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Review Article

Review on base and inter storey seismic isolation systems for high rise buildings

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Abstract

In recent decades, the construction of high-rise buildings has accelerated in modern urban areas as a response to the world's expanding population and demand for efficient space utilization. These high- rise buildings are inherently more susceptible to hazards such as strong winds, earthquakes, and human activities, which could jeopardize structural stability. However, when this rapid growth in high-rise construction continues in earthquake-prone regions it highlights the need for cautious design and oversight measures to guarantee the comfort of occupants and overall safety of buildings. So, the necessity to adopt vibration control strategies in structural engineering is therefore becoming more and more clear. As technology is advancing, several control strategies were created and implemented for high-rise buildings around the world. This review article provides a comprehensive overview of base-isolation and inter-storey isolation systems for high-rise buildings, which is accomplished by extracting useful insights from analytical and design features of real-life high-rise buildings equipped with these base isolation and inter-storey isolation systems. In detail the article explores the basic concept and the characteristics of the Base isolation system, and types of isolation bearings used for buildings. The fundamental concepts and benefits of inter-storey isolation system over base isolation. Additionally, the importance of vibration control strategy for buildings, and the different types of vibration control systems were also discussed.

1. Introduction

Tall or "high-rise" buildings are constructed to a degree that distinguishes from low or medium rise structures in terms of their architectural and structural design considerations, construction methodology used, its multipurpose usage and its unique engineering among buildings in a region [1]. Many nations, like Singapore, China, the United States, the United Kingdom, and Japan are working to advance in construction of tall buildings as they add prestige and demonstrate a nation's economic power [2]. According to Indian standards (IS 16700), categorized these tall buildings when larger than 50 meters and smaller or equals to 250 meters in height [3]. The CTBUH (Council on Tall Buildings and Urban Habitat), characterized the buildings based on architectural height into the following categories. The buildings are classified as "tall" or "high-rise" if their height is 100 meters (328 feet), "super-tall" if it exceeds 300 meters (984 feet), and "Mega tall" if it exceeds 600 meters (2000 feet) [1,4]. Moreover, the high-rise buildings in earthquake prone regions are inherently more vulnerable to earthquake forces due to their height, slender profiles, and complex structural systems. In a typical earthquake resistant design for buildings, the columns and beams are designed to be strong and flexible enough

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to resist ground motions [5]. But during a strong ground motion, these buildings might behave with inelastic action causing plastic deformation in the structural components such as beams, columns, and damage to non-structural components of buildings, which are difficult to repair and restore after the earthquake. Then seismic design of high-rise buildings through ductility, mass variation or higher stiffness alone could not avoid the structural damages during a strong earthquake [6]. So, the use of response (or) vibration control strategies plays a crucial role mainly in structures such as fire stations, hospitals, schools, radio stations, nuclear power plants, and other structures which are to be safeguarded for functionality during and after a seismic event [7-9].

1.1. Vibration or Response Control Systems for Buildings

The vibration control approach's primary intent is to protect the structure from seismic risk by mitigating vibrational energy that avoids resonance at each segment of structure and to restore the lateral integrity of structure after earthquake and wind induced vibrations [10,11]. The vibration control also provides some instant of time for occupant of structure to reach safe destination. This response control can either be achieved by construction with lateral load resisting systems or isolation of structure from its supporting ground. In general, this vibration control originates from structure's flexibility, which intends to increase the natural period of building [12]. Based upon the magnitude of vibration control to be achieved for the buildings, selection of the type of dampers or control devices required is done. The response control systems for buildings could be classified as passive, active, or semi-active, hybrid (figure1) on the energy source requirement for energy dissipation during a seismic event [13].

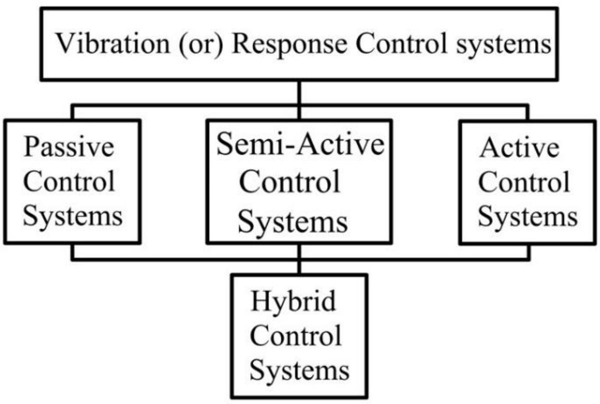


Fig. 1. Classification of vibration control systems

1.1.1 Passive Control Systems

The Passive response control systems are those which do not demand any external energy source, the structure's motion during earthquake being utilized for energy dissipation [14,15,16]. Passive response control devices like seismic isolators, fluid viscous dampers (FVD), friction dampers, pressurized sand dampers (PSD), viscoelastic dampers and other dynamic vibration absorbers such as tuned mass damper (TMD), tuned mass damper with inerter (TMDI), tuned liquid column dampers systems (TLCD) are currently in practice. Passive Fluid Viscous Dampers are composed of a piston rod moving through a hollow cylinder filled with a viscous fluid (such as silicon oil). These FVDs under dynamic excitation, the movement of piston within the cylinder, forces the viscous fluid to flow through provided orifices at piston head. This movement produces a damping force that opposes the motion of the structure, which reduces the structural response [17-19]. Torre

Mayor, a 57-storey building in Mexico City skyline was the first high-rise building to utilize the FVDs as their primary means for vibration control system [20]. Numerous bridge structures such as San Fransico Okland bay bridge [21], 91/5 highway overcrossing bridge [22] were equipped with fluid viscous dampers.

Friction Damper is a passive control type device that shows hysteretic behaviour and dissipates the kinetic energy by friction generated from sliding in between two solid surfaces. These friction dampers tend to downtrend motion of structure by principle of "bracing rather than breaking" [18,23–27]. These devices were less affected by number of load cycles, temperature changes, load frequencies and exhibits the rigid plastic behaviour [28]. Pall A S et al. [29] proposes X- braced damper, a type of friction damper which shows equal energy dissipation in both tension and compression braces due to presence of four links. This phenomenon will take place under the condition when the slippage of device is adequate to completely align any deformed braces. The three-story and nine-storey steel frame structures employed with friction dampers were experimented on shake table at University of British Columbia in 1985 and University of Berkeley in 1987. The shake table results have shown that responses of friction damped braces were far superior to the responses of moment-resisting braced frame and the members of friction damped frame remained elastic till 0.84g acceleration, while the moment resisting frame yielded at 0.3g acceleration. Tsampras G et al. [30] conducts numerical and experimental investigations on a full-scale deformable connection designed to link the floor system of a flexible gravity load resisting system to the stiff lateral force resisting system (LFRS) in earthquake-resistant buildings. In this study the deformable connection comprises a friction device (FD) and carbon fiber-reinforced bonded low-damping rubber bearings (RB) referring to the FD + RB connection. The experimental results validate that force-deformation responses of this FD + RB connection was stable under earthquake loading histories, quasi-static sinusoidal, and dynamic sinusoidal. The results also shown that FD's elastic stiffness regulates the overall elastic stiffness of the FD + RB connection, while the FD's frictional force governs the shift from elastic to post-elastic behaviour.

Pressurized sand damper (PSD) is a type of particle damper and a passive control system used to mitigate the vibrations from structures. The development of these PSD's was motivated from the failures of fluid dampers such as failure of end seals leading to detrimental leaking while accommodating for longer strokes, occurrence of occasional displacement limitations in buckling-restrained braces [31]. These PSDs mainly composes of moving piston in damper housing with pressurized sand. The sand particles in damper are enclosed within a sealed chamber and subjected to pressure, causing them to behave like a semi-solid material [32]. This allows the pressurized sand to shear that generates significant energy dissipation over a wide range of frequencies. The pressurized sand diminishes the vibrations through friction and deformation, converting kinetic energy into heat, which is then harmlessly dissipated [33,34]. These PSDs can be implemented in areas with extreme high and low temperatures, where use of fluid dampers may be challenging. Karimipetanlar M et al. [35] provides a numerical model by discrete element method to explain the mechanical behaviour of pressurized sand dampers subjected to cyclic loading. Different computational simulations of PSD were trialed and compared with different initial pressures and stroke amplitudes. The results regarding the energy dissipation have increased with increment in stroke amplitude. The specific damping capacity in all cases of simulations was shown to be near to one.

Viscoelastic Dampers are one of the earliest types of passive control systems used for high rise structures to mitigate seismic and wind induced vibrations. The viscoelastic material involved in dampers is usually made from copolymers or glassy substances that exhibit both viscous and elastic characteristics. These dampers combine the properties of both elastic solids and viscous fluids, offering to dissipate energy through material deformation and internal friction and respond to deformation with time dependent strain that provides damping effect to the structure [36,37]. The dual behaviour of viscoelastic damper makes effective in structural applications demanding both instant response to sudden loads and long-term resistance to cyclic loads. Real life examples such as twin towers of World trade centre buildings in New York (38,39) and Columbia Sea First building in Washington (38,39) are first buildings to use viscoelastic dampers in practical implementation. Xu ZD et al. [40] explores the efficacy of viscoelastic dampers utilized with several kinds of viscoelastic material based on different matrix rubber developed. The high-order equivalent fractional derivative model was developed for numerical analysis to describe the characteristics of viscoelastic dampers. Viscoelastic dampers based on silicone rubber (SR) matrix and nitrile butadiene rubber (NBR) matrix used for experimentation. The results indicated that the performance of viscoelastic dampers is dependent on viscoelastic material's energy dissipation properties. The viscoelastic dampers based on NBR matrix have shown stable performance under different loading conditions when compared to dampers based on SR matrix.

Rubber or seismic isolators also known as base isolators are devices installed between foundation of structure and its super structure to mitigate the effects of seismic activity on crucial structures such as hospitals, bridges, etc. These seismic isolators behave as a flexible interface allowing the super structure to move independently to ground motions [41]. These seismic isolators are used to accommodate the movements in structures, such as both static and dynamic displacements due to creep and shrinkage and thermal effects [42]. Furthermore, the seismic isolators are classified based on several factors such as their characteristic behavior, material used for system and desired level of seismic mitigation are discussed in section 2.2.

Dynamic vibration absorbers are a class of passive control systems, which achieve energy dissipation through transference of some part vibrational energy to absorber rather than direct dissipation. The system typically configures with secondary mass, stiffeners and damping components, whose dynamic properties must be matched to those of primary structure. Devices such as Tuned mass dampers (TMD), Tuned mass damper with inerter (TMDI), Tuned Liquid Column Damper (TLCD) are some examples of dynamic vibration absorbers present in practical usage [28].

