry. In addition, it has many behavioral models wich can be used for modeling various materials with different properties and behaviors (e.g., plastics, polymers, composites, reinforced concrete, spring foams, brittle materials, and geotechnical materials including soil, rock and stone, etc.) Since ABAQUS is a general modeling tool with wide applications, its use is not limited to solving Solid Mechanics problems (i.e., stress-strain problems). Rather, this software can also be used to solve many other problems including heat transfer, mass penetration, thermal analysis of electrical components, acoustics, seepage, and piezoelectric problems. In spite of its widespread abilities, ABAQUS is basically simple to apply, and can solve the most complicated problems via simple modeling methods. For example, problems with multiple parts can be solved by generating an individual model for each component, attributing material properties to the same, and then, assembling the different parts to obtain the final results. In most modeling cases, even those with high nonlinearity, the user only has to determine engineering data such as the problem geometry, the relevant material behaviors, the boundary conditions, and the loading conditions. During a nonlinear analysis, ABAQUS automatically selects the required load increments as well as convergence tolerances. In addition, throughout the analysis, the values of these are constantly modified for achieving the correct solution. Consequently, the user rarely needs to determine the control parameters for the numerical solution.

Modeling of Elastomeric Isolators

These isolators were discussed in the previous chapters. Elastomeric isolators can be used for seismic isolation of lightweight structures (e.g., isolating floors). Advantages of these isolators include their simple construction, their behavior being temperature independent, their loading history, and time lapse possibility. Their single disadvantage is their limited damping property. But this problem can be solved by adding a damper to the system. To utilize the advantages of elastomeric isolators in seismic isolators – in isolation of lightweight structures in particular – and to spread the use of these systems, we have to find simpler solutions for their design, thus reducing their associated costs and making them economically viable. The next section discusses the main characteristics of an elastomeric isolator.

Geometric Characteristics

Isolator Shape: Elastomeric isolators are generally designed in circular and square forms since these sections would create isotropic properties (similar properties in two mutually perpendicular directions) in the isolator. Fig. 4.3 shows an example of each section.

Isolator Diameter: Diameter of an isolator is another variable which usually varies in the following range:

250mm =< D =< 1000mm

Diameter of the Isolator Internal Plates

These diameters are a function of the isolator diameter and are generally 10-20 mm less than the external plate diameters. In other words, the internal plates are placed 5-10 mm from the edge of the isolator.

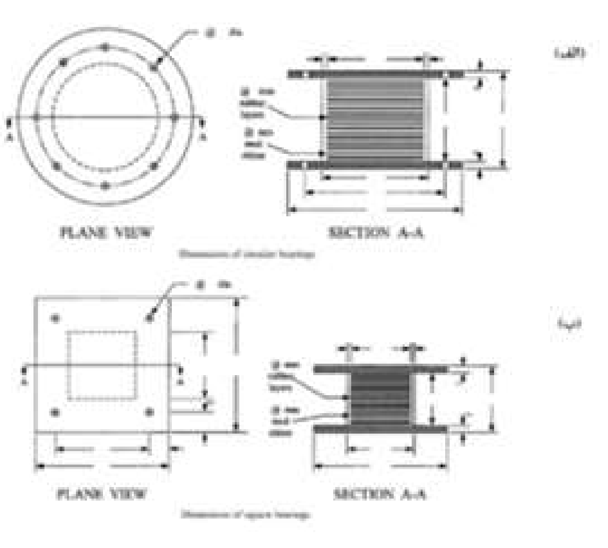


Fig. 4.3: Schematic of square and rectangular elastomeric isolators

Diameter of External Isolator Plates

These diameters are functions of the isolator diameter as well as the diameter of the column placed on each.

Rubber Layer Diameter: Diameter of this layer is equal to that of the isolator.

Thickness of Isolator External Metal Plates: A thickness of 25mm is generally assumed for these plates, but, due to the limitations imposed on the market in this regard, this thickness generally varies within the following range:

20mm=<t=<25.4mm

Thickness of Isolator External Metal Plates:

The thickness of these plates is obtained from the existing standards for thin sheet metal and generally varies within the following range:

2 mm=<t=< 3mm

Number of Rubber Layers: This number is obtained during the design phase based on design displacement and maximum strain energy in shear, and generally varies in the following range:

5 mm=<nr=< 20mm

Number of Intermediate Isolator Plates

This number depends on the number of isolator rubber layers and is always equal to the number of rubber layer minus one.

Number of External Plates: This is always equal to two.

