Terminology for Seismic Isolation Systems

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Abbreviations:
CM: construction manager
Exp. J.: expansion joint
LRB: laminated rubber bearing
MLIT: Ministry of Land, Infrastructure, Transport and Tourism
MOC: Ministry of Construction
SE: structural engineer
SI: seismic-isolation / seismically isolated

1. Seismically isolated (SI) buildings

acceleration

This is the rate of change per unit of time. When the unit of velocity is cm/s, which is commonly used, the unit of acceleration is cm/s^2, also called gal (gravity acceleration: 980 cm/s^2).

aspect ratio / ratio of the height of a building to its width

This is the ratio of the height of a building to its narrow-side width, also referred to as the tower ratio. Usually the narrow-side width is measured from the center of one outer isolator to the center of the other outer isolator. When the tower ratio is high, the variation of axial-force in all of the isolators during an earthquake is greater, especially at the sides and the corners of the building, and/or under seismic walls.

center of rigidity

When horizontal forces such as earthquake loads, or wind loads, act on SI structures, these forces are resisted by isolators and dampers. As stiffness of each device is not equal, the structure will rotate about the center of rigidity. This center of rotation is usually referred to as the center of rigidity. If the center of mass in SI layer does not coincide with the center of rigidity, the torsional moment developed will be greater in relative to the distance between those centers, resulting in rotation of the structure. It is common practice to reduce the eccentricity, which is the distance between these two centers in SI layer, as much as possible.

clearance / moat / gap

The space around an SI structure is to allow for movement of the structure during earthquakes. This prevents collision between the structure and the retaining walls or other structures. Generally, this value must be set with an allowance after the response-displacement is calculated by time history response analysis. This space is referred to as clearance, moat, or gap. There are two types of clearances; horizontal space and vertical space, which allow horizontal and vertical displacement in the SI layer during earthquakes.

design clearance

Horizontal clearance must be decided by SE with consideration for the maximum response -displacement. Vertical clearance must be decided by SE, with consideration for creep and vertical displacement during earthquakes.

design criteria

SE must set the seismic criteria of an SI structure for earthquakes. These criteria are made for the superstructure portion, the substructure portion and SI devices. SE decides the design values for the story drift, story acceleration, story shear-force for the superstructure and substructure portions, also horizontal displacement, bearing stress, tensile stress and damping factor for SI devices.

eccentricity

This is the distance between the center of rigidity and the center of mass in a story. The displacement at the corners of SI structure with large eccentricity increases because displacement due to rotation of the structure is added to the translational displacement during earthquakes.

Exp. J. for SI system

Expansion Joint function as architectural members, such as a bridge between an entrance of SI structure and the outside, or between SI structure and other structures. They are mainly fixed to SI structures . The opposite side is not fixed, but is supported as it should move during earthquakes.

natural period

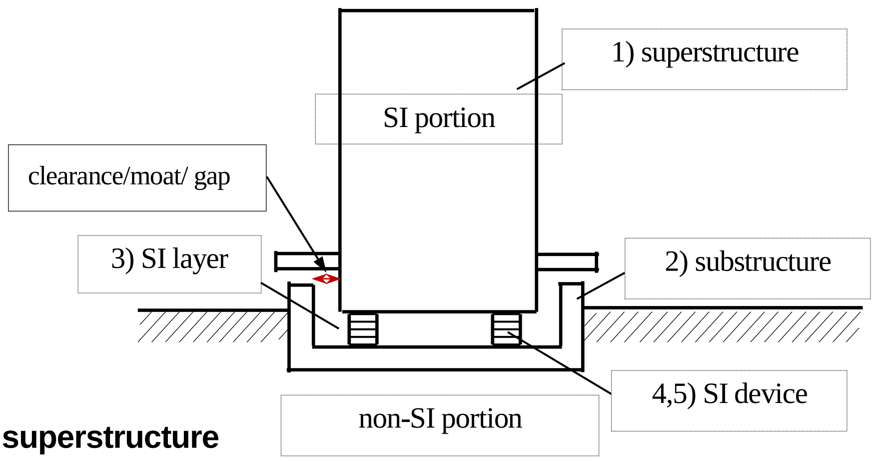
The structure vibrates for a certain period when a force is applied to it and is then removed. The structure shakes with the most swayable period, this period is called natural period.

natural period of structure with seismic isolation

An SI structure, assumed to be a rigid body, has a natural period of T_f, due to the stiffness of LRBs. The natural period of SI building: $T_f = 2\pi\sqrt{(M/K_f)}$, using mass M of structure at stiffness K_f, which is the horizontal stiffness of LRBs.

seismically isolated structure/ structure with SI

An SI structure has an SI layer under the superstructure. It consists of LRBs, which support the structure, and dampers, which absorb earthquake vibrations.