Passive Tuned mass Damper (TMD) contains an oscillating secondary mass connected by means of linear stiffeners and with dashpots (viscous dampers) to the top of the primary (hosting) structure, that oscillates in response to the structural vibrations [43]. The TMD's working efficiency in controlling the structural response counts on its adjustment to match the fundamental mode of vibration of the hosting structure at fixed attached mass, with its damping and stiffness properties [44]. In other words, when TMD tunes to frequency closer to the hosting structure's natural frequency, TMD resonates itself by vibrations in structure and dissipates maximum kinetic energy of primary structure during major earthquakes [45]. However, TMD systems are successfully installed in many tall skyscrapers for wind response control, bridges such as the Taipei-101 Tower (508m) in Taiwan [46], the Millennium bridge in London [47].

While TMD's have demonstrated its effectiveness in mitigating vibration across various practically engineered structures, it suffers from "detuning" of seismic and wind induced vibrations due to several reasons such as the primary structure's non-linear behaviour and uncertainties caused to dynamic properties of primary structure over time. These detuning affects could significantly influence the vibration suppression ability of TMDs [48]. The vibration suppression abilities of TMDs are closely related to its inertial characteristics: larger the TMD's mass, more the reliability and resilient the TMD behaves against qualms in structural properties [49,50]. Nevertheless, such practical constraints influenced by architectural and structural considerations have an impact on maximum weight and volume of TMD that can be incorporated into the primary structure. Such constraint might be critical for tall buildings, where the TMD's mass typically remains below 0.5 to 1% of total building's mass [51]. To address such constraints in TMD's and utilize them for tall buildings to mitigate wind induced vibrations, Marian L et al. [52] introduces optimally engineered the Tuned Mass Damper with Inerter (TMDI), represents a passive vibration damping system. It integrates the conventional tuned mass damper (TMD) with an inerter device, designed to supply enough additional damping force proportional to the relative acceleration response of structure. This damping force was regulated by its inertial constant termed "inertance", capitalizes the mass amplification phenomenon and higher-mode damping effects of inerter device to improve vibration suspension capacity of conventional TMDs and mitigates relative acceleration responses on building [53–57]. Several recent studies have been conducted on optimal design of TMDI's, Marian L et al. [43] analytically demonstrates the efficiency of optimally designed TMDI's to reduce variance in displacement for undamped single degree of freedom (SDOF) systems under white noise excitations. Furthermore, the study validates the effectiveness of TMDI's through a numerically optimization in 3-Degree of freedom (3-DOF) damped primary structure when subjected to stationary noise excitations. The study concludes that inclusion an inerter into the TMDI can either diminish the required vibrating mass for lightweight passive vibration control or enhance the performance of the conventional TMD for a given mass. Pietrosanti D et al. [58] conducts a shake table testing under harmonic excitations to evaluate the performance of Tuned mass Damper Inerter (TMDI) in structures with non-ideal inerter behaviour and non-linear responses. The study utilizes a single degree of freedom (SDOF) structure specimen equipped with a custom-built rack and pinion Fly wheel inerter to link the TMDI secondary mass to ground. The experimental data highlighted the practical advantage of TDMI to showcase improved vibration suppression when compared conventional TMD through increasing inertance without increasing the TMD's mass and maintained for non-linear structures.

Tuned Liquid Column Damper (TLCD) comprises of a rigid piping system integrated into the primary structure and partially filled with viscous fluid, preferably water. The oscillating motion of TLCD facilitates the transfer of vibrational energy from primary structure to TLCD, consequently initiating a movement in the water column. This transferred energy was mitigated utilizing by viscous and turbulent fluid damping, that can be controlled by installation of hydraulic resistances (e.g. orifice plates) to attain desired damping characteristics [59, 60]. In Japan a 26-storey hotel was constructed with adopting a TLCD based bi-directional vibration control system [61].

However, these passive control systems might face major drawbacks in adapting to changes in structural design and various loading conditions to building [62-64].

1.1.2 Active Control Systems

Active response control systems are considered as logical extension of the passive control technology [65]. These systems mainly depend on continuous supply of energy source for the operation of control devices like sensors, actuators, and computers that produce control forces in relation to the seismic response feedback into structure which counteracts the intensity of ground motion [62,66]. Active tuned mass damper (ATMD) and active tendon systems are some examples of Active control systems [67]. Active tuned mass damper (ATMD) works on similar mechanism to conventional TMD, usually consists of actuator connecting the oscillating secondary mass to primary structure. The continuous monitoring of structural response collects feedback from sensors installed in primary structure. Then a control algorithm computes optimal control force for actuator to drive the secondary mass to oscillate, there by dissipating the vibrational energy in primary structure under wind excitations [68]. The Shanghai World financial Center is tallest building in China with height of 492 m and utilizes an active control based tuned mass damper to mitigate wind induced vibrations in structure [69]. Active Tendon system consists of pre-stressed cables that can be positioned in between floors of a structure or at ends of cables of cable-stayed bridges. In the active tendon system, these cables were pinned to a location in a structure and subsequently threaded through pulleys to be connected to linear actuators. Then computed tensile forces are applied to cables by actuators, which can diminish wind-induced excitations in structure [68, 70]. Yanik A [71] adopts an 8-storey 2D shear building model with fully active tendon-control system to propose an optimized control performance index for active control of structures during seismic excitations. However, some key differences between tuned mass dampers as passive and active systems were discussed in Table1 and Table 2.

Table 1. Differences between passive and active tuned mass dampers

Passive Tuned Mass Damper (TMD)	Active Tuned Mass Damper (ATMD)
The Passive Tuned Mass Damper (TMD) system consists of secondary mass attached to the main structure through linear stiffeners and dashpots [44].	The Active Tuned Mass Damper (ATMD) system consists of secondary mass attached to the main structure by means of a mechanical actuator, sensors around the main structure for collection of structural response feedback [70].
Under Dynamic loading, the TMD counteracts the vibrations in structure in passive (not utilizing any power source for operation). These vibrations are dampened through dissipating kinetic energy on utilizing the mass-spring-damper mechanism [43].	Under Dynamic loading, the ATMD counteracts the vibrations in structure in active (on utilizing a power source for operations). These vibrations are dampened through dissipating kinetic energy on utilizing the damping forces generating from actuators [68].
The damping effect of TMD mostly depends on its tuning to structural response, stiffness, and damping properties of dampers provided.	The damping effect of ATMD depends on feedback from sensors, control algorithm and stiffness, continuous power supply for operation of computer control, sensors, and actuators.
It facilitates effective damping for a limited range of frequencies (determined on its design), which potentially exposes the structure to higher frequencies.	It facilitates effective damping for a broader range of frequencies by actively adjusting the damping forces in real time, thereby providing more protection to structure at higher frequencies.
The installation of TMD system was simple, cost effective, and less requirement for maintenance and operational oversight compared to ATMD due to its passively operating nature and no power requirement.	The installation of ATMD system was complex, expensive and more requirement for maintenance and operational oversight due to its actively operating nature.

Table 2. Key Differences between Conventional TMD, Tuned mass damper with Inerter (TMDI) and Active Tuned mass damper (ATMD)

Characteristics	Conventional Tuned Mass Damper (TMD)	Tuned Mass Damper with Inerter (TMDI)	Active Tuned Mass Damper (ATMD)
Type of response control system	Passive	Passive	Active
Components	Consists of Secondary mass, linear stiffeners, and dampers	Consists of Secondary mass, damper, linear stiffeners and an inerter device	Consists of Secondary mass, damper, linear stiffeners, actuators, and control systems
Tuning Mechanism	TMD tunes to match the natural frequency of structure.	TMDI also uses frequency matching technique.	ATMD utilizes real time feedback control using sensors and actuators to adapt for uncertainties and frequencies in real time
Energy Dissipation	Dissipates energy through dampers	Dissipates energy through dampers and inerter	Dissipates energy through dampers and actuators
Frequency range and Effectiveness in High Frequencies	Effective over narrow frequency range, mainly tuned to a specific resonance frequency	Effective over a broader range of frequencies and more effective in higher frequencies due to inerter.	Effective over a broader range of frequencies and highly effective at higher frequencies, leveraging active control and real time adjustments.

However, in practical execution, these active control systems could run into difficulties such as modelling errors, errors in generating control forces, and the unavailability of a power source during a seismic event [63,66]. The utilization of external energy makes the active control setup costlier compared to passive control system.

1.1.3 Semi-Active Control Systems

Unlike passive response control systems, which does not acclimate with structural changes and rely on fixed elements like dampers, and active systems, which involve continuous energy input, researchers have developed the semi-active control systems utilizes the structure's motion to produce large control forces and these control forces are regulated typically by a small external energy source (e.g... battery) [15,62,66,72]. They include adaptive controls which increase efficiency and intelligence of the system [28]. Semi-active control systems differ over an active system by their lower power utilization for operation (in order of tens of watts) and semi active systems can even be powered during a seismic event [11,15]. Electrorheological (ER) dampers, Magnetorheological (MR) dampers are examples of semi active control devices [28]. Electrorheological (ER) dampers are semi automotive suspension devices, filled with a mixture of low viscous fluid and particles sensitive to electric field, also known electrorheological fluids [73]. When a structure is exposed to vibrations, a computer control receives feedback from sensors that are integrated into the structure. This feedback enables the computer control to adjust the electric field that is applied to the damper. The application of this electric field causes the electrorheological fluids to act as a viscoelastic material. This means that these fluids exhibit ideal behavior like that of a solid when subjected to lower stresses, but flow like a viscous fluid when the forces applied surpass their yielding stress [74]. This viscoelastic behavior of fluid allows ER dampers to have adaptive damping control and effectively mitigate structural vibrations. Magnetorheological (MR) dampers are semi auto motive hydraulic devices similar to Electrorheological (ER) dampers, filled with mixture of low viscous fluid and micro-sized suspended magnetic particles which are sensitive to magnetic field, also known as Magnetorheological fluids [75]. In MR dampers at absence of magnetic field, allow fluid to flow without any restrain, resulting in minimal damping. Whereas a higher magnetic field creates an unyielding damper filled with semisolid fluid [76]. This variation of the magnetic field alters the fluid's damping characteristics, which allows for a precise control over damping force and mitigation of structural vibrations.

1.1.4 Hybrid Vibrational Control System

By amalgamating different vibration control systems such as passive, active, and semi-active devices, the hybrid vibrational control system attempts to control structural response as well as address the drawbacks in these devices there by achieving optimal performance, stability, and efficiency [11,77]. These systems offer several benefits, including enhanced structural safety, improved occupant comfort, and reduced maintenance costs. Hybrid mass damper (HMD) is one example of hybrid vibrational control systems. The Hybrid Mass Damper (HMD) system composes of passive control device such as Tuned mass damper (TMD) and active control devices for suppression of vibrations in high-rise buildings during strong winds and moderate earthquakes. These HMDs work on similar principle of ATMDs and much more energy efficient for vibration control, which uses about 1/3rd-1/4th of ATMD's consumption [78]. Maebayashi K et al. [79] proposed a hybrid mass damper system which aims at fulfilling the demand for mitigating earthquake and wind induced loads on structures. A prototype of HMD system was also installed at a 7-storey building, built in 1991 at the Institute of technology of Shimizu Corporation. The HMD system is composed of actuators driven by AC servo motors and an auxiliary mass anchored to multi-stage rubber bearings. Forced vibration tests were conducted in both x and y directions of building evaluating the dynamic characteristics of building and HMD system. The experimental findings also confirmed that HMDs could be suitable solution for mitigation of earthquake and wind induced vibrations in tall buildings.