Materials Specification

Properties of Isolator Steel Plates:

- Density: 7800 Pa
- Modulus of elasticity: 2 x 10^5 MPa
- Poisson’s ratio: 0.3

Properties of Isolator Rubber Plates:

- Density: 1000 Pa
- Shear Modulus (G): MPa ≤3 G ≤ MPa0/3
- Poisson’s ratio: circa 0.5
- Damping: In elastomeric isolators, rubbers with both high and low damping properties are used, depending on the designer’s decision, the locatin in the structure where these are used, type of the structure, and the conditions of the site. Generally, the damping ratio of these lies in the following range:

2% =< damping ratio =<15%

Using ABAQUS to Define Materials

Elastomeric isolators consist of two materials: rubber and steel, placed as laminates one on top of the other. Upon defining the model geometry in the software, the materials specification of the isolator system must be defined exactly. Then, the loads, boundary conditions, type of analyses, the required outputs, etc. must be defined. Ultimately, the necessary analyses are conducted on the prepared models.

Rubber

Rubber materials have low compression stiffness and high shearing ductility. These materials are generally modeled by hyperelastic materials. ABAQUS has a special family of hybrid elements for modeling incompressible rubber materials. The elements used for these materials must be elastic, isotropic, and consistently incompressible, and include nonlinear effects. Hyperelastic materials are described in terms of their strain energy (the energy stored in the unit basic volume of the material expressed as a function of strain energy at a point in the material). Therefore, rubber is represented as a second order polynomial hyperelastic material with the following strain energy:

$$U=\sum_{i+j=1}^{2} C_{ij}(I_1-3)^i(I_2-3)^j+\frac{(J^{\mathrm{el}}-1)^2}{D_1}, \qquad \text{………(4.1)}$$

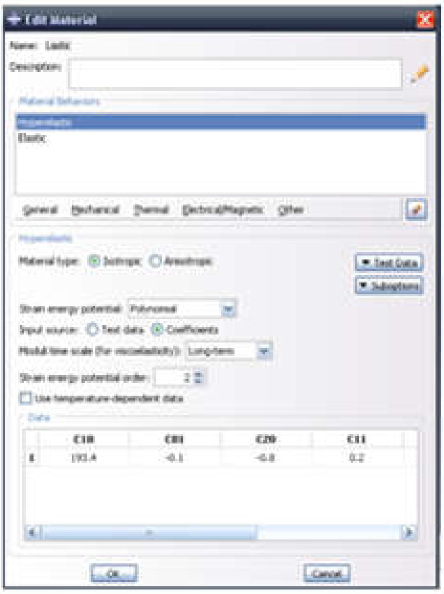
Where Cu and D1 are materials parameters, I1 and I2 are the first and second variances of strain, and Jel is the volumetric ratio of the rubber. PRubber elements parameters are its shear modulus (G) and initial stiffness (K), defined as:

$$G=2(C_{10}+C_{01}),\ K=2/D_1 \qquad \text{………..(4.2)}$$

The values used in modeling are presented in Table 4.1 where Cu and D1 are --- kPa and ---kPa-1 respectively. In this study, the rubber element was modeled by entering as input to ABAQUS the coefficients and constant values of strain energy functions given in the table below.

Table 4.1. Values used for the rubber polynomial model

Rubber model	C_{10}	C_{01}	C_{20}	C_{11}	C_{02}	D_1
Polynomial	193.4	−0.1	−0.8	0.2	0	0



Material Behaviors: Hyperelastic, Elastic

Material type: ● Isotropic ○ Anisotropic

Strain energy potential: Polynomial

Input source: ○ Test data ● Coefficients

Moduli time scale (for viscoelasticity): Long-term

Strain energy potential order: 2

☐ Use temperature-dependent data

	C10	C01	C20	C11
1	193.4	-0.1	-0.8	0.2

Fig. 4.4. Feeding ABAQUS with the coefficients and constants of strain energy functions for modeling rubber elements

Steel

In ABAQUS, steel is modeled as a linearly elastic material with the following properties:

- Acceptable behavior within the elastic range only (strain rate below 5%)
- Can be isotropic, orthotropic, or fully anisotropic
- Can be temperature dependent
- Can be defined for volumetrically continuous elements

The simplest form in materials is the linear elastic form where stress-strain relations are:

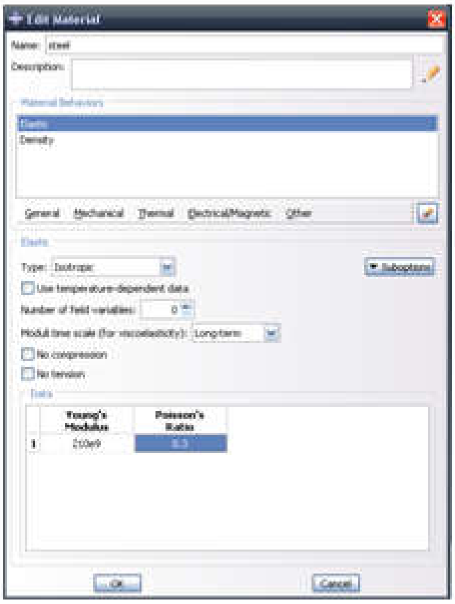
$$\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \gamma_{12}\\ \gamma_{13}\\ \gamma_{23}\end{Bmatrix}=\begin{bmatrix}1/E & -\vartheta/E & -\vartheta/E & 0 & 0 & 0\\ -\vartheta/E & 1/E & -\vartheta/E & 0 & 0 & 0\\ -\vartheta/E & -\vartheta/E & 1/E & 0 & 0 & 0\\ 0 & 0 & 0 & 1/G & 0 & 0\\ 0 & 0 & 0 & 0 & 1/G & 0\\ 0 & 0 & 0 & 0 & 0 & 1/G\end{bmatrix}\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \sigma_{12}\\ \sigma_{13}\\ \sigma_{23}\end{Bmatrix} \qquad (4.3)$$

