Structural Engineering

Inter-Story Isolation Systems (IIS) For Tall Buildings: Design Considerations

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Abstract

Inter-story isolation systems (IIS) are currently gaining significant popularity, mainly in Japan, where more than 60 applications have been realized in the past 20 years. But the conceptual framework for dealing with related design problems is not well established, as it is in the case of base-isolation systems (BIS). Two very different actual IIS-equipped buildings are examined here using modal and time histories, in order to cross-reference the latest design practices with academic research. One is a paradigmatic example of IIS, with a very rigid superstructure, and with frequencies of two structural parts well-separated from the isolation frequency. The other building is a non-typical IIS case, with the upper structure being less rigid than the lower, and both structural portions remaining quite flexible. The results clearly show the vibration characteristics of mid-story isolation and how they affect the structural response under seismic input.

Keywords: Seismic, Structural Engineering

Introduction

Seismic isolation is today a mature design strategy, thoroughly studied by the international scientific community since the 1980s, refined by more than 30 years of design practice, and characterized by a diverse range of applications. Thanks to the growing confidence in the seismic performance achievable by isolated buildings, new fields of application of the isolation principle have recently emerged, pushing the boundaries of the well-established original concept and posing challenging new design issues. Inter-story isolation systems (IIS) have been applied in more than 60 cases since the late 1990s, mostly in Japan, both for the seismic design of new buildings and for retrofit of, or addition to existing buildings (Kobayashi & Sasaki 2009).

Shifting the position of the isolation system from the base of the building to a level closer to the midpoint along the elevation enhances the feasibility of the isolation strategy in several situations, such as in densely populated areas. Further, IIS is an advantageous solution for mixed-use buildings, in which different occupancies along the elevation give rise to different architectural plans and structural grid

	Iidabashi First Building (IB),Tokyo	Shiodome Sumitomo Building (SSB), Tokyo
Location	Tokyo	Tokyo
Structural Engineer	Nikken Sekkei	Nikken Sekkei
Year of completion	2000	2004
Building occupancies	offices, apartments	hotel, offices
No. stories	14 + penthouse	25
Plan dimensions (m)	130.1 x 39.6 (offices), 130.1 x 15.0 (apartments)	109.6 x 39.5
Floor area (m²)	5,152.0 (offices), 1951.5 (apartments)	4,339
Total floor area (m²)	43,324	108,475
Height (m)	63.2	126.1
Interstory height (m)	4.1 (offices), 3.05 (apartments)	4.2
Structure	SRC + RC + S	S
Isolation System	40 RBs (Φ800)	41 RBs (Φ1300, Φ1100, Φ1000)
	212 LD Φ180	100 LD + 14 SD
Key:	SRC = Steel + Reinforced Concrete RC = Reinforced Concrete S = Steel	RB = Rubber Bearing LD = Lead Damper SD = Steel Damper

Table 1. Basic data of the two subject buildings examined in this study.

Figure 1. Iidabashi First Building, Tokyo. Source: MAPA Japan

Figure 2. Shiodome Sumitomo Building, Tokyo. © Terri Meyer Boake

layouts, thus identifying a level of structural discontinuity that can be ideally utilized for placing the isolation system. Additionally, tall buildings are good candidates for seismic isolation, thanks to the introduction of an optimally-placed IIS that can remarkably improve the response of both structural sections, above and below the isolation system (Zhou, Singh & Huang 2016). Finally, the vertical addition of new floors, isolated on the top of existing buildings, is a retrofit strategy that allows the increase of usable area and real estate value without increasing the seismic demand, thanks to the so-called "mass damper effect" exerted by the upper part on the existing substructure (Chey et al. 2013, Ryan & Earl 2010, Tsuneki et al. 2008, Tsuneki et al. 2009).

However, despite the large number of applications of IIS, the design approach is not so well defined, and is less straightforward than the base-isolation system (BIS). A review of the main scientific contributions in the literature reflects a variety of approaches, both in the formulation of the problem and in the definition of the design objectives and parameters. Basically, three major conceptual approaches can be clearly identified, each mainly focusing on one single aspect of the IIS behavior, namely: energy dissipation, isolation, and mass damping.

The authors have conducted a literature review, case studies, formulated problems and identified the governing design parameters, parametric analyses, and definition of design objectives and criteria. The research aim is to cover the range of actual and potential applications of IIS, and to identify the predominant role among the behavioral aspects of isolation, dissipation and mass-damper effects by varying the design parameters. Here, two real-world applications of IIS are thoroughly analyzed, in order to interpret the latest design practice against the latest research. In the following paragraphs, the major data obtained from publications and communication with the designers yields an approximate prediction of, and a preliminary discussion on the dynamic properties of the three structural parts of each building, and, consequently, on their expected dynamic interaction. Additionally, a straightforward comparison between the anticipated dynamic behavior of the two buildings is presented. Modal and time-history analyses are then conducted on multi-degree-of-freedom (MDOF) models of the two buildings; the main results are reported and design implications are discussed, in the context of previous observations, and of the provisions suggested in the existing scientific literature.