2. Base Isolation System (BIS)

The Base Isolation System (BIS) is one of the popular passive structural control design approaches, in which the superstructure and substructure of building are disintegrated through a low friction interface layer also known as base or seismic isolators, which allows the superstructure to move independently from the foundation when subjected to wind-induced vibrations or earthquakes. This relative movement allows to dissipate seismic energy and reduces the forces transmitted to the building [80-83]. These systems are crucial in regions prone to earthquakes, as they help protect structures and occupants from damage and injury. The installation of an isolation system at base prevents the seismic forces entering the structure directly [84]. The concept of seismic isolation has spread around the world especially in earthquake prone regions of countries such as Japan, China, United states, Indonesia, New Zealand etc. However, this seismic isolation system is most used and economically appealing in low-rise to medium-rise buildings.

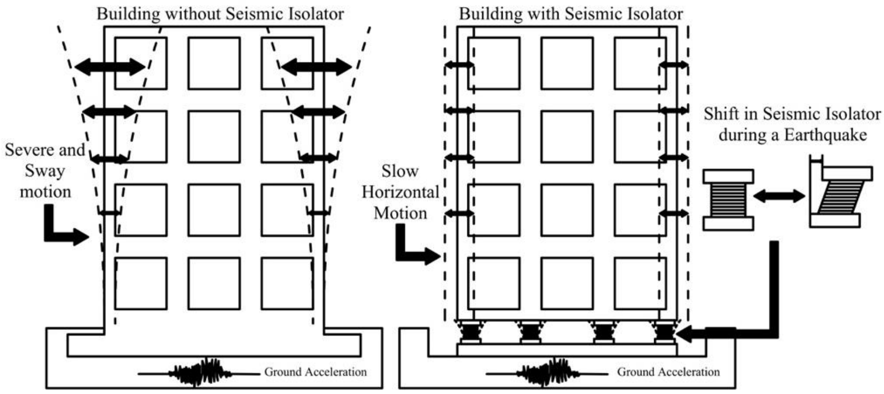


Fig. 2. Comparison between fixed base and base isolated building

Since the 1970s, the first application of base isolation was to an elementary school in Skopje, Yugoslavia. The three-storey concrete frame structure, Pestalozzi school was equipped with unreinforced rubber bearings disparate the recently exploited bearings. These unreinforced rubber bearings were developed to bulge sideways under the weight of the structure.

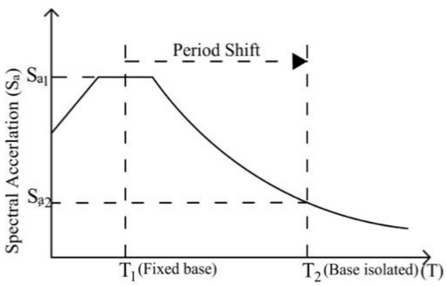


Fig. 3. Spectral Acceleration vs Natural period without isolation effect [12,87,88]

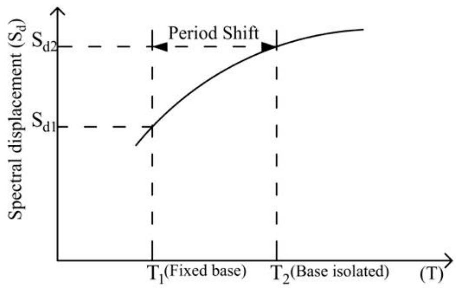


Fig. 4. Spectral Displacement vs Natural period without isolation effect [12,87,88]

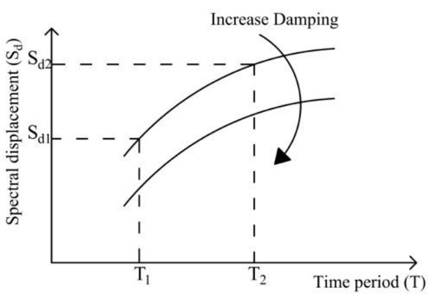


Fig. 5. Spectral Acceleration vs Natural period with isolation effect [12,87,88]

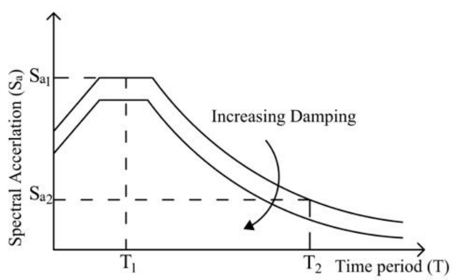


Fig. 6. Spectral Displacement vs Natural period with isolation effect [12,87,88]

Glass blocks were introduced as seismic fuses, which break after a certain limit of seismic loading. The swaying back and forth motion of structure during the seismic events has resulted from its isolation system's equal approximation in horizontal and vertical stiffness [85]. In general, the natural period of a fixed base building is significantly lower such that could correlate with the natural period of a major earthquake. Moreover, this could result in an inelastic action that increases accelerations at every floor from bottom to top. This increase in floor accelerations might induce distress within the columns between floors [86]. The building with base isolation work on principle to diminish the response accelerations on building compared to a fixed base structure in acceleration response spectrum perspective by shifting or lengthen the building's fundamental natural period away from the span of the frequencies for which greater impacts of amplification of ground waves are anticipated, (i.e.) from T_1 of fixed base to T_2 of base isolated structure as illustrated in figure 3 [10]. The extension in the building's natural period lowers the floor accelerations, but it could record higher displacements with the superstructure in displacement response spectrum perspective, as shown in figure 3&4. These higher displacements and accelerations are compensated through strong dampening characteristics of the isolation system to an acceptable limit, in displacement and acceleration response spectrum perspective as illustrated in figure 5&6 [12,87,88].

Furthermore, the period shift caused by base isolation system alters the structure's fundamental mode of vibration. This alteration transforms the structure's behavior from cantilever mode, characterized by significant inter-storey drifts and storey shear forces, to rigid (isolation) mode. In this rigid mode the deformation responses concentrated at the isolation level, allowing the superstructure to experience minimal storey shear forces and inter-storey drifts [89]. The reduction in demands, the superstructure remains to be elastic or virtually elastic after a design-level seismic event [90]. In some exceptional cases by installing external mechanical dampers or by incorporating additional damping in isolation system, the excessive displacement response that the base isolators are susceptible to can be mitigated [67, 91].

2.1. Characteristics of Isolation Systems

The Base isolation system for a structure mainly composes a group of flexible pads also known as base isolators or bearings are located underneath super structure to offer resistance against lateral displacements [92]. During an earthquake the isolator sways in lateral direction as shown in figure 2 due to its low horizontal stiffness and its excessive deflection is controlled through steel shims in between rubber layers in case of elastomeric bearing or through higher coefficient of friction in between slider and surface plate in case of sliding bearings. Malu G et al. & Beirami Shahabi A et al. [93,94] points out that most of isolators do not absorb seismic energy, rather they collectively deflect and dissipate the seismic energy by making use of dynamics of system and other effective techniques. This filtration of seismic energy allows only partial amounts of ground accelerations to impart ~~the~~ structure. Some of the crucial parameters that influence the efficiency of an isolation system are the energy dissipation rate of an isolator, the superstructure's flexibility, and the mass ratio between the isolation system and the superstructure [6,95]. These isolators are meant to be built effectively, if the structure's seismic behavior can be dominated by simply the initial mode of vibration and when storey drifts in structure can be relatively lowered [8,85]. Some of the prerequisites of a good seismic isolator are as follows [96-98]:

- Horizontally flexible (or) low horizontal stiffness enough to extend the structure's natural period.
- Vertically stiff to withstand vertical or gravity loads (i.e., isolators to have a high compressive modulus).

- Should have adequate capacity to dissipate seismic energy (damping) for minimizing storey drifts during an earthquake.
- Should have ability to cut down the contributions from the higher modes of vibration.
- Provide adequate rigidity to the structure under service loading.
- Should have self-centering capability after a seismic event.
- Repeated cyclic loading on isolator should not suffer loss in its force-resisting capacity.

2.2. Types of Isolation System

Several nations prepared guidelines for seismic design of structures suggests that the feasibility in design can be achieved with accurate prediction of seismic response and selection of isolation systems to be utilized, analytical procedure for structures. Based on characteristic behavior of isolation systems have been categorized into Elastomeric bearing approach and bearings with sliding approach for hands-on usage in structures such as buildings, bridges, etc [90,99-102].

2.2.1 Elastomeric Bearing Approach

It's the most common approach practiced in construction of seismically isolated structures due to its simple design and installation process. This approach comprises of several bearing systems such as Natural Rubber Bearings (NRB), Lead Core Rubber Bearings (LCRB), High Damping Rubber Bearings (HDRB). Natural Rubber Bearings are also referred as elastomeric bearings, are a common type of base isolator used in structures.

Natural rubber bearings (NRB's) also known as Laminated Rubber Bearings primarily composed of layers of elastomeric material, made from synthetic or natural rubber compounds. These elastomeric layers are added on top of reinforcing thin steel shims (or) plates, together bonded by process of vulcanization [85]. NRB's behave flexibly under lateral loads and hold up higher vertical loads, where the steel shims can provide stiffness in the longitudinal direction and rubber can make it resist shearing in lateral direction [6].

Primitively, these NRB's are more extensively used in providing seismic protection for bridges [103]. The intial application of these NRB's (laminated) was for a school at Lambesc near Marseilles, France [104]. The school was supported on total of 152 isolators with 300 mm in diameter in size and 40mm in thickness. These isolators can be utilized for low-income housing buildings. one such demonstration of isolators using these NRB's has been shown for Four-storey low-income housing having confined masonry in Santiago, Chile [105]. Lead Core Rubber Bearings (LCRB) are developed from the constraints within the NRB's and composes of several elastomeric layers, steel plates placed in alternate and a lead plug at core of rubber bearing [106]. The lead core yields in shear under lateral loading, providing additional rigidity and hysteretic damping to dissipate energy against strong winds and minor seismic events [72]. these bearings achieve effective isolation on reducing structural response to 1/2-1/8 of traditional structural response [92]. Following a seismic event, these bearings can retreat their original shape and position with the help of lead core and get ready to adapt for future seismic events. In the early ages of invention LRB's, it gained more popularity as retrofitting strategy. However, several historical buildings such as first retrofitted building in United States, Salt Lake City and County Building located in Utah [107], Oakland city hall located in California [108] were retrofitted utilizing these LRB's. These LRB's were employed in construction of real-life crucial structures such as Wellington Central Police station located at New Zealand in late 1980's [109], Bhuj district Hospital in 2001[110].