The elastic properties of these materials arre fully defined via modulus of elasticity (E) and Poisson’s ratio (v). The shear modulus can be obtained from these two parameters as:

$$G=\frac{E}{2(1+\vartheta)} \qquad (4.4)$$

Therefore, properties for the steel used in the model are:

$$E=2/1\times10^{6}\ kg/cm^{2},\ \vartheta=0/3\ ,\ G=8/08\times10^{5}\ kg/cm^{2}$$



Name: steel

Material Behaviors: Elastic, Density

Type: Isotropic

☐ Use temperature-dependent data

Number of field variables: 0

Moduli time scale (for viscoelasticity): Long-term

☐ No compression

☐ No tension

	Young's Modulus	Poisson's Ratio
1	210e9	0.3

Fig. 4.5. Entering the steel element properties in ABAQUS

Meshing Size

Before meshing, we need to determine the number of the necessary elements in the layer and as well as on the surface so that we can obtain better results and reduce volume at the same time. To achieve suitable numbers for layer and surface elements, we conducted 6 analysis series, the results of which are given in Figs. 4.6 and 4.7.

Table 4.2. Properties of elastomeric layered isolators

Number	Number of Element Rows on the Surface	Number of Elements in Layer Depth (Thickness)
1	3	1
2	3	7
3	3	17
4	5	1
5	5	7
6	5	17

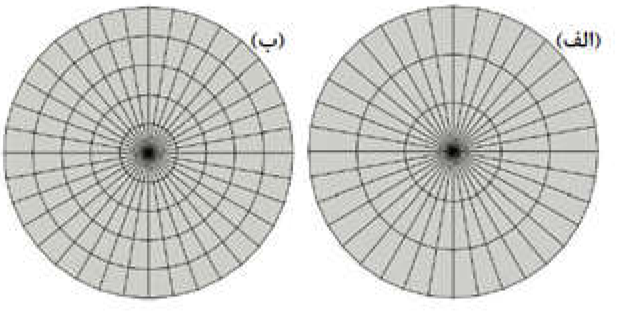


Fig. 4.6: Number of elements on the surface: a) three element rows; b) five element rows

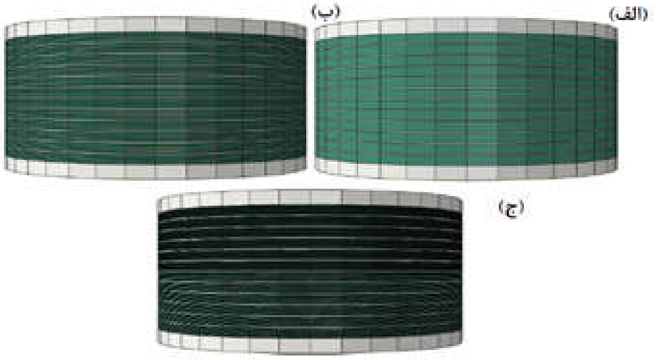


Fig. 4.7. Number of elements along the depth (thickness) of each layer: a) one element per layer thickness, b) seven elements per Layer thickness, c) 17 elements per layer thickness

We can observe in Figs. 4.8 and 4.9 that increasing the number of elements along layer thickness produces more exact results. However, this number has no significant effect on the results and only increases the computational time as well as volume required for the analysis. For this reason, we selected a meshing with three elements on the layer surface and seven elements along its thickness, thus obtaining a 90% accuracy at a computational time of about one eight (as compared with that obtained for greater element numbers).

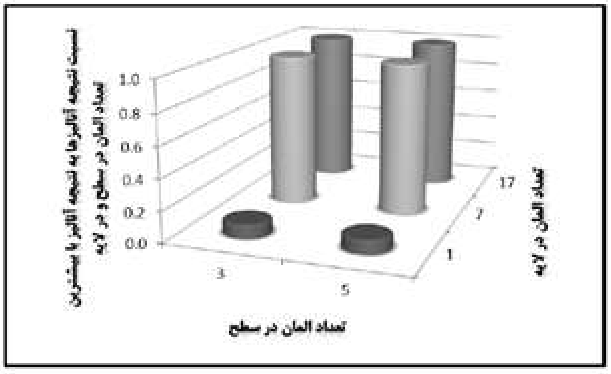


Fig. 4.8. Effect of the surface and thickness element numbers on the output results