> **" The second and third modes obtained for the Shiodome Sumitomo Building Rubber Bearing model involve displacements both in the upper and lower stories, thus suggesting higher mode coupling, which can produce an undesirable amplification effect in the seismic response of the structure. "**
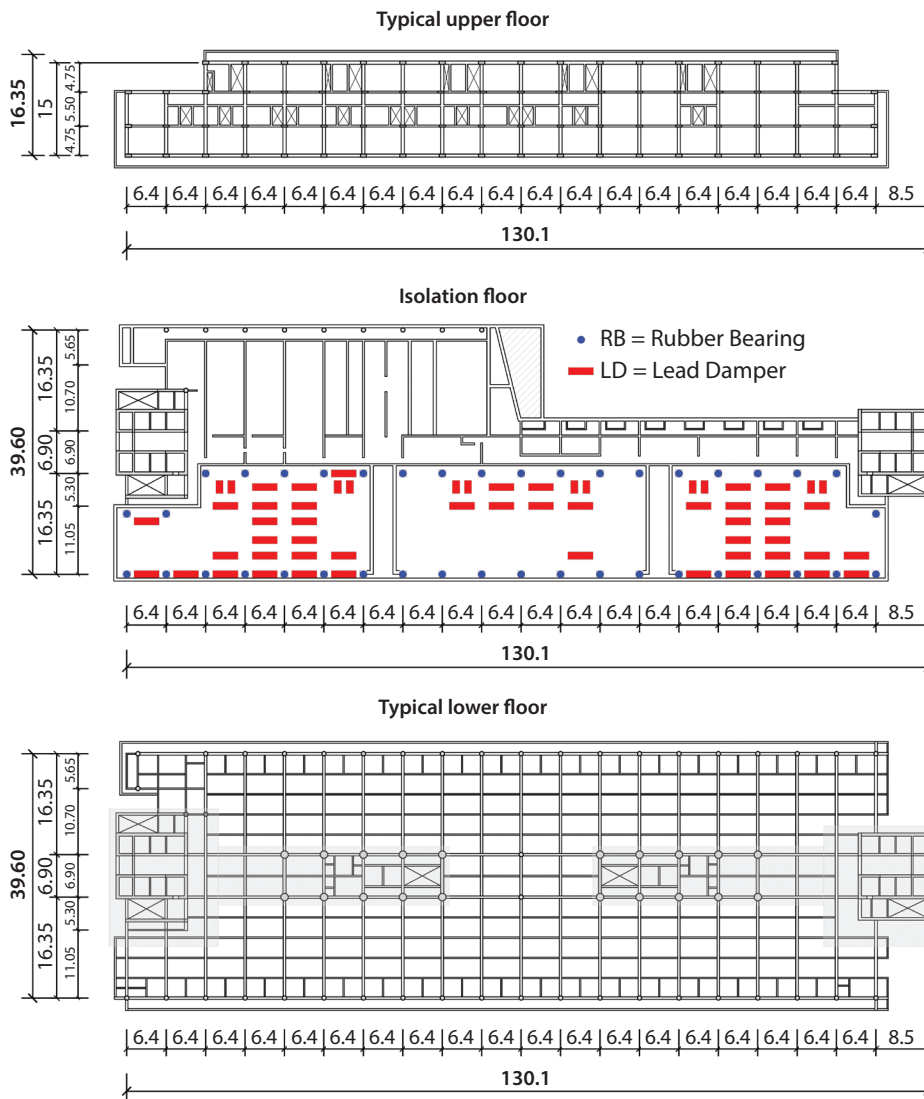
Typical upper floor

16.35
15
4.75 5.50 4.75

| 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 8.5 |

130.1

Isolation floor

39.60
16.35 16.35 6.90 6.90 16.35
5.65 10.70 5.30 11.05

- RB = Rubber Bearing
- LD = Lead Damper

| 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 8.5 |

130.1

Typical lower floor

39.60
16.35 16.35 6.90 6.90 16.35
5.65 10.70 5.30 11.05

| 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 6.4 | 8.5 |

130.1

Figure 3. Iidabashi First Building, Tokyo (IB) – floor plans. Source: Murakami, 2000.

The Case Studies: Simplified Modeling and Dynamic Properties

Two high-rise buildings with intermediate-story isolation systems (Murakami et al. 2000, Sueoka, Torii & Tsuneki 2004, Tsuneki et al. 2009) are selected on the basis of two criteria: availability of data and representativeness of the range of IIS applications in the current design practice. They are the Iidabashi First Building (IB) and the Shiodome Sumitomo Building (SSB) (see Figures 1 and 2). The basic data of the buildings is displayed in Table 1. A view of the buildings, the framing elevation and the typical plan of the upper, intermediate and lower structures and the arrangement of the isolators and dampers are shown in Figures 3 and 4.