High Damping Rubber Bearings (HDRB) are the most adopted isolators for construction and retrofitting of crucial infrastructure such as hospitals, bridges, and emergency centers where serviceability of structure during and after a seismic event is essential. The HDRB's are made from elastomeric layers and the steel shims, placed in alternate layers similar kind to NRBs [111,112]. In contrast to LCRB's, the HDRB bearings are more viable in structures with special requirements as they retain grater stiffness before yielding and show better breaking effect when subjected to wind load [113]. These HDRB bearings adapt rubber made from materials such as carbon black which provide high damping capacity for isolator explicitly between 10 to 20% of critical damping at its full shear strain capacity to provide a higher level of energy dissipation, horizontal flexibility, and high vertical stiffness to compensate for similarities with NRBs. These HDRB's were primitively used for Foot hill Communities 'law and Justice Center, California built in 1984 [114]. However, HDRB's have gained huge popularity by its economic aspects and engineers have started to adapt them for vital structures such as hospitals and emergency centres. Several such examples of vital structures include a Medical Centre at Italian Navy, Ancona, Italy built in 1991[115], The Los Angeles County Fire Command and Control Centre, a 2-story steel structure located in City Terrace area of East Los Angeles. Moreover, these HDRB's were also utilized as retrofitting strategy in such as Mackay School of Mines located in Reno, Nevada [108] and Oliveto G et al. [116] conducts an analytical investigation on two identical residential buildings located at Solarino town, East Sicily which were retrofitted through using hybrid type of isolation system that contain mixed use of laminated rubber and slide bearing systems. This laminated bearing system is composed of three distinct types of bearing include Lower Damping (LDRB's), Medium Damping (MDRB's) and High Damping rubber bearings (HDRB's). One of the residential buildings employed with this Hybrid system was subjected to free vibrations to assess the behavior of Hybrid isolation system.

2.2.2 Bearings with Sliding Approach

The bearings with sliding approach, often referred to as sliding isolation systems commonly used as retrofitting strategy and known for their operational simplicity [117]. This approach uses the principle of friction as a working mechanism. The bearings are composed of flat or spherically polished surface stainless-steel plates coated with sliding composites such as high-density polyethylene (HDPE) or PTFE (polytetrafluoroethylene) which is commonly known as Teflon and an articulated slider in between these plates that starts sliding or a low-friction movement between super structure and substructure when seismic excitation is greater than the frictional force in sliding isolators [118]. Harvey PS et al. [119] gives a complete review about historical and future developments in sliding or rolling type isolation approach that includes explanation of its basic concepts, types and applications of sliding or rolling type isolators. Roller bearings are type of sliding seismic isolators, typically comprises of series of cylindrical or spherical rollers to facilitate the controlled horizontal movement in structure that reduces the forces transmitted to structures during seismic events, thus protecting structural integrity of structures [120]. The isolators are simple in design, cost-effective to fabricate which renders them suitable for application in low income countries and for light weight structures [121,122]. Katsamakas A A et al. [123] studies effectiveness of rolling bearings by utilizing grout filled tennis balls rolling on concrete plates as a seismic isolator. This proposed isolation system can be available at low cost in low-income countries for isolation of light weight structures. The study focuses on characterizing the axial response of proposed isolation system by comprehensive testing of isolators at full-scale under combination of compressive and lateral cyclic loading. The key findings of experimentation have indicated an increment in rolling friction coefficient within these isolators unlike the sliding isolators with increase in compressive loads and independent to influence of velocity and temperature changes. Lee G C et al. [124] has developed roller seismic isolator for use of highway bridges. This isolator to achieve seismic isolation utilizes rolling of cylindrical rollers on V-shaped sloping. The isolation system was characterized by its self-centering capability, an essential property for seismic applications. These isolators reduce seismic response on structures through its in-built sliding friction mechanism. The study presented performance of proposed rolling bearings when subjected to base excitations. Katsamakas AA et al. [102] conducted an experimental investigation on low-cost isolators used for houses in low-income countries. The low-cost isolator design is mainly based on rolling rubber sphere on spherical or flat surfaces. The experimental results showed effective reduction of acceleration responses in building. The author suggests such a type of isolation device for low rise structures. Fenez D M et al. [125] introduces sliding isolation bearings with adaptive behaviour. Furthermore, the study explores the operational principles and force displacement relationships of three innovative spherical sliding isolation bearings. These relationships are important to understand and predict the bearings mechanism. These sliding isolation bearings are passive control devices but still demonstrate adaptive damping and adaptive stiffness. This adaptive behaviour aids the sliding isolation bearings to be optimized for various levels of seismic event. The fabrication of these sliding isolation bearings composes of several concave surfaces and the adaptive behaviour was imposed by various combinations of surfaces upon sliding surface on which sliding occurs. The variation of stiffness and effective friction in these bearings occurs accordingly to variations in surfaces upon which sliding occurs. Furthermore, the study provides a procedure to identify the surfaces which are active and to derive the force-displacement relationships, which was grounded by first principles.

In relation to the advancement of sliding type isolation bearings, it was initially proposed with Pure friction isolation system (P-F) comprises an articulated slider positioned in between two flat stainless-steel plates, slides over these plates surface under seismic excitations. It is a basic type of isolator in all base isolation system that works on sliding friction [126,127]. Under the principle of Coulomb friction damping, the initiation of motion in slider happens when the external disturbance force overcomes the sliding friction of the interface. As a result, the slider will move accordingly to the sliding surface, thereby initiating the desired seismic isolation functionality [128]. Sometimes the isolator's flat geometric surface could contribute unnecessary movement in buildings even under low earthquake motions [93]. To use this isolation system, a structure must be designed either with an appropriate coefficient of friction or should include complementary devices along the isolator [85]. Etedali S et al. [129] conducts parametric study to assess the efficacy of Pure Friction (P-F) and Resilient friction (R-F) isolation systems which were employed in eight storey building models and compared to fixed base building models. The results shown during seismic excitations the restoring device of R-F system has the capability to reduce displacements at base storey and position back to original point. While increase in damping ratio of restoring device showed reduction in base displacement, raise in top story displacements and drifts and no effect on residual base displacements of building. Wei B et al. [130] conducts numerical investigation on a pure friction isolation (P-F) system using shake table test models to inspect whether the friction action would scale in practical modern buildings. The investigation concludes that P-F systems could result in unallowable errors in mitigation of vibrations on scaling of friction action due to its flat geometric surface. The author suggests that it is possible to reduce unallowable errors through proportionally varying the friction coefficient and geometric surface through the sliding surfaces. Avinash AR et al. [118] explains about the deficiency of restoring mechanism in P-F system that could shift the building permanently from its intial position after an earthquake. This constraint leads engineers to adapt sliding systems with restoring ability.

Friction Pendulum Isolation system (FPI) is designed to overcome the main constraint of P-F system which do not contain an appropriate restoring mechanism. The FPI system consists of an articulated slider positioned within the two reinforcing steel plates and having a true spherical concave surface [88,118,131,132]. During an earthquake, the pendulum effect and concavity in sliding surface of isolator provides necessary restoring force to restore its original position and dissipating energy [93]. The selection of radius of curvature (r) of concave surface and type of friction bearing material used can influence the natural period of structure [133]. In general, These FPI's are utilized in Medium-rise to High-rise structures. These FPI's have been notable all over the world for its precise control over structural displacements, which made it adopt for many historical structures such as Burex Arts building [134] and U.S Court of Appeals, San Francisco [134], which was one of largest building to be base isolated till date as retrofitting strategy. Cardone D et al. [135] has investigated the re-centering capability of friction pendulum isolation system, which involved nonlinear analyses of finite no of SDOFs. A regression analysis was performed to obtain a relation between residual displacements and parameters that influence the dynamic behavior of Friction pendulum system. However, FPI systems when intended for a specific intensity of excitation may perform ineffective over higher or lower range of earthquake frequencies than specified [136]. Due to the constant radius of curvature (r) of the isolator surface, the building may come to resonance for smaller frequency of ground motions. To overcome constraints in FPI and P-F systems Pranesh et al [136] have proposed an isolator namely the variable frequency pendulum isolator (VFPI) contains non spherical surface chosen to provide a progression in period lengthen at different response levels and softens the restoring mechanism at larger displacements. In the case of low earthquake frequencies, VFPI exhibits behavior akin to FPI, while in case of big earthquake frequencies, it exhibits behavior akin to that of the P-F system [137,138]. The researchers have also developed isolations based on friction to have multiple sliding surfaces such as double concave friction bearings, Triple friction bearings (TP) which have 4 concave surfaces [118].

2.3. Advantages of Base Isolation System

The utilization of base isolation technique has been a crucial aspect of earthquake engineering over years, used to mitigate the adverse effects of seismic and wind induced vibrations on structures. In contrast to Conventional fixed-base structures, these base isolated buildings have been demonstrated a range of following benefits:

- Show improved structural performance: The studies shown improved structural performance of a structure to seismic, and wind induced vibrations with use of base isolation technique is attributed from its main key factor, reduced transfer of seismic and wind forces with separation of superstructure from ground by the low friction interface [139].
- The base isolation system ensures protection of both structural and non-structural systems by dissipating the seismic or wind excitations through its low friction interface. To evaluate the performance of secondary systems at isolated structures, several industrial experts have conducted through finite element modelling of analytical models and the shake table testing for full scale test models equipped with secondary systems or non-structural components such as ceiling, electrical appliances and isolation systems subjected to substantial loading conditions [140,141]. Dolce M et al. [142] carries out seismic simulation tests for isolated building specimens to study impact of different of isolation systems on the damage sustained by equipment and contents. The study focuses to investigate the effectiveness of a newly developed shape-memory alloy isolation device. The results suggest that highly nonlinear isolation systems in particularly those characterized by metallic yielding induced damping induce vibrations of high frequency. Moreover, the study reveals that existing analytical techniques effectively captures the frequency content of the acceleration

response. Wolff E.D et al. [143] summarized the response of secondary systems in isolated structures through analytical and experimental investigations. A six-story building model equipped with both Lead core rubber and Friction pendulum bearings were tested through shake table in order to obtain characteristics of isolation system for analytical modelling. The results indicated that an increment in energy dissipation, whether through hysteretic or nonlinear viscous damping, results in reduction in isolator displacement while causing an increment in primary and secondary system response. Morgan T A [144] investigated the sensitivity of non-structural component's response parameters to the properties of isolated buildings. The study includes subjecting the Two moment-frame buildings, each with different natural periods, to seismic records with different source characteristics and soil types. The research considered isolation systems with bilinear behaviour, with variation of characteristic strength and elastic period. The key findings from the study indicated that the considered isolation systems exhibited favourable response in non-structural when compared to the conventional structure. However, during the analyses several challenges were confronted, particularly related to numerical instabilities that could impact high-frequency acceleration response in the isolated building. Furthermore, the study accounts the impact of modification in isolator characteristics over long-term as well as the influence of vertical acceleration and these effects later have shown least importance in speculating the secondary system's response. Van Enegelen N.C et al. [145] explains that base isolation technique provides enough protection for both Structural components such as beams, columns, slabs, etc and Non-structural or secondary components such as ceiling walls, ducts, partitions walls, cladding, windows in a structure by mitigation of wind and seismic forces that may exert on a building by employing of isolation devices beneath super structure, thus safety of occupants and passers-by will be ensured [146]. Kumar P et al. [147] compares the seismic performance of non- structural (secondary) systems held in base isolated and non-base isolated buildings. The study considers two similar 3-storey reinforced concrete frame buildings, one with conventional foundation and other being isolated with lead core rubber bearings (LCRB's) as Structural (primary) system, while a steel frame was depicted as non-structural (secondary) system. The numerical simulations have shown significant reduction of acceleration response in building employed with isolation system and ensured with minimal damage in secondary system when compared to building with conventional foundation. The base isolation systems could contribute to long-term durability of a building by reducing the cumulative damage caused by repeated seismic events. Occupants in important buildings such as schools, hospitals, offices etc can remain safe and safe destinations from collapse of buildings and allow to maintain the functionality of structure during and after an earthquake [148].