(Number of elements per layer – Ratio of analysis results to those obtained using the maximum number of elements on the surface and along the layer thickness)

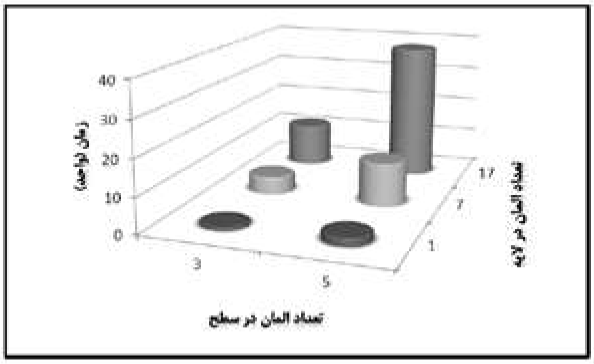


Fig. 4.9: Effect of the surface and thickness element numbers on computation time

(Number of elements per layer – Number of elements on the surface – Time (unit))

Other Modeling Considerations

ABAQUS uses a family of hybrid elements for modeling rubber. Hybrid elements have isotropic nonlinear properties and are used for modeling materials exposed to instantaneous response at high strain rates. Most rubbers have negligible compressibility as compared with their shear ductility (flexibility). However, fully incompressible materials cannot be used in modeling except in plane stress uniaxial problems. As a result, if no specific value is provided for compressibility, ABAQUS would,, by default, assume a compressibility of 20 for the material. This default value would provide a suitable solution for the unconfined elastomers used in this study. The only remaining problem is the way of connecting the elements together. In actual models, rubber is put under high pressure and temperature upon vulcanization and connected to steel inside the die through special adhesives. In actual models, an effort is made to provide complete binding between the rubber and steel sheets. In ABAQUS, this was fully achieved by merging the contact points between the elements, thus creating a complete bind between the materials.

Conclusion

Introduction

In this chapter, the results of the conducted analyses and studies are described in greater detail. Ultimately, the general results and recommendations for future research are presented.

Effect of Shape Factor on Vertical Stiffness of the Isolator

General

Shape factor of a layer of elastomeric isolator is defined as the ratio of that layer's plan area to the area of that part of the layer capable of being deformed under shear. Shape factor greatly influences the compression stiffness in an isolator system. For example, shape factor in a single-layer rectangular isolator without holes is calculated as:

$$S_i = LW/[2h_{ri}(L + W) \quad 5.1$$

Where L and W are the rectangle's dimensions along the longitudinal and lateral directions, and hn iis the thickness of the i-th layer in the elastomeric isolator.

At each layer of the isolator, the average compression must be below the allowable compression. The relation between the compression applied and the shear stress developed in the isolator as the result of this compression directly depends on the shape factor of the isolator. Higher shape factors would lead to greater capacities for the isolator. The UBC97 Code calculates the vertical stiffness of an isolator as:

$$K_V = \frac{E_C A}{t_r} \quad 5.2$$

Where A is the plan area of the isolator, tr is isolator thickness (depth), and Ec is the compression modulus of the isolator.
For a circular layer, the compression modulus Ec is obtained in terms of isolator shear modulus (G), isolator volumetric modulus (K), and isolator shape factor (S) as follows:

$$E_C = \frac{6GS^2K}{6GS^2+K} \quad 5.3$$

Studied Models

As can be observed isolator vertical stiffness is directly dependent on isolator shape factor which is in turn dependent on isolator layer thickness and its diameter. Therefore, we tried in this section to check the vertical stiffnesses in the construction codes by comparing them with the corresponding values generated for the models by ABAQUS. This was done by obtaining the stiffness values for isolators with different layer diameters and thicknesses. To this end, 16 geometric models were constructed for laminated isolators, the properties of which are given in Table 5.1. In the previous chapter, the modeling process followed for these isolators was explained in sufficient detail. Figs. 5.1 and 5.2 show an example of the isolators modeled via ABAQUS as well as its rubber layers (in different diameters and thicknesses) generated through by the software.

Table 5.1. Geometric properties of the studied elastomeric isolators

Number	Rubber Layer Thickness (mm)	Isolator Radius (mm)
1	5	150
2	5	300
3	5	450
4	5	600
5	10	150
6	10	300
7	10	450
8	10	600
9	16.7	150
10	16.7	300
11	16.7	450
12	16.7	600
13	20	150
14	20	300
15	20	450
16	20	600