1) superstructure

This is the SI portion, which is in the upper portion of the structure (above SI layer). The acceleration of the superstructure is decreased due to the reduction of vibration energy in the superstructure by SI devices. Thus, the occupants' perception of motion is greatly minimized.

2) substructure

Non-SI portion, including equipment below SI devices, such as footings, base and retaining walls, is referred to as the substructure. It is necessary to address additional bending moments that occur in connecting parts of LRBs, due to the movement of the structure, and to design the parts of the substructure to resist these moments.

3) SI layer

The SI layer is the space where SI devices are installed. Also in this space, there is equipment, such as piping, electrical wiring and small spaces for maintenance purposes.

4) SI device

SI devices commonly consist of isolators and dampers. Isolators are able to support loads while moving horizontally, and dampers absorb vibration energy.

5) other SI devices

Base plates for the setting of devices, as well as flexible pipe-joints and Exp. J., are other devices related to the SI structures.

seismic shear-force for design

Stress of members in a building is calculated using the design shear-force, which is used to calculate the eccentricity ratio and the story stiffness-ratio of the building. The shear-force distribution is decided after response analysis. The type of distribution is usually an inverse-triangle.

standard for SI buildings in Japan

The technical standard for SI buildings was issued with a standard for SI devices in Notification No. 2009, 2000, by MOC.

story drift / story deformation-angle

Story drift is defined by the deformation angle, which is divided by the story height. This deformation angle occurs when horizontal forces act on a structure, such as during earthquakes or from wind.

time history response analysis / dynamic response analysis

A vibration model is used for time history response analysis for external forces, such as earthquakes and wind loads. The model is used to evaluate the vibration characteristics of the structure on the basis of vibration theory. Response properties of the structure are analyzed at each digitized time to determine the situation of the building by the time history response analysis method. It is important for the analysis that both the appropriate vibration model and the evaluation of external forces are used. Recently, response analysis has been performed by factoring in the effect of the interaction between the building and the ground.

velocity

Velocity is the variation in displacement of an object per second. Velocity is generally used as an index to express the intensity level of earthquake ground motion in correlation with the damage of a structure. The maximum amplitude of velocity is concerning damage of structures.

2. Seismic isolation devices

bearing / isolator

The bearing is a device that supports vertical loads, and it is connected to the superstructure and to the substructure. Bearings are designed to deform horizontally while supporting a superstructure, isolating the building from ground vibration. At the same time, the natural period of the structure must be higher. There are three types of bearings: laminated-rubber, slider, and rotating-ball.

・laminated-rubber bearing (LRB / elastomeric isolator)

Laminated-rubber bearings consist of alternate layers of steel plates and rubber sheets. They are capable of supporting large vertical loads, and they have high vertical rigidity. They have low stiffness in the horizontal direction, due to the shear-deformation of rubber and they have the capacity to deform. There are four types of laminated-rubber bearings, with their properties as follows:

・natural laminated-rubber bearing (NRB)

Laminated natural-rubber bearings are the most common type used in SI structures. The relationship between shear strain and shear force becomes relatively linear, which makes NRBs suitable for use in combination with dampers.

・high damping laminated-rubber bearing (HDR)

They are made of synthetic rubber, which has energy-absorption performance for lateral deformation, HDR has both elasticity and damping performance.

・laminated-rubber bearing with lead plug

Lead-plugs inserted in laminated-rubber bearings are also used as isolators, which provide non-linear elasticity and damping function.