- Retrofitting of existing buildings and incorporation into new construction projects with seismic isolation can be integrated in building's design with minimal disruption and be replaced if damaged during its lifespan, makes it a cost-effective technique compared to traditional strengthening methods [99]. Over the few decades several historical buildings such as Salt Lake City and county building [107], constructed in masonry and bridges such as South Rangitikei Rail Bridge [104] were being retrofitted through use of base isolation technique.
- The initial construction costs of base isolated buildings might be higher when compared to conventional building construction, but they show savings and benefits in the long-term. These long-term benefits include reduced structural damage, lower maintenance costs, and insurance premiums. Melkumyan [149]

mentions that retrofitting of existing building with isolation system at base or roof nearly costs three to five times in comparison to cost of conventional retrofitting technique. Ryan K.L [150] conducts cost-benefit analysis for base isolated and conventional buildings. the author finds out the life cycle benefits of base isolated buildings are more significant when compared to conventional and more cost effective for businesses which are unable to relocate after large seismic events.

2.4. Base Isolation Systems for High Rise buildings

The primary concern with base isolation system lies in constraining the large relative displacements within the isolator without amplifying the ground accelerations into structural and non-structural elements in superstructure. Then application of these isolation systems for high-rise buildings in seismically active regions might present with greater difficulties such as insufficient structural stiffness, development of tension in vertical members due to their slender profile, longer natural vibration period, weight distribution, and adaptability to local seismic conditions. So, the Base isolation system's effectiveness is limited for low to medium rise buildings or in buildings whose natural period is less than one second [13]. However, several research experts in the field of extensive research have pointed out a few constraints for ineffectiveness of base isolation in high-rise buildings. Shinozaki Y et al. [151] identified possible constraints such as in increase with construction costs, slender high-rise buildings are susceptible to uplift due to vertical loads during large seismic events and overturing which might damage the isolators at corner. Takewaki I et al. [152] has numerically illustrated through a two degree of freedom model that overall damping in structure diminishes on increase in number of stories and concluded that robustness of base isolated high-rise building is smaller than low or medium rise base isolated buildings. Ariga T et al. [153] concluded that base isolated high-rise buildings mainly buildings with friction type bearings are near to resonance for an intensity of long period ground motion recorded in Japan. Ogura K et al. [154] conducted parametric analysis using lumped mass approach for base isolated high rise building and concludes that Base isolation system achieves response reduction effect irrespective of structure's range of fundamental periods yet depend on whether structure is a low or high-rise. Following above Literature review demonstrates that the conventional approach in base isolation system for High rise buildings could present certain disadvantages in terms of cost, intricacy of design and its partial effectiveness within a specific range of ground frequencies.

2.5. Real-life Application of Base Isolation adopted in High-Rise building – Sendai MT Building: A Case Study

The 18-storey office building, SENDAI MT was constructed in 1995 at Sendai City, Miyagi Prefecture, East Japan (figure 7). At 85 meters high, it is the first base-isolated high-rise building constructed in Japan. Its construction has a strong emphasis on seismic resilience and maintainability even after a seismic event and incorporated with several notable features in structural design as follows [151]:

- The Sendai MT building utilizes high-grade steel rebars (SD 490) for longitudinal reinforcement and high-strength concrete (Maximum of 60 N/mm^2 for columns, joints, and Maximum of 48 N/mm^2 for beams, slabs) in precast to ensure both quality and economy in construction.
- Figure 8 represents the structural frame elevation, incorporated with hybrid structural beams of 15-meter-long span composing of steel in mid part connected with reinforced concrete at both ends of span to have an optimized space for office use.

- For effective seismic performance of building, an innovative application of base isolation system known as Hybrid TASS system was being utilized. The Hybrid TASS system in Sendai MT Building composes with two type of isolation bearings namely rubber bearings(1100mmØ,1200mmØ) and sliding bearings(1300mmØ) with varied sizes and properties are arranged as shown in figure 9 at isolation level, below ground storey to achieve effective seismic performance. The sliding bearing's damping ratio in the isolation level is designed to maintain a yield force that exceeds the wind force and were positioned beneath inner columns, where variation in axial forces due to earthquake is minimum. The rubber bearing's shape and rubber stiffness are designed to have soft stiffness following yield which excepts good seismic performance in case of large earthquakes.

Fig. 7. Exterior View of Sendai MT [196]

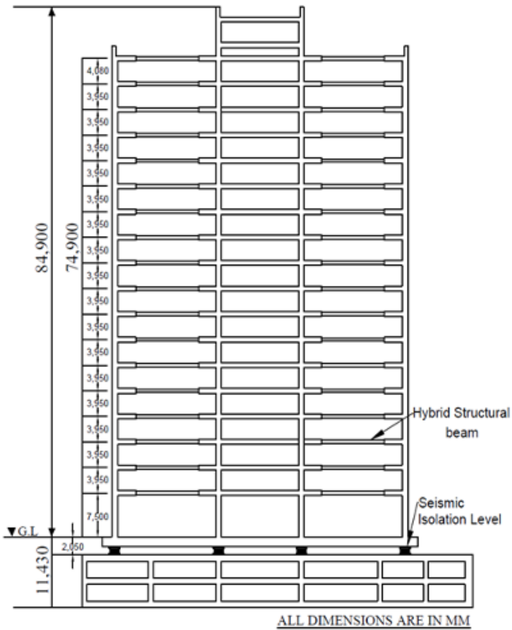


Fig. 8. Frame elevation of Sendai MT [155]

Komuro T et al. [155] compared the force-deformation relation of Hybrid TASS and ordinary isolation systems as presented in figure 10, which explains that TASS system was designed to have yield force which can exceed the design wind force and achieve good seismic performance at a large seismic event as stiffness after yield is equivalently soft.

A dynamic analysis was performed on utilizing a lumped mass model under several earthquakes. The recorded input ground motions of earthquakes such as El Centro (1940 NS), Hachinohe (1968 NS), Sendai TH-038, Taft (1952 EW) are categorized from level 1 to 3 based on probability of occurrence during building's service life. The analytical results of level 1 defined the design base shear coefficient of super structure to 8%, the drift gradient is smaller than 1/330 rad for level 2 and smaller than 1/230 rad for level 3 shown in figure 11.

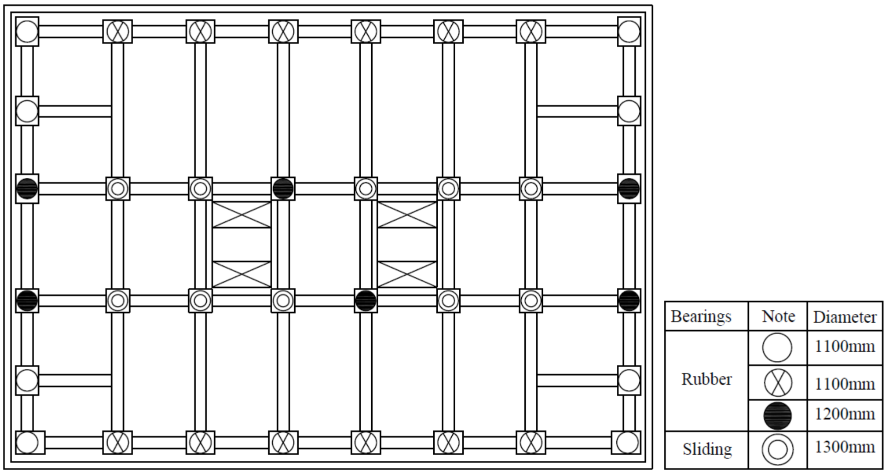
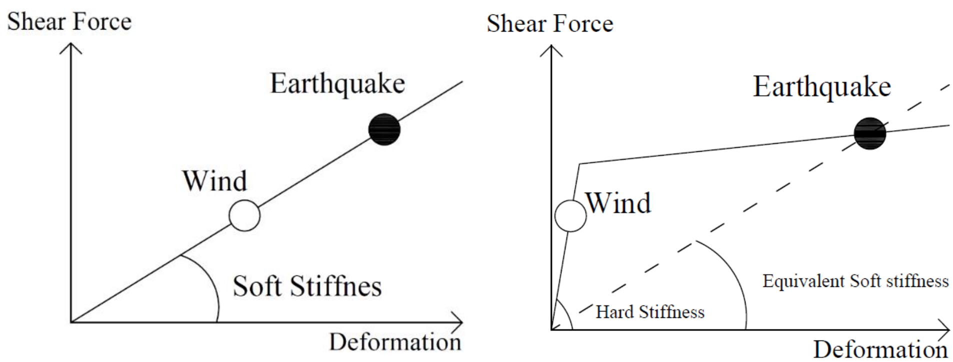


Fig. 9. Arrangement of Different Isolators in Hybrid TASS System [155]

The author reaches a conclusion that Hybrid TASS system or other structural systems along with base isolation systems brings an advantage for construction in terms of cost and seismic performance, can used in low to high-rise buildings. The Base Isolation system in high-rise buildings could still shows significant reduction in responses and building can be protected from huge earthquakes by employing with proper design of isolators [10]. So far, the Base isolation has been employed in several notable high-rise buildings, such as the Thousand Tower in Kawasaki City and Shimizu Corporation headquarters in Tokyo [156]. Furthermore, this technique has been utilized as retrofitting strategy for Historical high-rise structures like the Los Angeles City Hall, the San Francisco City Hall, and the Utah State Capitol building [13].