Simplified lumped-mass MDOF models are developed and utilized for an in-depth analysis and discussion of the buildings' dynamics. For both buildings, three different MDOF models are considered, namely: with rubber bearings (RB), with rubber bearings plus dampers (RB+D), and free-body (FB) models. In the RB models the isolation layer is only represented by the isolators, while in the RB+D model both isolators and dampers are taken into account; finally, the FB models for each building are composed by the degrees of freedom of the lower and upper structures, without the one corresponding to the isolation system.

The data necessary for the construction of the MDOF models, i.e., the floor mass values, the inter-story structural stiffness distribution, and the characteristics of the isolators and dampers, are all derived from papers (Murakami et al. 2000, Sueoka, Torii & Tsuneki 2004) and/or have been kindly provided by the designers.

The IB is represented by 15 lumped masses: 9 in the lower part, one in the intermediate isolation layer and five in the upper part; the SSB is represented by 26 masses, 11 in the lower part, one in the intermediate isolation layer and 14 in the upper part.

Unit of measure	IB	SSB	IB vs. SSB		
M_{TOT}	69,092	75,498	1 : 1.1	IB	Iidabashi First Building
				SSB	Shiodome Sumitomo Building
m_{US} (t)	10,899	47,528	1 : 4.4	M_{TOT}	total mass of the whole building
				M_{US}	mass of the upper structure
m_{ISO}	4,022	4,030	1 : 1	M_{LS}	mass of the lower structure
				M_{ISO}	mass of the isolation level
m_{LS}	54,171	23,940	2.3 : 1	T_{FB}	natural period value of the entire fixed-base structure
T_{FB}	1.17	3.27	1 : 2.8	T_{US}	natural period value of the upper structure, considered as a standalone, fixed-base structure
T_{US} (s)	0.21	2.18	1 : 10.4		
$T_{ISO,RB}$	3.33	5.02	1 : 1.5	$T_{ISO,RB}$	natural period value of the isolation system with rubber bearings
$T_{ISO,RB+D}$	2.61	3.90	1 : 1.5	$T_{ISO,RB+D}$	natural period value of the isolation system with rubber bearings + damper
T_{LS}	0.98	1.06	1 : 1.1	T_{LS}	natural period value of the lower structure, considered as a standalone, fixed-base structure
k_{US}	9.76	0.39	24.7 : 1	k_{US}	global stiffness parameter of the upper structure
$k_{ISO,RB}$ (GN/m)	0.053	0.081	1 : 1.5	$k_{ISO,RB}$	global stiffness parameter of the isolation system with rubber bearings
$k_{ISO,RB+D}$	0.087	0.134	1 : 1.5	$k_{ISO,RB+D}$	global stiffness parameter of the isolation system with rubber bearings + damper
k_{LS}	2.23	0.84	2.6 : 1	k_{LS}	global stiffness parameter of the lower structure

Table 2. Mass, Natural Period and Stiffness values; comparison between IB and SSB

The structural horizontal stiffness at each level is represented by an equivalent linear shear spring, while the stiffness of the isolation interface is represented by means of two springs working in parallel: an equivalent linear elastic spring, which describes the global behavior of the rubber bearings, and an elastic-plastic spring with bilinear restoring force characteristics, which represents the total contribution of the hysteretic dampers. In the MDOF models, viscous damping equal to 2% is assumed in the upper and lower structures, while at the seismic isolation interface, no viscous damping is considered, since the major source of dissipation is given by the hysteretic response of the lead and steel units, explicitly accounted for by means of the bilinear force-displacement model.

Assumptions

Some assumptions have been made in the simplified calculation of the global values of the stiffness parameters (see Table 2). The global stiffness of the upper strutures (US) and lower structures (LS), i.e., k_{US} and k_{LS}, are defined by combining in series the shear stiffness of the relevant floors; the results are then compared to the ones derived from the equivalent single-lumped mass (SDOF) models for the LS and the US, showing close values. Concerning the isolation system, $k_{ISO,RB}$ is the global stiffness given by the rubber bearings, while $k_{ISO,RB+D}$ is the secant stiffness given by the combination of rubber bearings only and dampers at the design displacement, respectively equal to 40 centimeters for the IB and 50 centimeters for the SSB. Analogously, two values of the isolation period are reported, namely $(T_{ISO,RB})$ and $(T_{ISO,RB+D})$, both derived considering a SDOF model, with mass equal to $m_{US} + m_{ISO}$, and stiffness given by $k_{ISO,RB}$ and $k_{ISO,RB+D}$ respectively.