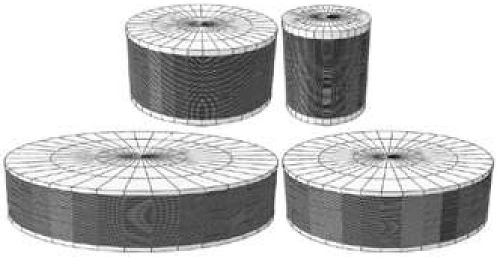


Fig. 5.1. An example of the isolators modeled via ABAQUS

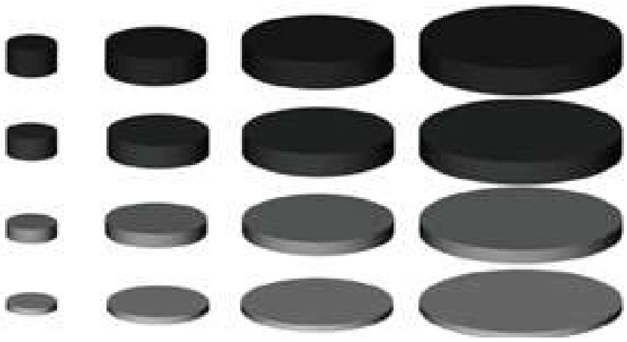


Fig. 5.2. Rubber layers generated via ABAQUS

ANALYSES RESULTS AND DISCUSSION

In this section, we discuss the results obtained from analysis of vertical isolator stiffnesses. The purpose here is to examine the effective factors on layered isolator vertical stiffness. To this end, the rubber layer thickness (t) and the isolator radius (R) were studied. Upon generating the initial models, we subjected to vertical loading and recorded the results. The incremental load analysis was performed. The following conditions were applied to all the models: 1) distributed vertical load at the upper external late, 2) rubber and steel were fully attached via adhesives at all point of their contact plane, and 3) the lower external plate was connected to the ground via a fully fixed joint. Fig. 5.3 shows the layered isolator before and after loading

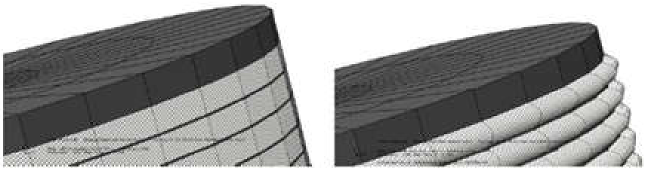


Fig. 5.3. Isolator ABAQUS model before and after loading

Due to the confinement of the internal rubber and incompressibility of the rubber material, vertical loading of the isolator would be almost evenly distributed among the points located on the internal rubber (according to Pascal's Law). Therefore, in elastomeric isolators with metal rings, stress distribution at the central rubber would be hydrostatic ($\sigma 11 = \sigma 22 = \sigma 33$). Upon applying stress onto the isolator, we can obtain its vertical stiffness by inversing the vertical displacement (drift) per unit vertical force. In the following section, the results obtained for vertical stiffness of the isolator system are given (the isolator layers diameter and thickness were increased). As can be observed from the figure, increasing isolator radius at different rubber layer thicknesses (which in turn increases the shape factor) leads to increased vertical stiffness. In addition, Fig. 5.5 shows that increasing isolator layer thickness would increase the slope of the diagram, emphasizing that increasing isolator radius is more effective in thicker isolators.

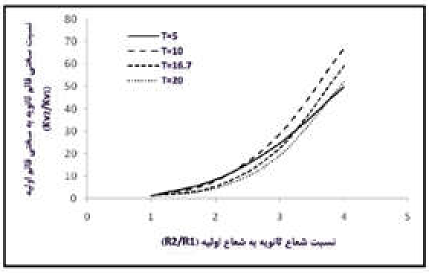


Fig. 5.4: Effect of layered isolator radius on isolator stiffness at different thicknesses under vertical loading (Ratio of secondary radius to initial radius – Ratio of secondary vertical stiffness to initial vertical stiffness)

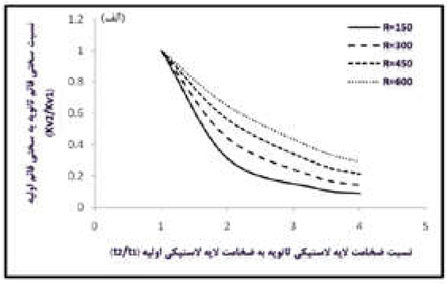


Fig. 5.5: Effect of layered isolator radius on isolator vertical stiffness at different thicknesses under vertical loading (Ratio of secondary-to-initial rubber thickness – Ratio of secondary-to-initial stiffness)

In the meantime, we calculated (using Equation 2.5 in UBC97) the stiffnesses of isolators with different radii at an initial thickness of 10mm and presented the results in the diagram obtained from ABAQUS.