・laminated-rubber bearing with steel damper

This is also a laminated-rubber type, but with hysteretic steel dampers, but which has steel rods bolted to flanges of the laminated-natural rubber bearing.

circumference rubber-cover

Rubber sheeting used to surround the circumference of isolator parts provides many years of protection to the internal rubber sheets and the steel plates of the laminated-rubber bearings from oxidation, ozone, ultraviolet rays, and water. Synthetic rubber is often used for the rubber cover.

creep

Creep is permanent plastic-deformation by long-term compression stress in LRBs, which support the building. Currently, the leve1 of creep can be predicted by measuring the amount of short-term creep over one or two years. An equation for estimating the amount of creep is extrapolated from the amount of creep over a certain amount of time. By extrapolation of this short term creep, the amount of 1ong term creep can be predicted. It is usually several percent of the vertical height after 60 years.

damper

The damper is a device with the capacity to dissipate dynamic energy. Damping function is necessary for SI systems. There are various types of dampers: steel dampers and lead dampers (utilizing metal hysteretic characteristic), viscous dampers and friction dampers. There are also isolators that have damping function, such as high-damping rubber bearings and lead-plugs that are inserted into laminated-rubber bearings. High-damping rubber bearings and lead rubber bearings each provides damping function. (See “bearing / isolator”)

deformation performance of LRB

Deformation performance is expressed as the ratio of the horizontal displacement (δ) to the total thickness of the rubber (H). For example, when lateral deformation is roughly twice the total thickness of the rubber, the deformation ratio is called "200% strain". As each isolator has a different maximum deformation-value, the specifications must be checked carefully before LRBs are ordered.

・performance of horizontal deformation of LRB

Horizontal deformability of LRBs is high, usually more than 400% in shear strain.

The suggested upper range of usage is usually less than 250%, which is before hardening occurs. It is necessary to know the various dependencies that affect the performances of isolators, such as bearing, distortion and temperature dependency.

・restoring-force characteristic / force-deformation characteristic

This is the relationship between load and deformation in structural members, and the relationship between stress and strain in materials. It is usually expressed by a skeleton curve and then is modeled for structural analysis.

Hysteretic models, such as normal bi-linear, degrading tri-linear or Romberg-Osgood are used, depending on structural type. The bi-linear model is used when SI devices are either laminated-rubber bearings with lead plugs or laminated high-damping rubber bearings.

The modeling method is used to determine the appropriate model, in order to attempt not to deviate from the actual restoring-force characteristics, nor to overestimate the energy-absorption capacity. This is because restoring-force characteristics of the SI layer influence the overall response of the structure.

・primary-shape factor (S1)

The primary-shape factor is the ratio of the compression area (cross section) to the free area of one rubber sheet of laminated rubber. The primary-shape factor, "*S1*", is expressed by the following equation:

$$S1=\pi D^2/(4\pi D\cdot t)=D/(4\cdot t)$$

Here, "D" is the diameter of the rubber and "t" is the thickness of one rubber sheet.

The primary-shape factor shows the flatness of one rubber sheet of the bearing, which dictates compression stiffness and bending stiffness of LRB.

・secondary-shape factor (S2)

The secondary-shape factor is the ratio of the overall height of the rubber sheet to the diameter of LRB. The secondary-shape factor; "*S2*", is expressed by the following equation:

$$S2=D/h$$

Here, "D" is the diameter of the rubber and "h" is the total thickness of the rubber sheets of an LRB. It is a standard factor which indicates the flatness of LRB. The secondary-shape factor is related to the vertical-load dependency and the deformability of bearings. The vertical-load dependency is small when the secondary-shape factor is large. Thus, a large deformation has relatively stable restoration performance.

・allowable load

There are two types of allowable load for LRBs. One is long-term load and the other is short-term load. Generally, it is expressed as an interaction curve which concerns the allowable load and deformation of LRBs.

・bearing stress / axial stress

This is the mean stress in the vertical direction, determined by dividing the axial-force by the cross section of LRBs. The bearing stress of the laminated-rubber bearing is generally determined for stress that is equivalent to the long-term loading stress.

deterioration due to aging

The performance of rubber materials diminishes with the passage of time, as well as due to the influence of environmental factors, such as ozone, oxygen, ultraviolet rays. As a result, the characteristics of LRBs also diminish.

friction damper

One type of hysteresis damper is made of solid friction-material, between two plates. It is commonly used to control frictional force.