The values provided in Table 2 permit an approximate guess of, and a preliminary discussion on the dynamic properties of the three structural parts of each building, and, consequently, on their expected dynamic interaction. In addition, a straightforward comparison between the anticipated
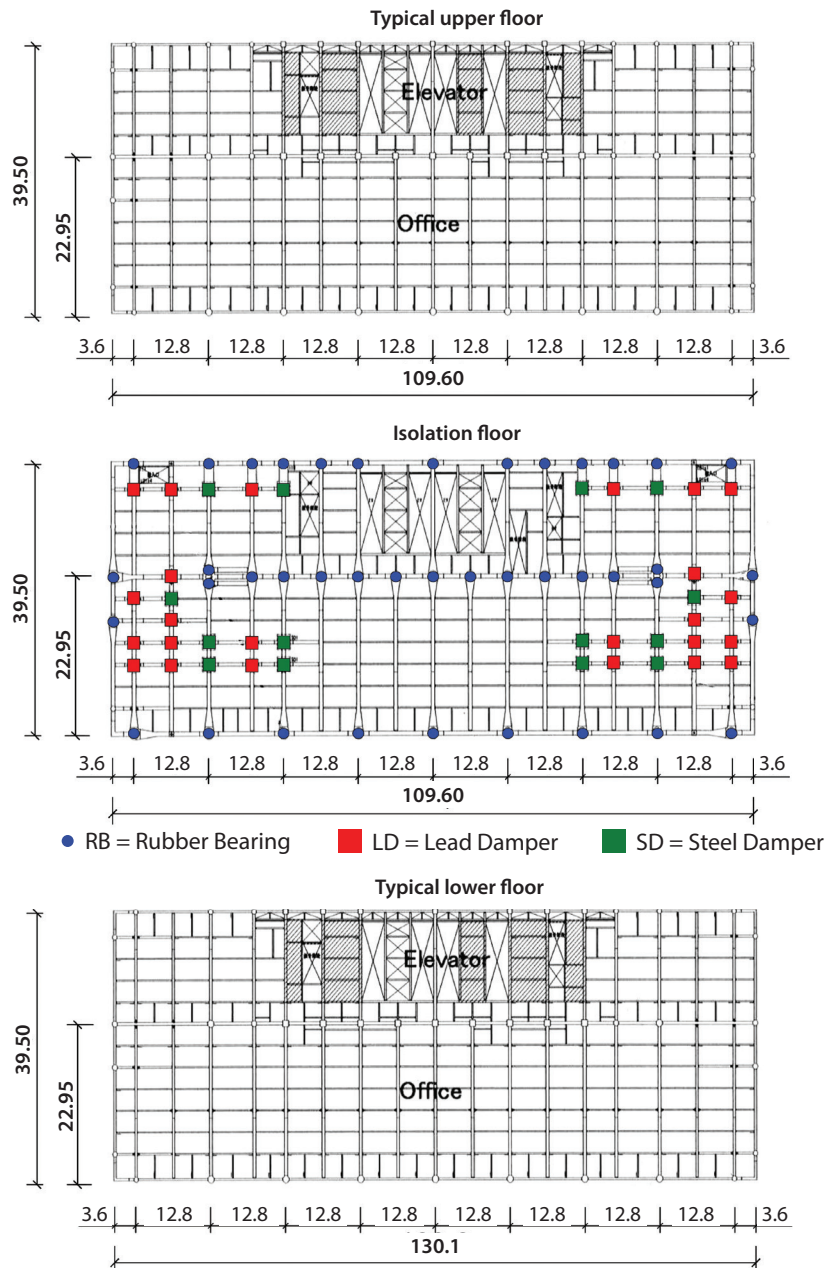

Figure 4. Shiodome Sumitomo Building, Tokyo – floor plans (SSB). Source: Sueoka, 2004.