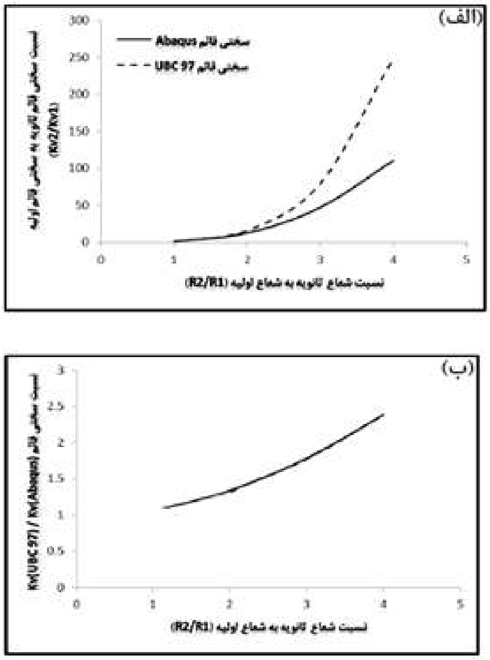


Fig. 5.6. Effect of isolator layer thickness on the vertical stiffness (a) and UBC97 Stiffness (t=10mm) and comparing them to the corresponding results obtained from ABAQUS (Ratio of secondary-to-initial rubber thickness – Ratio of secondary-to-initial stiffness) (Ratio of vertical thicknesses)

As can be observed, in this code, the effect of isolator radius on vertical stiffness is greater than that obtained in ABAQUS analyses. In addition, increasing radius would increase the rate of increasing stiffness through increasing the slope of the diagram. Therefore, a greater stiffness is required in the equation given in the above code.

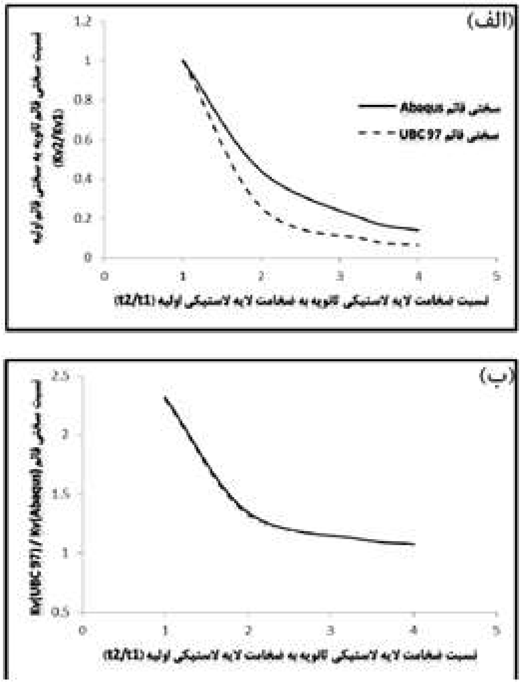


Fig. 5.7. Effect of isolator layer thickness on vertical stiffness (a) and the ratio of results obtained from UBC97 to those obtained from ABAQUS (R=300mm)

(Vertical stiffness – ABAQUS; Vertical stiffness- UBC97; Ratio of the secondary rubber layer thickness to the initial rubber layer thickness; Ratio of the secondary vertical stiffness to the initial vertical stiffness)

Effect of Shape Factor on Isolator Shear Strain

According to the results obtained in the previous section, changing the rubber layer properties including its thickness, radius, and shape would totally change the general distribution of stresses and shear strains in the layer volume as well as the isolator lateral load bearing capacity. This emphasizes the significance of shape factor in the design process. In practical applications, layered isolators sections are generally circular or close to square. In bridge structures, however, these take the form of oblongs.

The maximum shear strain resulting from loads applied on the rubber plate is calculated as:

$$\gamma_c = \frac{P}{AGS}$$

……………….(5.4)

In this section, we analyze the rubber layer shown in Fig. 5.8 to study the maximum shear strain developed in the rubber layer under pressure. Under pure vertical loading, a single rubber layer develops the maximum shear strain at its external side. Therefore, to examine the effect of the rubber layer shape factor, we adjusted the dimensions of the rubber layer to obtain shape factors of 5, 20, and 30.

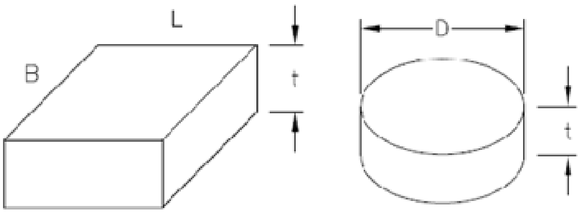


Fig. 5.8. Geometric characteristics of different shapes of rubber layers

We assumed a thickness of 10mm for the rubber layer, and calculated its stiffness by applying a displacement of 1mm (from the FEM model). The layer radius was selected so as to produce shape factors of 5, 20, and 30.