hardening

Strain hardening is sometimes observed when shear strain of rubber bearings is more than 250% in the standard compression stress. Hardening of rubber bearings can occur when the secondary-shape factor is high. The stress-strain curve of rubber bearings shows a soft-spring characteristic, below the 200%-strain domain. However, a hard-spring is characterized by sudden increases in stress and strain, from 200 to 300%. This is called the stress-hardening phenomenon, so elastomeric isolators are used in the strain range, before hardening can occur.

hysteretic damper

This damper provides damping performance through plastic deformation, due to hysteresis, or through friction of materials. There are three types of dampers in practical use: steel dampers, lead dampers and friction dampers.

lead damper

Lead has the characteristic of extremely high plastic-deformation capacity. The hysteresis shape is nearly rectangular, which provides high damping-performance.

oil damper

This damper has the capacity to absorbing vibration energy by regulating the flow of oil into and out of an orifice.

roller bearings / ball bearings

Rotating-ball bearings are constructed by arranging steel balls or rolling cylinders on a flat steel-plate.
Ball- and roller-bearings roll on a flat steel-plate or a curved surface.
Rail-type roller bearings have rollers instead of balls, which travel on rails.
Both types of bearings have a super-low friction coefficient: almost zero in practical use.
However, LRBs are commonly used in combination with rotating bearings because rotating bearings have no restoration or damping functions. Roller bearings with a curved surface have a natural restoration function.

standard for SI devices in Japan

Manufacturers of SI devices can produce isolators or dampers that are approved by MLIT in Japan. The technical standard for SI devices stipulates performance items, such as fundamental performance and dependencies, in Notification No.1446, 2000, by MOC.

slider / sliding bearing

A slider is a device that slides on a plane or curved surface that has low-friction force.

- **sliding material**

  Sliding material has low friction and is usually PTFE material.

・**sliding plates**

Sliding plates are made of materials that facilitate the function of the slider. They are made of stainless steel, hard-chrome or steel with special surface-coating.

・**slider with elastomer**

The properties of natural rubber-based LRBs are effective in the small horizontal-deformation zone. Sliders are bearings that absorb energy of vibration through friction.

steel damper

This damper absorbs vibration energy through the plasticity of steel. The hysteresis loop is a spindle shape. These dampers consist of either four or eight steel rods.

test for devices

・**product test**

This test is a test to confirm the basic performance of SI devices that is conducted by the manufacturer before shipment. Test should be carried out by the factory staff under supervision of SE, regarding appearance and dimensions, and performance (horizontal stiffness, vertical stiffness, equivalent damping factor, etc.) of devices. The number of devices to be tested should be decided by SE and randomly conducted.

・**prototype test in Japan**

Prototype test should be applied to each type of device unit for fundamental performance of device, as specified in Notification 1446, 2000, by MOC.

・**fundamental performance of LRB**

Fundamental performance of LRBs concerns properties such as compression, shear, tensility, dependencies, ultimate states and durability.

ultimate compressive strength

This strength is critical when axial-force applies to LRBs. It is difficult to determine the actual compressible limit-strength of LRBs. As such, the value is provided by an estimating equation.

vertical stiffness

This is the compression stiffness, or vertical spring-constant of LRBs, and is shown by a ratio of vertical load to vertical deformation.

Generally, it is expressed in the secant stiffness of the vertical hysteresis loop with the compression stiffness dependant on the primary-shape factor.

viscous damper

This damper operates through the resistance of a high-viscosity material. There are two types: a model similar to an oil damper, and a wall type, installed in between beams and columns.

A wall-type damper regulates vibration energy through the velocity of the shear strain of viscous material in spaces between steel plates.

3. Construction and other

base plate for isolator

A base plate is a plate that connects the isolator (with bolts) to the superstructure and to the lower structure.

construction clearance

It is generally decided by allowing for construction error in the design clearance. Thus the actual clearance is more than the design clearance.