66 An Inter-Story Isolation System (IIS) is an advantageous solution for mixed-use buildings, in which different occupancies along the elevation give rise to different architectural plans and structural grid layouts. 99
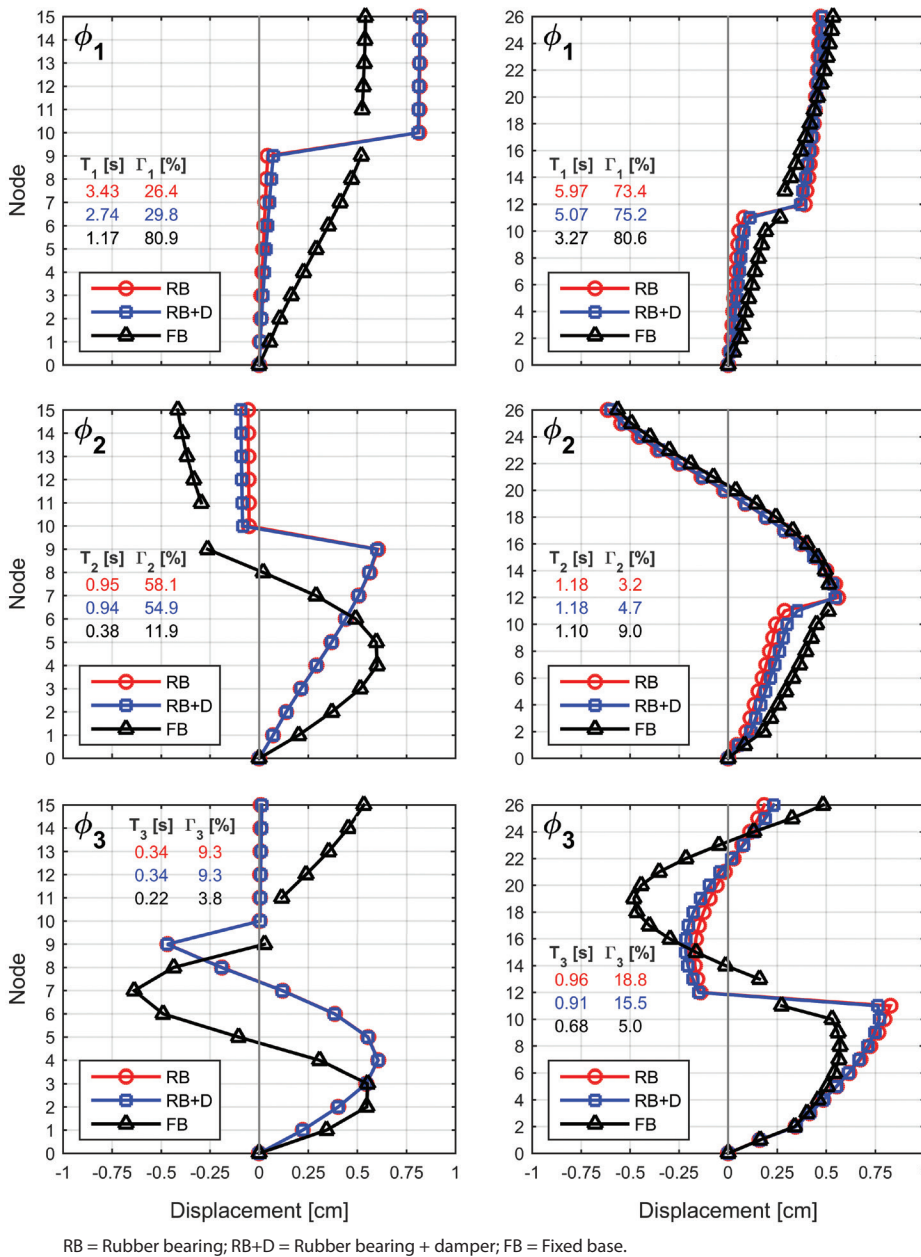
RB = Rubber bearing; RB+D = Rubber bearing + damper; FB = Fixed base.

Figure 5. Vibration modes: IB (left) and SSB (right)

base structure (T_{FB}, neglecting the presence of the isolation layer) is 40% shorter than its SSB counterpart.

Looking at the isolation system in the two buildings, very similar mass values can be observed. The global stiffness given by the isolators only ($k_{ISO,RB}$) and by the combination of isolators and dampers ($k_{ISO,RB+D}$) in the SSB, are respectively 1.5 and 1.6 times larger than in IB, while the yield shear coefficient $\alpha_s{}'$ is equal to 2% for IB, and 3% for SSB. However, as the upper part of SSB is approximately 4.4 times heavier than its IB counterpart, the isolation period values ($T_{ISO,RB}$) and ($T_{ISO,RB+D}$) are much longer for SSB than IB, namely 5.02 vs. 3.33 seconds, and 3.90 vs. 2.61 seconds.

Modal Analysis

Modal analyses are carried out on the MDOF models (RB, RB+D, and FB) of the two buildings; in the following, the main results are reported and discussed. The first three natural vibration modes obtained for the MDOF models of the IB and SSB are depicted in Figure 5. The three graphs on the left refer to the results obtained for the IB, while the ones on the right refer to SSB; the values of periods and participating mass ratios are also provided in the single charts. A first consideration is that the RB+D models provide results very similar to the RB counterparts, with almost overlapping displacement distributions for both buildings in the three modes, and close values of natural periods.

The first modal shape for both buildings represents the first mode of the US isolated at the base, with the LS contributing somewhat to the deformation mode. Also, for both buildings the first period $T_{1,RB}$ is nearly coincident with the SDOF isolation period $T_{ISO,RB}$, and the participating mass ratio, Γ_1 is very close to the ratio $(m_{US}+m_{ISO})/M_{TOT.}$

Some differences arise across higher modes: the second and third modes of the IB RB model are representative of the first and second mode of the LS (considered as a

dynamic behavior of the two buildings is possible.

Results

The IB and SSB buildings, despite being different heights (63.2 vs. 126 meters, respectively), have similar total mass (the SSB is only 10% greater). A large atrium in the LS covers about 40 meters' height and approximately 50% of the plan area. On the basis of both mass and stiffness comparison, the US of the IB is lighter and more rigid than the US in the SSB; in fact, as a standalone structure, IB's superstructure has a natural period 10 times shorter than SSB's (0.21 vs. 2.18 seconds). The IB LS is heavier and more rigid than the SSB LS, but the ratio between the mass and the stiffness are quite similar, so the natural period of the two substructures is comparable (0.98 vs. 1.06 seconds), with a scatter of 8%. Globally, IB is slightly lighter (10%) and much more rigid than SSB; thus, the first natural period of the IB overall structure, considered as a fixed-