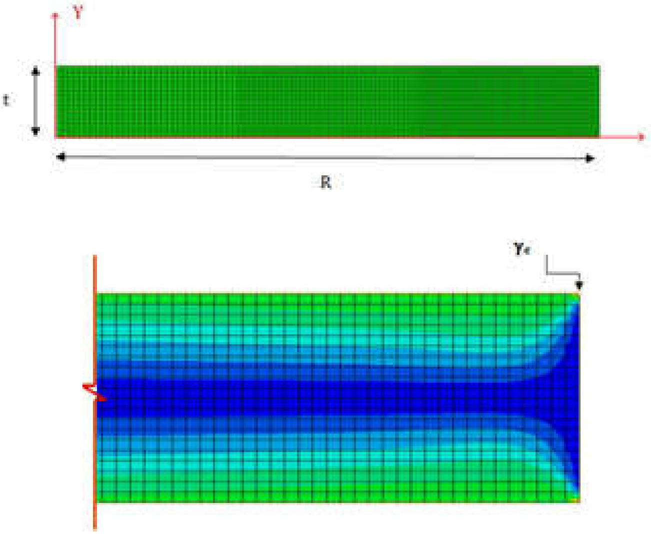


Fig. 9.5. The circular model geometry and its schematic stress distribution

To model rubber, we used axi-symmetric materials of the fourth (displacement) order, thus analyzing only half of the rubber layer and reducing computation time considerably. The boundary conditions for the model were:

- Zero displacement (drift) along the x-axis and zero drift at the base along the y-axis
- Zero drift along the x-axis and a downward drift at the upper part along the y-axis
- Zero drift at the axis of symmetry along the x-axis

Using these values, we obtained the maximum strain ratio produced by ABAQUS so as to be able to calculate the correct shear strain (on the basis of shape factor) at the isolator by applying the coefficient f in Equation 5.4. Fig. 9.5 shows the geometry of the circular model as well as its stress distribution. Fig. 5.10 shows the shear strain distribution in terms of strain (Equation 5.4) along the radius of the circle. As can be observed, increasing shape factor leads to a significant difference between the strain ratio obtained for the total radius and that obtained from Equation 5.4.

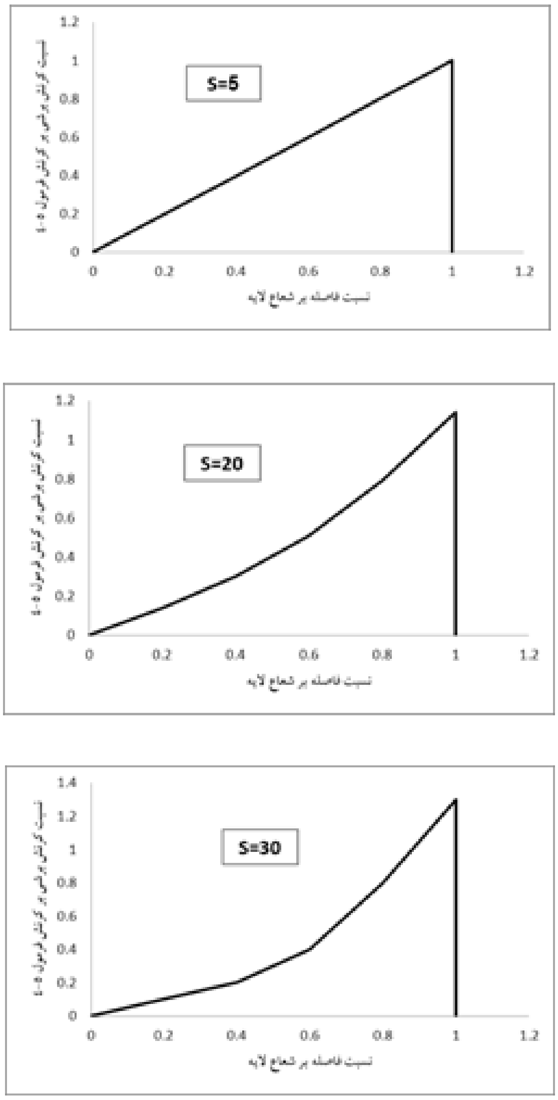


Fig. 5.10. Shear strain distribution vs. strain obtained from Equation 5.4 along the circle's radius

- (Ratio of distance to radius – ratio of shear strain to strain obtained from Equation 5.4)
- (Ratio of distance to radius – ratio of shear strain to strain obtained from Equation 5.4)
- (Ratio of distance to radius – ratio of shear strain to strain obtained from Equation 5.4)

In addition, three rectangular elements with length ratios of 0.2, 0.6, and 1 were used in this research. Fig 5.11 shows this model and the schematic stress distribution thereof. Here, a 20-node element was used to model the rubber. Due to the symmetry, only one-fourth of the model was analyzed (rubber layer dimensions: length x ½ width x ½ thickness). The boundary conditions were:

- Zero displacement (drift) along the y-axis at the base
- Zero drift along the x and z axes and a downward drift at the upper part along the y-axis
- Zero drift at the base level at the isolator center along x,y, and z axes

Ultimately, shear strain distribution along the rectangle length under unit loading applied at the top of the rubber layer was obtained for a ratio of 0.6 from ABAQUS and from Equation5.4 (Fig. 5.12).