Nominal Isolation System   Hybrid TASS System

Fig. 10. Force-Deformation relation of different Isolation systems [151]

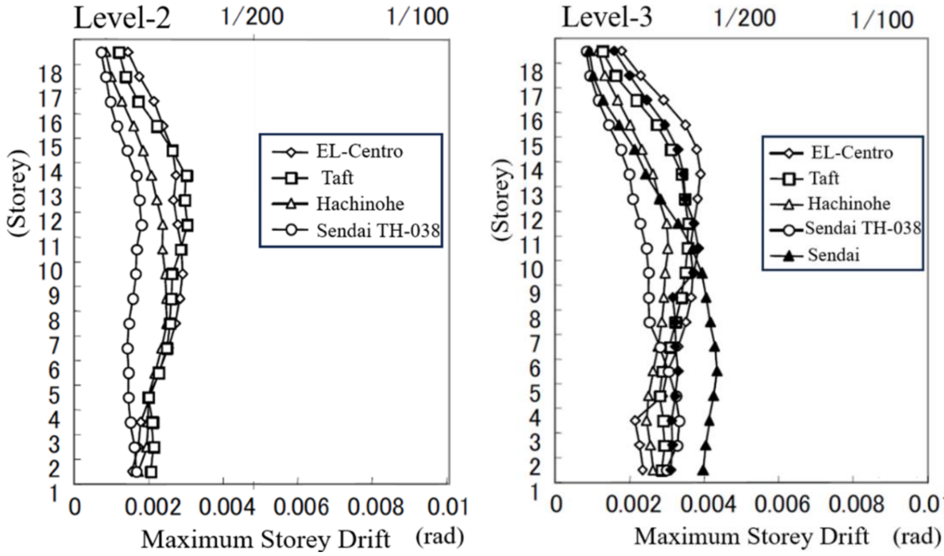


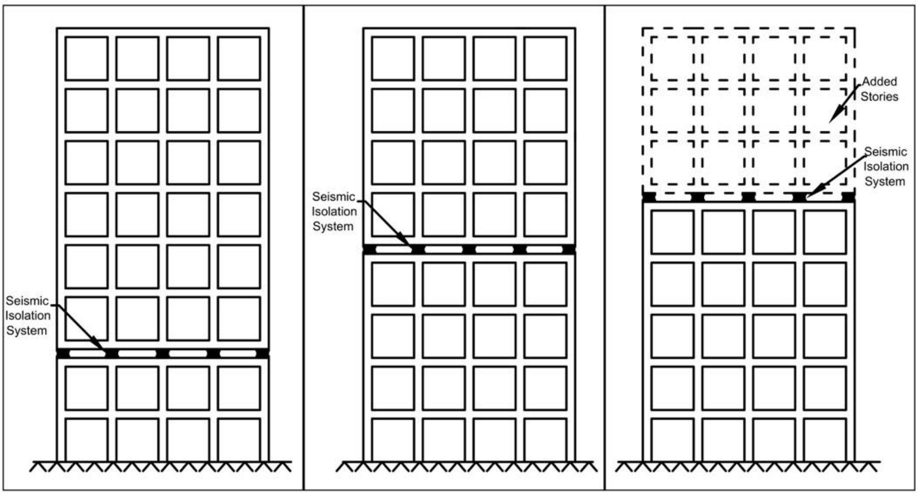
Fig. 11. Maximum Response storey Drift (in radians) for Level 2 & 3 Ground Motions [151]

3. Inter-Storey Isolation Systems

Over years of extended research in base isolation, the research professionals have recognized infeasible in medium and high-rise buildings due to super structure's flexibility and overturing behavior, provision of seismic gap or moat wall around structure to accommodate for significant relative displacements at the isolation level and prevent building pounding with adjacent structures often arise aesthetics concerns which is infeasible in densely built regions [157-161]. So, the necessity to address the concerns related to architectural and functionality, to enhance the construction feasibility particularly at densely populated areas, promoted the researchers to propose the Inter-storey Isolation System (IIS), which serves as an alternative to base isolation system and effective approach to provide seismic protection to buildings [162-164]. The Inter-storey or Middle-storey isolation system includes employing a flexible isolation level akin to BI's, positioned either at mid height or at a specific level within building's height. This shift of isolation level divides the super structure into upper and lower structure as shown in figure 12(a) allowing the upper structure to move independently of lower structure during an earthquake. The upper structure represents as a base isolated structure and as a mass damper mounted on top of the lower structure which demonstrates a Combined effect of seismic isolation and mass damping (unlike tuned mass damper) thus, enhancing the seismic performance of a building subjected to significant earthquake excitations [165, 166]. In elaborate, the response reduction effect occurs in lower structure with unconventional Tuned mass damper (TMD) effect from upper structure, in which a portion of upper structure's structural mass appears to be a mass absorber, while retaining to their structural and control function [158,167,168].

The seismic response reduction effect on upper structure occurs with its isolation from ground created by the lower structure and depends on mass ratio (i.e. ratio between the mass of upper structure and total mass of superstructure of building) [169]. While the response reduction effect on lower structure occurs with suitably optimized damping and stiffness characteristics of the isolation system in relation to isolated mass ratio [166].

Middle storey-isolation systems are akin to Inter-storey isolation but exhibit the variation in response reduction due to presence of isolation level at mid height of structure.



a) Inter-storey Isolated Building with Large Upper Structural Mass

b) Middle-Storey Isolated Building

c)Inter-storey Isolated Building with added Stories on existing building

Fig. 12. Inter-storey Isolation System in building at various Heights

The Middle-storey isolation system separates the building's super structure into two structures as shown in figure 12(b), which are approximately equal in height and structural mass. This separation has shown effective seismic performance when adopted for high-rise buildings such as Shiodome Sumitomo Building [170]. These Inter-storey or middle storey isolation systems consist of isolation bearings such as HDRB's, FPS, LCRB's akin to base isolation system, designed to have high shearing strain, high damping and vertical load carrying capacity. In Inter-storey Isolated buildings, the location of Isolation level is mainly chosen based on type of structure, required level of response mitigation, cost implementation and many other factors [171]. The dynamic properties of Inter-storey Isolated buildings are characterized using simplified two-degree, three-degree, or multi-degree of freedom models due to presence of complex mechanisms rather than in base isolated buildings [162]. The unconventional TMD in Inter-storey system can overrule the constraint of inadequate added tuned mass which limits response reduction effect in structures with conventional TMD. Several researchers likely designated these Inter storey isolation systems also as building mass damper (BMD), non-conventional Tuned Mass Damper, mid or middle-storey isolation, or added storey isolation systems [172].

3.1. Advantages with Inter-storey Isolation Systems

The utilization of Inter-storey Isolation System adds on following advantages:

- These Inter-storey Isolation systems always permit for greater flexibility in both structural and architectural design for tall and multi-purpose buildings. Consequently, a sustainable solution for buildings allows for saving land use in densely built areas [173,174].
- Eliminates the accommodation of seismic gap or an expansion joint around the structure during construction of base isolated structures which allows for larger relative displacements at isolation level during earthquakes, presenting the economic feasibility and aesthetic desirability of these isolation systems [175,176].

- Eliminates the framing of base slab over isolators when located at base reduces the complexity in construction of foundation in such as erection of retaining walls [162].
- The Inter storey isolation systems at multiple level separates the structure into distinct individual occupancies which are diverse in both structural and functional characteristics, allowing for contrary arrangement of all the structural elements and columns at each occupancy [177].
- This IIS technique has potential to be utilized as a seismic retrofitting strategy for existing buildings as shown in figure 12(c), allowing to accommodation for additional stories without increasing the base shear and maximum acceleration response on structure which is termed as added storey Isolation system and exhibit better seismic performance and feasibility rather than base isolation [178-181].

However, These Inter-storey isolation systems can be effectively utilized in structures where use of base isolation might not be appropriate in such as offshore structures and densely built areas, in buildings with irregularity requirement (such as parking structures), mixed-use type buildings and for medium rise to high-rise buildings especially in regions of high seismic activity [178].

3.2. Inter-storey Isolation Systems for High-Rise Buildings

The concept of Inter-storey isolation system for High-rise Buildings is currently widespread and gaining a lot of traction, especially in Japan despite the fact more than sixty real-life applications were developed over the course of nearly two decades [182]. Some notable examples of high-rise structures with Inter-storey isolation systems in Tokyo include the Iidabashi first building [84], the Roppongi Grand Tower [183], Shiodome Sumitomo Building [170], Nakanoshima Festival Tower [184]. However, Several Experimental and analytical studies were undertaken to review the effectiveness of Inter-storey isolation for High-rise buildings.

Villaverde R et al. [185] conducted a feasibility study out of a 13 - storey building with the roof isolation system which intends diminish the response of a structure during seismic events. The proposed isolation system comprises of isolators in between a building's roof level and columns supporting the roof and were also complemented with viscous dampers connected in between the isolation level. This feasibility study investigates the assessment of the building's response with and without the proposed isolation system using a two-dimensional analytical model under severe ground motions, which determines the required size and properties of an isolation system. The study finds out that the proposed system shows effectiveness in response mitigation and has the potential of attractive solutions for low-rise and medium-rise buildings.

Taylor P et al. [177] conducted a feasibility study on inter-storey isolation systems using both linear and nonlinear devices. The study investigated the efficacy of inter-storey isolation systems using a linear and non-linear Time History analysis for building models installed with linear and non-linear isolation devices at different levels. Three distinct approaches were proposed for choosing the optimum design deformation of a non-linear inter-storey isolation system. The findings in study revealed that stiffness in isolators decreased with the shift of inter-storey isolation system vertically up for a structure, as result of smaller portion of mass being isolated and the roof isolation system is proven to hold a merit as economical retrofit application.

Wang SJ et al. [162] carried out an experimental investigation on base and mid-storey isolated building models using shake table analysis to study their dynamic behavior. The results of the shaking table test reveal that the middle-storey isolated building has a smaller number of modal quantities (fundamental) compared to a base-isolated. During the study it observed that lower structure's seismic response is directly influenced by its fundamental mode of vibration, whereas the lower structure's seismic response is influenced by higher mode responses. The author suggested the Response Spectrum Analysis for the initial design of middle-storey isolated structures before performing a nonlinear time history analysis.

Chey MH et al. [186] investigated the efficacy of an innovative seismic retrofitting strategy for buildings namely the "added stories isolation" systems (ASIs). The added stories isolation system comprises of newly added upper stories isolated on top of existing building, acts as a storey mass damper (unlike conventional Tuned mass damper) to overcome the requirement for larger tuned mass in structure with conventional Tuned mass dampers. The evaluation of seismic performance was analyzed for "12+2" and "12+4" Storey moment resisting frame models using the time history analysis. The study concluded that the proposed ASI system has potential to mitigate the seismic response for multi-degree-of freedom systems across a wide range of ground motions without requiring troublesome additional mass.

Faiella D et al. [187] explored the productivity of an Inter-storey isolation system through its two distinct real-life case studies. The selected buildings, the Iidabashi first building (IB), the Shiodome Sumitomo building (SSB), elevates Japan's advancement in design practice of the inter-storey isolation systems for high-rise buildings. Frequency and Modal response analyses were executed for simplified two or three degree-of-freedom models, where these models of reduced-order could influence the governing design parameters of the dynamic problem. Whereas for multi degree of freedom (MDOF) models, the Modal response and non-linear time history analyses were conducted. The study concludes that a good seismic performance can be expected through a proper balance in dynamic characteristics of structural portions and adopting for larger mass ratio and longer isolation period.

Forcellini D et al. [188] analyzed the proficiency of inter-storey isolation for high-rise buildings on utilizing the 20-floor building models (B0, B1, B2) with isolation layer at several heights. The resultant performance of each model was analyzed for assessing the best location of isolation layer throughout the structure's height. The seismic behavior improvement was observed from the mass damping effects of this system on the substructure. Several important aspects such as dynamic effects of building at higher modes, P-delta effects, material non- linearities, stability effects of isolators by interaction of horizontal and vertical loads, etc. were considered during this study. The Analytical results prove that B2 building model with isolation system at mid height has been effective approach to diminish the acceleration responses on building and improve the seismic performance. Even though implementation of inter-storey isolation effectively diminishes the acceleration responses and deformations in between the stories of the structure, its practical application might contain several constraints.