standalone fixed-base structure), with almost no deformation in the US. On the contrary, the second and third modes obtained for the SSB RB model involve displacements both in the US and LS, thus suggesting higher mode coupling, which can produce an undesirable amplification effect in the seismic response of the structure. This mode coupling effect (MCE) has been addressed in the literature (Wang et al. 2011, 2012, 2013; Kobayashi & Koh 2008). The authors, recognizing that the global dynamic behavior of a mid-story isolated structure depends on the vibration characteristics of the US and LS, have recently investigated the MCE through parametric analysis and analytical formulations. The results can be summarized as follows: no MCE arises if all higher mode periods of the base-isolated US (i.e., the US as a standalone structure isolated at the base), are far from all periods of the fixed-base LS (i.e., the LS as a standalone structure conventionally fixed at the base). In particular, the largest MCE occurs when the first period of the fixed-base LS is close to either the second or the third period of the base-isolated US.

Time History Analyses

In order to assess the response of the IB and SBB buildings under seismic inputs, the MDOF RB, RB+D and FB models have been utilized for carrying out time history analyses. The RB+D models fully account for the nonlinear behavior of the isolation devices and dampers, while both the US and LS are considered elastic. The seismic waves considered for the analyses are obtained from three ground motion records, El Centro S00E (PGA = 0.457 g), TaftS69E (PGA = 0.343 g) and Hachinohe NS (PGA = 0.515 g), scaled in order to set the maximum velocity to the target value of 50 cm/s, as specified by the Japanese seismic code.

Peak displacements

The story drift envelopes obtained from the time history analyses of the three MDOF (RB, RB+D, and FB) models of the Iidabashi and Shiodome buildings are shown in Figure 6. Each graph pair refers to the results obtained

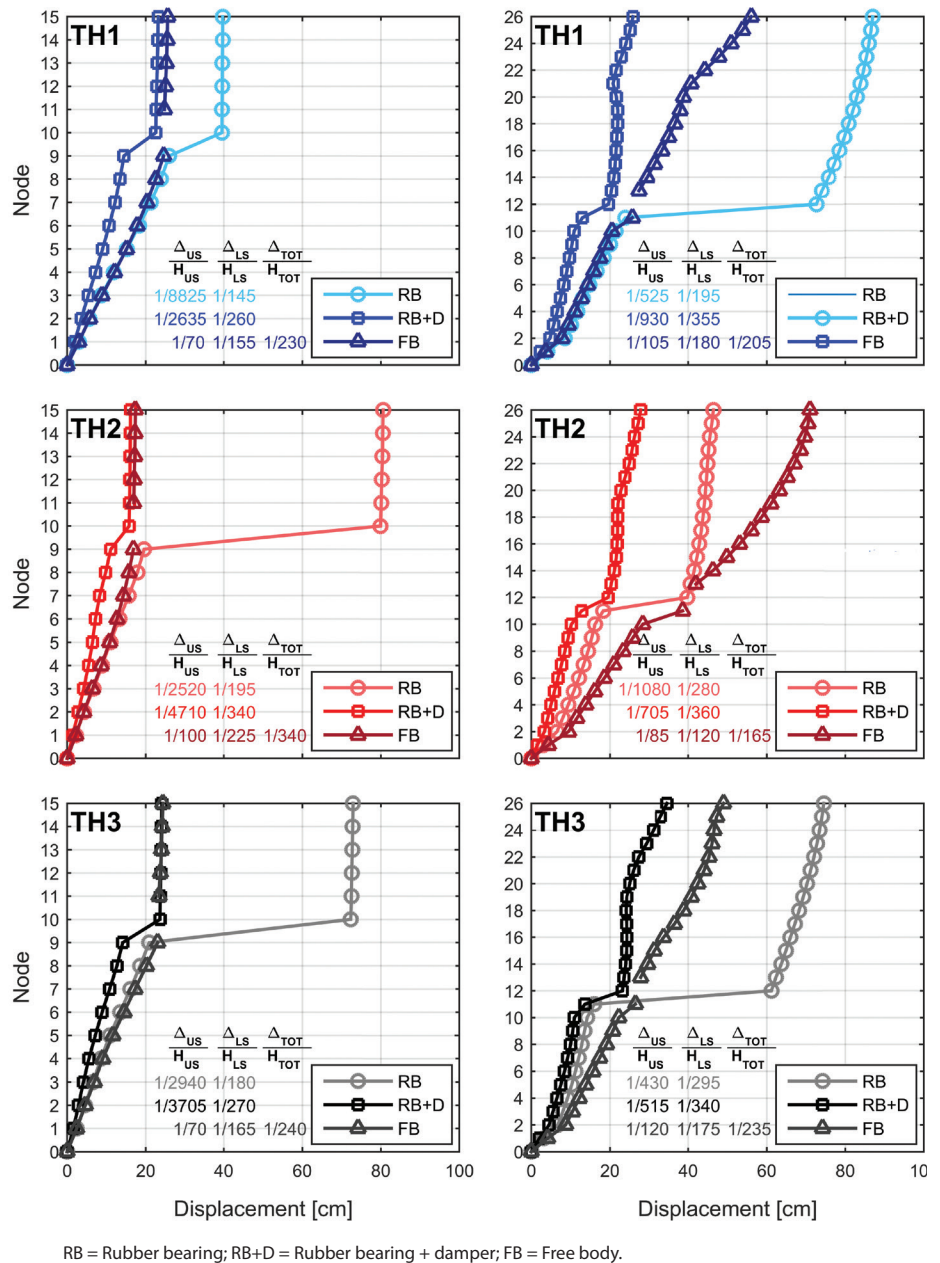RB = Rubber bearing; RB+D = Rubber bearing + damper; FB = Free body.