CM for SI buildings in Japan

JSSI provides training and a qualification test for construction managers (CM) for SI buildings. Qualified engineers should work on site to ensure the quality of SI buildings.

fire protection for isolator

When the space of the SI layer is used as a parking area, or the SI layer exists within a story, isolators should be fireproofed, and must be made to follow the movement of the building during earthquakes. There are several types of fire protection, such as board type and blanket type.

flexible pipe-joint

Flexible pipe-joints are installed in the SI layer and absorb large relative displacement between the superstructure and substructure. Ready-made flexible pipe-joints are available for SI buildings.

ground type / ground classification

Ground is classified into three groups under the Japanese Building Standard Law:
Type 1: hard like rock, gravel, sand
Type 2: medium
Type 3: soft
V_E is the velocity of shear wave for soil which is dictated by *Recommendation for the Design of Seismically Isolated Buildings* (Dec., 2016) of the Architectural Institute of Japan, using the energy spectrum for designs with a period within a range of 1.0-5.0 seconds. V_E must have the following values according to the type of soils:
Ground type 1(Soft soil): V_E = 120cm/s
Ground type 2(medium): V_E = 150cm/s
Ground type 3(hard): V_E = 200cm/s

grout

Grout is used to fill the space between the base plate and the footing of the isolator. This is done in order to ensure the transfer of weight from the superstructure. Usually no-shrinkage mortar is used as the grout.

high-flow concrete

High-flow concrete has a slump-flow value of 60 to 65 cm. It is used for foundations that are under the base plates of isolators.

horizontal restraint

Temporary horizontal restraints must be applied to avoid movement of isolators when displacement interferes with the construction of the superstructure. CM should discuss the necessity and details of restraints with the supervisor.

inspection

・**conditions for inspection**

Conditions for inspection of SI devices are generally specified in the inspection plan by the SE, after which they are given to the supervisor.

・**inspection during construction**

This is an inspection of structures that have an SI system. It should be done during building construction to confirm that values such as horizontal and vertical clearance are sufficient.

・**inspection at completion**

This is an inspection carried out to check the SI system when a building is completed. In order to maintain SI performance, scheduling of inspections and maintenance are required for SI devices, as well as for horizontal and vertical clearances. Inspection includes measurements, the values of which are very important as initial values for comparison for future measurements. CM must report the inspection results to the building owner.

life cycle cost

The lifetime cost of a building includes expenses incurred for planning and design of the building, construction, and operations throughout the lifetime of the building.
The life cycle cost includes the initial cost and the running cost, such as energy cost, maintenance cost, repair / renewal costs, etc.

liquefaction

This is a phenomenon whereby the ground soil liquefies due to seismic vibration. Muddy water gushes from the ground surface due to earthquake vibration. There are some cases of uneven settlement of buildings and building collapse due to liquefaction.

maintenance of SI layer and devices

Maintenance of the SI layer should be done to properly ensure the function of the SI system during earthquakes. Inspections are classified into four categories: completion inspection, periodic inspection, inspection after major catastrophic events and detailed inspection.

notice board of SI building in Japan

A metal sign is installed on the outside wall of the building or near the entrance in a place where it is easy to see in order to draw attention to the fact that SI buildings move during earthquakes. This display of signage is stipulated by Notification 2009, 2000, issued by the Japanese MOC.

retrofit, retrofit with SI system

In the structural engineering field, retrofitting of existing buildings is usually carried out by upgrading or strengthening for improving earthquake resistant performance. Upgrading using SI system is called "seismic isolation retrofit".
Seismic isolation structures absorb vibration energy that is brought on by shaking from earthquakes in the SI devices, and little energy is transmitted to the superstructure.
When the seismic resistant countermeasures are necessary for existing buildings, SI systems can be adopted as one of retrofitting methods.

running costs / operating costs / maintenance costs)

The running costs are the costs required to maintain building equipment and systems. They include costs for water supply, electricity, heating and cooling, maintenance etc. In the case of a seismically isolated building, in addition to the maintenance cost of ordinary buildings, the cost of maintenance for the SI performance is also included in the running cost.

scaffolding for construction of SI buildings

Scaffolding must be connected to the superstructure with brackets. Additionally, the base of the scaffolding should be able to slide, following the displacement of the superstructure, in order to prevent collapse of the scaffolding. The sliding type, however, is not very common.

test device / monitoring device for confirming performance of applied devices

The test device that has the same performance as applied devices. It is used for periodic checks of the durability and performance of the applied devices. It is usually installed in the SI layer. CM should make sure that there is an entrance to bring the device in and a route to carry it to its place of installation.

tracer / orbiter

A tracer is a measuring instrument to record the horizontal displacement of SI buildings during earthquakes. The scribe-needle displacement recorder uses either a stainless steel plate, acrylic plate or aluminum plate.