Saha A et al. [167] demonstrated the hostile effects of pulse type motions (near fault) on the performance of Inter-storey Isolation systems (IIS). An Extensive Non-linear dynamic analysis has been executed for a group of buildings models ranging from low to high rise designed from the steel moment resisting frames and HDRB isolators placed at intermediate storey level and exposed to two groups of non-pulse type and one-directional pulse ground motions concerning to various hazard levels. These pulse type motions were exhibited to deteriorate the competence of an inter-storey isolation system and expand the seismic demands. The observed deficit of the bearing displacements been underestimated in the FEMA formulae was suggested with a revision, by accumulation of a modification factor. The results showed that low-rise to medium rise IIS building models are highly sensitive to medium pulse type ground motions, whereas the high-rise IIS building models are sensitive to extended period pulse type ground motions.

Dona M et al. [189] highlighted the necessity for additional damping to diminish the P-Delta effects triggered from drift between the structural parts of lower and upper structure separated by isolation system. As a solution, the Fluid Viscous Dampers (FVD) were introduced in complement to these inter-storey isolation systems for additional energy dissipation. The use of FVD's allows for the isolation systems to be designed at low activation forces despite the expected earthquake forces [190]. Duan C et al. [191] highlighted the consequences of implementing inter-storey isolation systems in high-rise structures. These isolated buildings, under substantial dynamic loading might induce an overturing moment and excessive deformations at isolation level and result an irreversible damage to the bearings. As a solution, a Dual Isolation System based on Friction Pendulum isolation System (FPS) in combination with inter-storey and base isolation system was introduced. These Dual isolation systems avoids the cause tensile damage within the isolators that arises from larger deformations at isolation level, diminishes the seismic response of buildings with high aspect ratio (height to width ratio) at higher modes and enhances the ability of high-rise buildings to resist the overturing effect.

The literature review provides summary that the inter-storey isolation is an effective seismic isolation approach rather than base isolation for High-rise buildings. However, the utilization of this isolation system alone for high-rise buildings might not be an effective solution to fulfill seismic demand. It was indeed true in some cases, especially when exposed to pulse type motions (near fault), long period ground motions, substantial dynamic loading due to heavy winds, blast loads. The researchers suggested that addition of structural damping components such as Fluid viscous dampers, shear walls, outrigger systems, steel bracings in isolated buildings and inclusion of appropriate considerations during the preliminary design and analysis phase of isolation system, allows to achieve an enhanced seismic performance in high-rise buildings. The considerations included the location optimization of isolation level, P-delta effects, influence of higher modes, material non-linearities, local seismic conditions. Furthermore, the proper selection of the mass ratio of upper and lower structures (α), Isolation period (T_n), type of isolation bearings, method of dynamic analysis, type of ground motions and building's structural configuration. Finally, it includes that IIS technique can be utilized as seismic retrofitting strategy during the additional storey construction over an existing structure, which is termed as added-storey isolation strategy as shown in figure 12(c). Some notable examples of real-life buildings with added-storey isolation systems includes The International Library of Children's Literature in Tokyo [192], The Munashino City Disaster Prevention and Safety Center [193].

3.3. Real-life Application of Inter-Storey Isolation adopted in High-Rise building -Marunouchi Tekko Building: A Case Study

Marunouchi Tekko Building is a multi-purpose, seismically isolated high-rise building, built about 200 meters wide near Tokyo Station (figure 13). This mixed-use type building consists of various commercial amenities such as business support service centres, shops, lounge for bus service, restaurants, located at low-rise and basement level. This Tekko building mainly consists of the Main Building on the north side with 136.5 meters in height, and the South building on the south side of building site with 98.5 meters in height and both integrated on 3-storey basement levels.

Fig. 13. The Tekko Building [197]

3.3.1 Structural Features of Tekko Building

The Main Building comprises of 26 stories and a 2-storey penthouse, the South building has 19 stories and 1-storey penthouse and together sharing a 3-storey basement. The Main building houses for office spaces and South Building for high stay serviced apartments on the 6th floor and above [194].

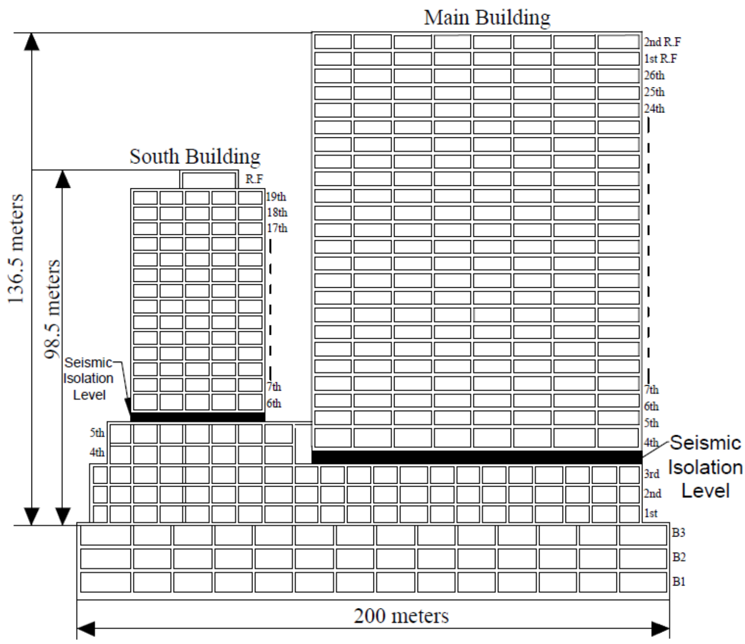


Fig. 14. Cross-Sectional View of Tekko Building

The Tekko building is so called “an intermediate-storey seismic isolated structure”, consisting of 2-seismic isolated buildings on an integrated lower part. The seismic isolation level is located in between the 3rd and 4th stories of the Main building and for South building between the 5th and 6th stories as shown in figure 14. The Main building composes of structural steel above ground and steel framed reinforced concrete below ground, with combination of piles and mat foundation. The office areas are more spacious as provided with no columns in between for longer span about 18 m. To ensure stiffness of structural frame the intermediate seismic columns are provided in the short direction within the core. Additionally, Steel bracings were provided at higher stories (9th, 17th and 24th Floors). The South Building above the Seismic Isolation level is a 2-span structure in shorter direction and intermediate columns started from floors above seismic isolation level.

3.3.2 The Seismic Isolation Strategy

The seismic isolation layer for the Main Building composes of 48 units of laminated natural rubber bearings (LNRB's) of distinct sizes (1000 Ø to 1500 Ø mm), 40 units of oil dampers in 8 with locking mechanism and 30 units of U-shaped steel dampers (Figure 15). While the South building composes of 10 units of laminated natural rubber bearings (LNRB's) with varied sizes (800 Ø to 1200 Ø mm), 8 units of oil dampers and a TMD mounted on top of building [194]. The Isolation levels of the Main building and the South Building were employed below the 4th floor and 6th floor, respectively. The oil dampers with a locking system are provided in short direction of building, to avoid the elevator's shafts from deformation during stronger winds. The oil dampers with a locking mechanism operate as normal oil dampers under nominal conditions, yet during the intense winds the oil dampers were locked with a return period of 4-5 years. This locking mechanism releases on using a timer, often released at a certain time after the locking mechanism being activated and can be controlled manually. The locking mechanism gets activated when an earthquake occurs, whereby the lock is released based on accelerometer measurements.

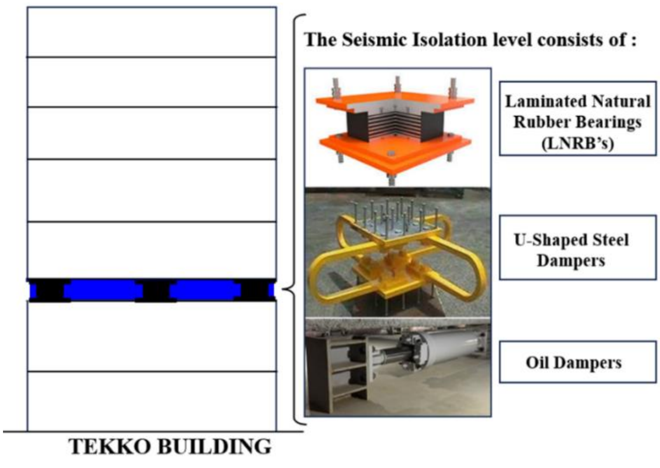


Fig. 15. Common Isolation devices used for Tekko Building

3.3.3 Seismic Design Strategy:

The seismic authentication of this isolated high-rise building was investigated through a Response Time History Analysis (RTHA). The Time history analysis used a set of predefined ground motions of Level 1 (rarely occurring) and Level 2 (extremely rarely occurring), categorized by probability of occurrence during building's service life. The ground motions include 3 calibrated waves from the past Hachinohe 1968 NS, Taft 1952 EW, and El Centro 1940 NS, and 3 waves prescribed from Kobe, Hachinohe, and an arbitrary phase. A coupled lumped-mass model was adopted for the vibration response analysis, where these two buildings were positioned in parallel to lower-rise integrated part below them. The structural frame of the Main and the South building were modelled as 23 lumped masses and 16 lumped respectively. The 1st to 3rd floor masses of the main, south building and boundary arranged in parallel are presumed to be rigid as illustrated in figure 16.

3.3.4 Wind Design Strategy

The wind load consideration also plays curial role in the initial design and construction phase of a high-rise structure. These wind loads show detrimental effects on shape, structural properties of tall structures. The Analytical framework included two levels of wind loading for design of building against wind. The analysis for the structural frame of building was executed under two levels of wind loads, whereas for seismic isolation system under the Level 2 wind load. The Response Time History Analysis was executed undertaking the elastic-plastic characteristics of isolation bearings and a fatigue analysis was carried out for U-shaped steel dampers.