Figure 6. Peak story drift envelopes: IB (left) and SSB (right)

for the two building models, subjected to a specific seismic input.

In general, looking at the displacement envelopes, both the isolation and the mass damper effects can be clearly observed for the two buildings. Considering the RB models, in which the isolation layer is represented by the isolators only, there is a reduction of the superstructure displacements with respect to the FB models (isolation effect). In the RB+D models, where

both isolators and dampers are considered at the isolation layer, a general reduction of the displacements throughout the building elevations, and in particular for the substructures (mass damper effect), can be observed with respect to the RB and FB models.

In order to compare the displacements of the upper and lower structures in the three models, the relative displacements are normalized to the partial heights. The ratio between the relative top-to-bottom drift of
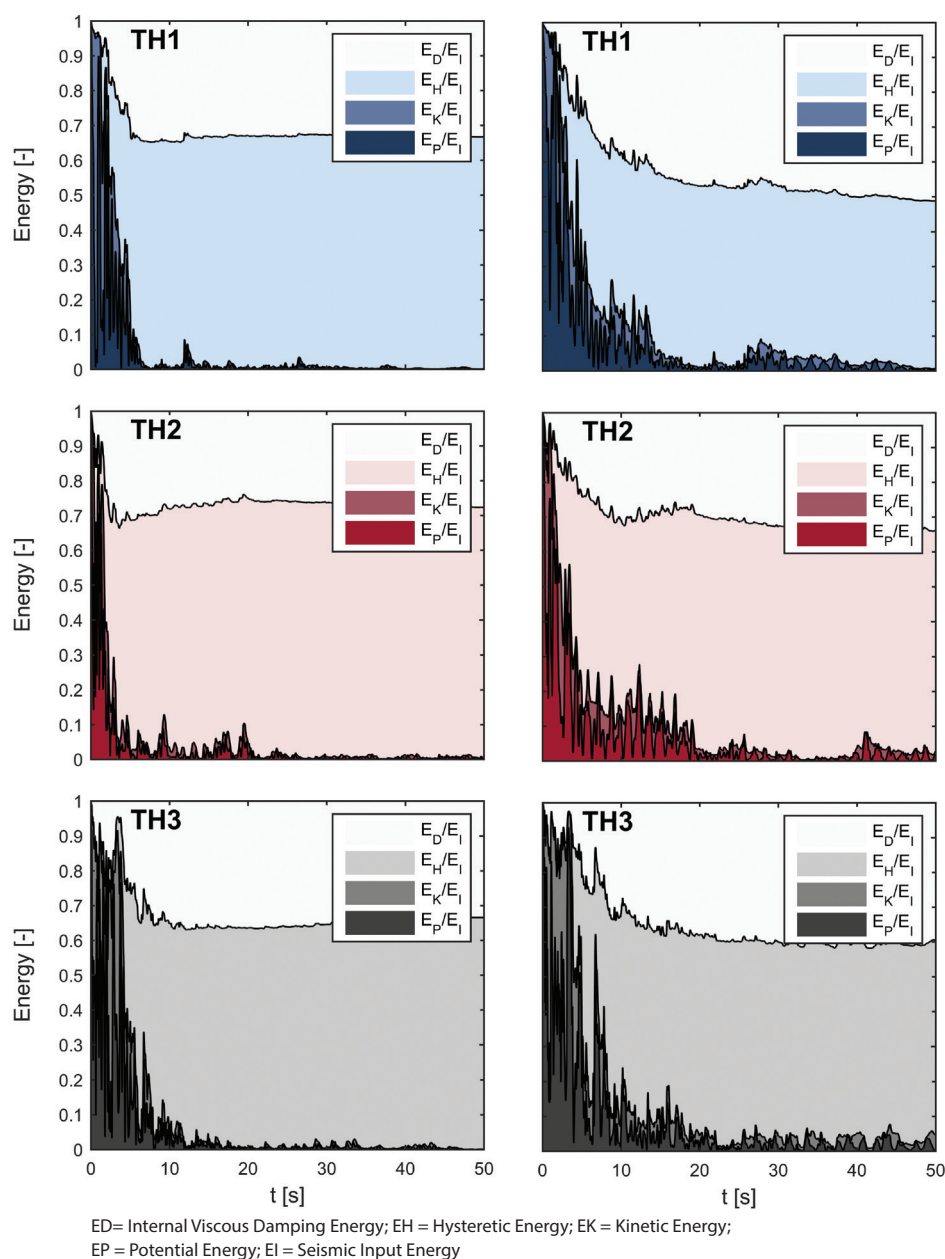
ED = Internal Viscous Damping Energy; EH = Hysteretic Energy; EK = Kinetic Energy;
EP = Potential Energy; EI = Seismic Input Energy