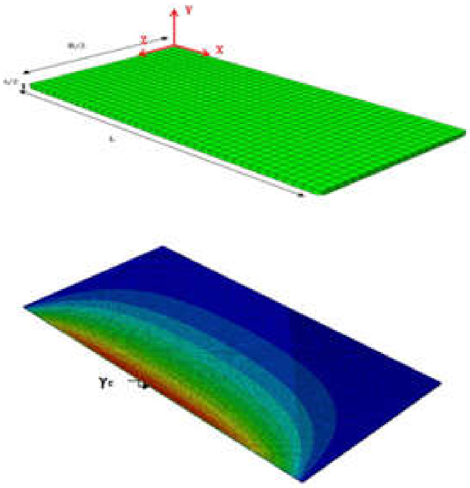


Fig. 5.11. Geometry of the rectangular model and its stress distribution schematic

- (Distance to Rectangle Length Ratio – ratio of shear strain to normal stress)
- (Distance to Rectangle Length Ratio – ratio of shear strain to normal stress)
- (Distance to Rectangle Length Ratio – ratio of shear strain to normal stress)

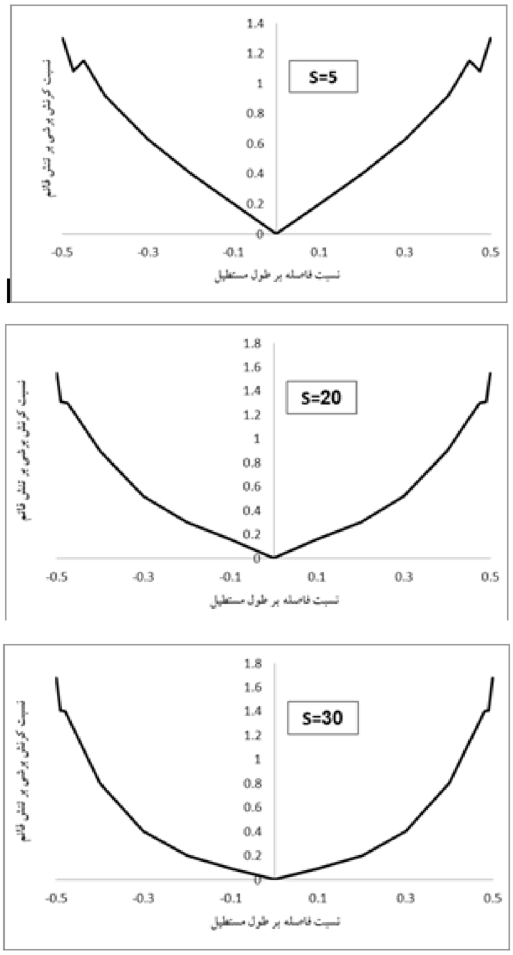


Fig. 5.12. Shear strain distribution along the radius versus the strain obtained from Equation 5.4

- (Shear strain-to-normal stress ratio- Ratio of distance to rectangle length)
- (Shear strain-to-normal stress ratio- Ratio of distance to rectangle length)
- (Shear strain-to-normal stress ratio- Ratio of distance to rectangle length)

The results obtained from these figures also emphasize the necessity of including another coefficient for correcting the shape factor. Based on the results obtained from these analyses, we calculated different values for f for the purpose of including them in Equation 5.4. These values are given in the following tables.

Table 5.2. Correction factors calculated for shape factor

a) Circular element

S	f
5	1.01
20	1.18
30	1.37

b) Rectangular element

S	L/B		
	0.2	0.6	1
	f	f	f
5	1.43	1.33	1.21
20	1.53	1.44	1.37
30	1.67	1.59	1.55

As can be observed, applying f=1 is only suitable for rubber layers with small shape factors. For higher shape factors, f can be applied to the shape factor in the form of a reduction factor.

Conclusion

The structural hybrid control technique is the most suitable control system since it comprises both active and passive control systems. The active and passive components of the hybrid control system act at high and low vibration amplitudes respectively, thus providing a better performance for the hybrid system. Isolating buildings from ground vibrations is a new method and the only method available for simultaneously reducing relative storey drift and storey acceleration. Soil type also plays an important role in isolation systems. Therefore, the structure must be built on hard soil for this method to be applicable. Another effective parameter is the structural height: base isolation is only applicable at low or medium structural heights. In addition, seismic isolators muse be so designed that they can retain their initial rigidity and stiffness against lateral nonseismic loads. At supports, steel sheets must be attached to the rubber layers to prevent lateral deformation due to vertical (normal) loading. The most important method for reducing drift is using dampers to dissipate as heat the stored energy that otherwise would cause severe motion in the structure. Lead-plastic bases (supports) are economic choices for seismic isolation of bridges. ABAQUS can be used for linear and nonlinear analysis, geometric shape, and different structural calculations at various structural points as well as for simulating complex problems via the FEM. Using this software, we can determine the specification of elastomeric isolator layers. Circular and rectangular elements provide better results. Therefore, by using circular base isolators, we can modify the shape factor more effectively as compared with rectangular base isolators.

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