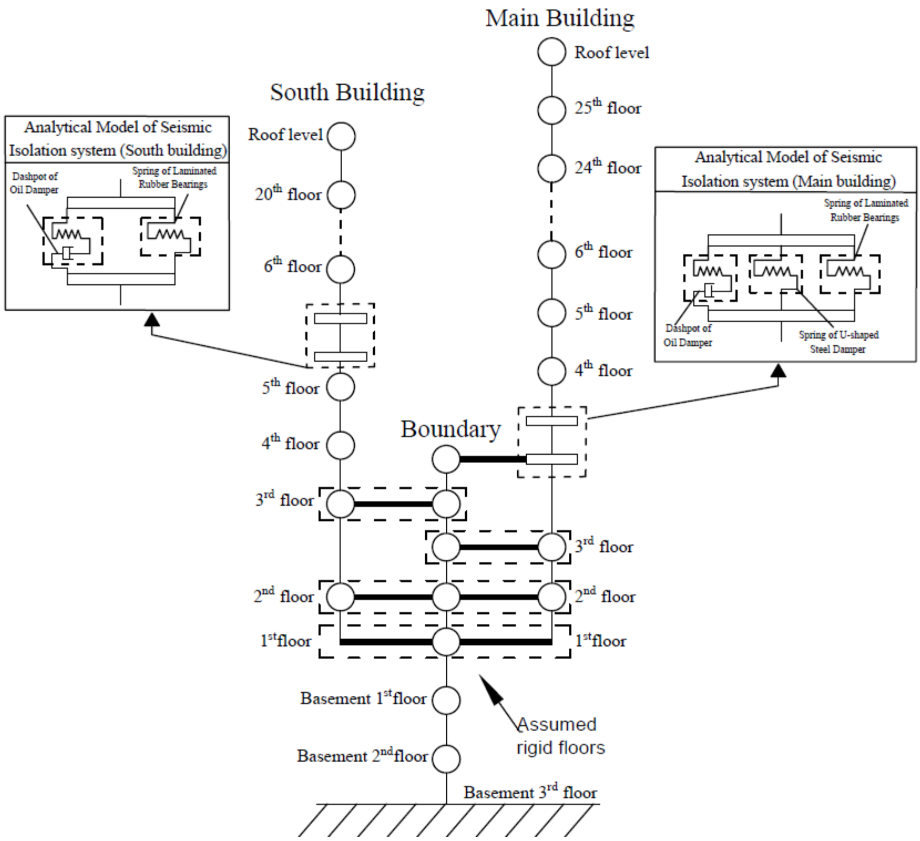


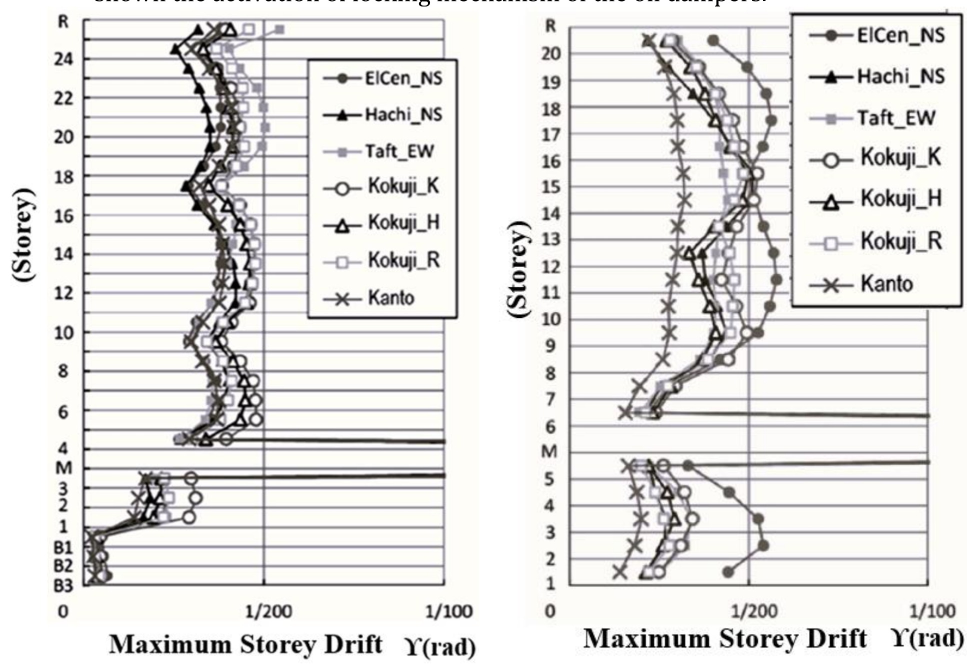
Fig.16. Vibration control analytical model for Tekko Building

3.3.5 Analytical Results

Tamari M et al. [195] conducted analytical studies considering seismic design and wind design strategies for Marunouchi Tekko Building and include the following findings:

- The fundamental natural period for the South building was recorded as 5.68 seconds and whereas for the Main Building with equivalent stiffness and when the deformation is 30 cm was recorded as 5.38 seconds.

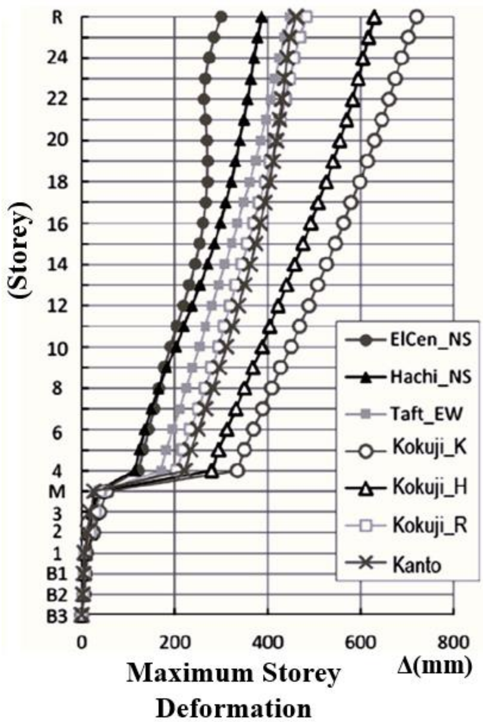
- The maximum storey drift (in radians) under the Level 2 ground motions in Y direction recorded as 1/184 for the Main Building, and 1/173 for the South Building. (figure17)
- The Main Building exhibits a deformation of 336 mm at seismic isolation level, whereas for South Building with deformation of 251 mm (figure 18). Despite the consideration of variation in the seismic isolation devices, still encountered a deformation of 376 mm for the Main Building and deformation of 285 mm for the South Building.
- The wind load analysis results include that the response shear forces for both buildings are less than design shear forces, whereas the shear stresses under the Level 2 wind load are less than the short-term allowable stresses.
- Under the influence of Level 2 wind load, the storey above the seismic isolation level experiences the shear forces in proportion to the design shear forces about 41% for South Building and 84% for Main Building.
- The seismic isolation level under Level 2 wind load exhibits a maximum deformation of 98.7 mm for the Main Building and 269 mm for the South Building.
- After a year completion of construction, the seismic measurements for building under earthquake intensity of 3 were measured twice, which each of them confirmed the seismic isolation effect. While the wind measurements for building were measured by a rapid maximum wind velocity for 2 days, during which shown the activation of locking mechanism of the oil dampers.



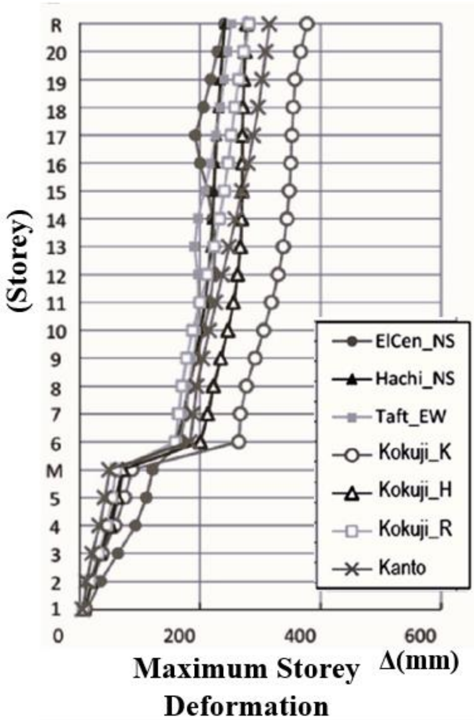
a) Main Building b) South Building

Fig. 17. Maximum Response Storey Drift (in radians) [195]

On Conclusion, the author describes that adopted structural scheme and the design strategies carried out while checking that there are no resonance effects for the Tekko Building are worked more effective at extreme conditions. Moreover, use of additional structural elements such as U-shaped steel dampers and oil dampers with locking mechanism have shown their effectiveness in mitigation of strong earthquake and wind forces.



a) Main Building



b) South Building

Fig. 18. Maximum Response Storey Deformation (in mm) [195]

4. Conclusions

In Conclusion, the vibration control design is a key factor in ensuring the resilience and safety of tall or high-rise buildings in earthquake prone regions. This review article provides a comprehensive overview of base-isolation and Inter-storey isolation systems for High-rise buildings, which is accomplished by extracting useful insights from analytical and design features of real-life high-rise buildings equipped with these base isolation and inter-storey isolation systems. In detail the article explores the basic concept and the characteristics of the base isolation system, and the types of isolation bearings used for buildings. the fundamental concept and the benefits of inter-storey isolation system over base isolation. Additionally, the importance of vibration control strategy for buildings, and the different types of vibration control systems were also discussed. From the literature of this present study, the following main highlights and conclusions can be obtained:

- The implementation of Base isolation and inter-storey isolation systems serves as viable solutions for shifting the building's natural period away from range of frequencies which show greater impacts on amplification of ground motions. However, these systems employ distinct mechanisms to enhance seismic performance of a structure.
- The Base isolated high-rise buildings are identified to have less robustness and tend to resonate at higher modes of vibration and under long period ground

motions. So, these base isolation systems are viable for low rise to medium rise buildings.

- The Inter-storey isolation systems for buildings utilize a combination of seismic isolation and TMD approach to achieve enhanced seismic performance when compared to base isolated buildings.
- The Inter-storey isolation system is also presented as a seismic retrofit strategy during the additional storey construction on top of an existing structure, which is termed as added-storey isolation strategy.

On study of distinct features of base isolation and inter-storey isolation techniques, several key differences were discussed as shown in table 2.

Table 2. Key differences between base isolation and inter-storey isolation technique

Base Isolation Technique	Inter-Storey Isolation Technique
The base isolation technique comprises placing flexible bearings, namely isolators between the building's super structure and substructure (foundation).	The Inter-storey Isolation technique uses isolators akin to base isolation but employed between consecutive floors of a building.
The technique aims mitigate the transfer of seismic forces to structure by decoupling the building from ground motion.	The technique aims to mitigate the transfer of seismic forces to adjacent floors of building, thereby minimizing inter-storey drifts and accelerations.
The technique targets to provide protection for entire structure from ground motions with low to medium range of frequencies.	The technique targets to provide localized protection to individual floors in structures form ground motions with medium to higher range of frequencies.
The technique requires provision of moat wall or seismic gap to allow for deformations at isolation level.	The technique does not require provision of seismic gap for allowing deformations.
The technique can be commonly used for low to medium-rise buildings.	The technique can be commonly used for medium to high-rise buildings.
The technique is cost effective in construction of new and existing structures as a retrofitting strategy when compared to conventional strategy.	The technique is cost effective in construction of existing and added storey structures as a retrofitting strategy when compared to base isolation system.

So far, these two case studies explore that use of traditional seismic isolation might not achieve to fulfill the seismic demand of high-rise buildings. Moreover, the use of other structural elements such as dampers, shear walls, outriggers along with seismic isolation system has shown effectiveness in mitigation of seismic and wind forces.

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