Figure 7. Time histories of energy distribution: IB (left) and SSB (right)

> **"The inter-story isolation system can be seen as a "concentrated type" of energy dissipation system, which differs from the common design approach of distributed energy-dissipation systems, where the dampers are spread throughout the building structure."**

the US (neglecting the displacement of the isolation system) and the US height, $\Delta_{TOP,US}/H_{US}$; and the ratio of LS top drift to LS height, $\Delta_{TOP,LS}/H_{LS}$, are shown. These are joined by the values obtained for the fixed base structures, considering either only the degrees of freedom of the US and of the LS, or the whole structure.

Looking at the values, it is also possible to grossly quantify both the isolation and the mass damper effects that occur in the buildings. In particular, the values $\Delta_{TOP,US}/H_{US}$ show that the presence of isolators (RB models) produces a reduction of the displacement in the US, with respect to the FB model, of about two orders of magnitude in the IB, and of one order of magnitude in the SSB. Then, the presence of dampers (RB+D models) slightly modifies the US displacements, and, more remarkably, gives rise to the so-called mass-damper effect, which mainly acts on the LS. This effect can also be grossly quantified by comparing the RB and RB+D models in terms of $\Delta_{TOP,LS}/H_{LS}$. The comparison, in the IB, reveals a reduction (from RB to RB+D models) of 80% for El Centro and of 50% for Taft. In the SSB, the behavior under El Centro is almost the same as the IB, and the displacement ratio $\Delta_{TOP,LS}/H_{LS}$ in the RB+D model decreases 80% with respect to the RB model. Conversely, a lower mass-damper effect can be observed for the other two seismic waves, since the displacement ratios $\Delta_{TOP,LS}/H_{LS}$ decrease from the RB to the RB+D model of 30% and 15% respectively for Hachinohe and Taft ground motions.

Of course, the presence of dampers (RB+D models) dramatically decreases the displacement of the isolation layer in both buildings: over 90% at IB, (Hachinohe case), and over 80% at SSB, (Taft case).

These results confirm the preliminary general considerations provided in Figure 7, the IB US is lighter and more rigid than the SSB US. Therefore, the isolation is more effective in reducing the US displacements. The IB LS is heavier and more rigid than SSB LS, yet the ratio between the mass and the stiffness are quite similar; therefore, the reduction of the

LS displacements is nearly or slightly greater in IB as compared to SSB, depending on the seismic input.

Energy components distribution

The distributions of the energy components obtained from the analyses of the RB+D models of the buildings are shown in Figure 7. In each graph are provided the time histories of the Potential Energy E_p, Kinetic Energy E_k, Hysteretic Energy E_h, and Internal Viscous Damping Energy E_d, all normalized to the seismic input energy E_i. Each graph pair refers to the results obtained for the buildings model's (IB and SSB) subjected to a specific seismic input (El Centro, Taft, or Hachinohe).

In both buildings, a large amount of the seismic input energy is dissipated through the hysteretic response of the dampers within the isolation system; the share of hysteretic energy is between 67% and 73% for the IB and between 50% and 67% in the SSB.

This distribution confirms that the inter-story isolation system can be seen as a "concentrated type" of energy dissipation system, which differs from the common design approach of distributed energy-dissipation systems, where the dampers are spread throughout the building structure.

Conclusions

The analysis of the buildings and the examination of their vibration characteristics has proved particularly interesting, since the selected case studies are very different from each other. IB is a paradigmatic example of building with inter-story isolation, with a very rigid superstructure, and frequencies of the two structural parts (upper and lower structure) are well separated from the isolation frequency, which gives rise to uncoupled higher modes. SSB is not an ideal case of IIS, with the upper structure being less rigid than the lower one, and both structural portions are quite flexible; thus, frequency ratios are not so high as to ensure decoupling of higher modes. However, the seismic response of both buildings, assessed through nonlinear time history analyses, appears very

satisfactory. The beneficial effects of isolation, dissipation, and consequent mass damping have been clearly identified, by accounting for isolators alone and for isolators and dampers combined; and by comparing the responses to reference fixed-base structures.

The peculiarity of the inter-story isolation system, and its greater design complexity with respect to base isolation, seems to come from the combination of isolation, dissipation, and mass damping. In fact, depending on the values of mass ratios, frequency ratios and dampers' yielding force, any of the above aspects may equally and effectively contribute to the structural response, or one behavioral aspect may prevail. From this perspective, the isolators have the most important role. They lengthen the first period of the structural complex, work as a distinctive "amplification system" for the energy dissipation devices concentrated at the isolation level, and allow the upper structure to move out of phase with respect to the lower one. ∎

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