The mass-reduction design concept utilizing frictional isolators

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Outline

- Introduction
- Equations of motion
- Strong motion records
- Investigation of a five-story structure with:
  - floating slabs on all floors
  - two consecutive floating slabs
  - two floating slabs separated by a single conventional floor
- Conclusions

Introduction

- Relatively stiff structures of small or medium height, with fundamental eigenperiod up to ~0.5*s*, are particularly susceptible to seismic excitations due to their common frequency content.
- As a result, the accelerations are increased, and through mass, the corresponding seismic forces are also increased in the superstructure.
- In case of strong seismic motion, these forces cannot be handled without the inelastic response of the structure. This entails damage in both the structure and its contents.
- Even if the stiffness and strength were such to ensure elastic response without damage of the structure , the accelerations would be enormous and the content would be severely damaged.

Introduction

- The classic design philosophy of structures, namely the conventional design, has been widely used around the globe and has been implemented in design codes since the 1940s.
- It is based on the plasticity of a structure so that it can sustain repeated cycles of inelastic deformation, without collapse and human fatalities.
- In case of strong seismic motion, however, it allows damage to the structural elements, as well as the contents of the structure. In certain cases, the damage may be so severe that the repair of the structure is not preferable to demolition.

Conventional design

$$\mathbf{K u} + \mathbf{C}\dot{\mathbf{u}} = -\mathbf{M}\left(\ddot{\mathbf{u}} + \ddot{\mathbf{u}}_g\right)$$

Introduction

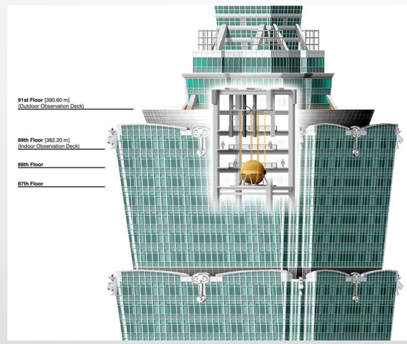
- A second category of seismic protection methods, or seismic mitigation methods, refers to energy dissipation devices such as Fluid Viscous Dampers (FVDs), Friction Devices, Steel Yielding Devices etc. In this category fall the Tuned Mass Dampers (TMDs).
- A TMD, sometimes referred to as a dynamic vibration absorber, is a classical engineering device consisting of a mass, a spring and a viscous damper.
- The basic principal of the TMD is the mitigation of the dynamic response of the system through energy transfer. A significant portion of the vibration energy of the structure is transferred to the mass of the device and then dissipated through the damper.

Supplemental Energy Dissipation Systems & Tuned Mass Dampers (TMDs)

$$\mathbf{Ku} + \mathbf{C\dot{u}} = -\mathbf{M}(\mathbf{\ddot{u}} + \mathbf{\ddot{u}_g})$$

Introduction

- Probably the first implementation of a TMD, in the form of internal open-surface tuned liquid dampers (TLD) to mitigate the roll of sea vessels, was proposed as early as 1883 by Watts.
- A contemporary example is Taipei 101 Tower, Taiwan:



(Steel sphere with a diameter of 5.5 m and a mass of 660 ton, suspended from the 92º floor and reaching down to the 87º floor).

Supplemental Energy Dissipation Systems & Tuned Mass Dampers (TMDs)

$$\mathbf{Ku} + \mathbf{C\dot{u}} = -\mathbf{M}\,(\mathbf{\ddot{u}} + \mathbf{\ddot{u}_g})$$

Introduction

- The third structural design approach utilizes the inertial term of the equation of motion. In this category fall the structural control methods, as well as the inerter devices.
- In this category also falls the seismic base isolation, where the superstructure is isolated from its foundation by means of flexible elements. The aim is to reduce the seismic forces imposed to the structure, rather than increase its bearing capacity. The method is well known from the ancient times:
  - In the Greek city-states of modern-day southern Italy, during construction a layer of sand was placed between the foundation and the superstructure (5th century BC).
  - The Mausoleum of Cyrus the Great in Pasargadae was built on top of six layers of smoothed blocks of stones (circa 550 BC).

Introduction

- The reduction of seismic forces is achieved by increasing the rigid body mode period of the isolated structure so that the spectral acceleration becomes small.
- As a result both the total acceleration of the floors and their relative drift are significantly reduced.
- The large deformations are confined within the bearings, which are designed accordingly.

Base isolation

$$\mathbf{K}\mathbf{u} + \mathbf{C}\dot{\mathbf{u}} = -\mathbf{M}\left(\ddot{\mathbf{u}} + \ddot{\mathbf{u}}_g\right)$$

Introduction

- Base isolation offers important advantages but is no panacea.
  - Base isolation is straightforward in new structures, not so in existing ones.
  - It is not suitable for limited plan space within an urban environment because of the bearing deformations.
  - It is applicable to low- to medium-rise buildings, as tall buildings already have large fundamental period of vibration by nature.
  - In general, the optimum value of the isolation period is 2–4s. Higher values are rarely used, as they have significant drawbacks due to the reduced stiffness of the bearings, i.e., large displacements and unwanted wind-induced movement.

Introduction

- Recently(*), the use of floating slabs, i.e. slabs that are detached from the skeleton of low- or high-rise buildings on certain, or even all of their floors, have been investigated as means of both structural control and mass damping. This approach has been termed “mass-reduction design concept”.
- The behavior of floating slabs is depended on the selected period of vibration, which is subject to design. In particular:
  - For short periods, close to the fundamental period of vibration of the whole structure, the floating slabs act as tuned mass dampers, with the additional advantage of the very large (and already existing) mass.
  - For long periods (>1.5 s), the floating slabs lead to the reduction of the effective seismic mass, with beneficial effect for the overall response.

(*) Charalampakis, A. E., Tsiatas, G. C., Tsopelas, P., “A mass-reduction design concept for seismic hazard mitigation”, Earthquake Engineering & Structural Dynamics, 49(3) (2020): 301–314, doi: 10.1002/eqe.3239

Introduction

- In this work, the implementation of the mass-reduction design concept through the use of frictional isolators is investigated. The previous work is extended in the following ways:
  - A nonlinear velocity-dependent frictional law is adopted for the modeling of the sliding isolators. Four different cases of friction, which are derived from actual experimental data, are assessed for their performance in a five-story building.
  - The set of motion records adopted in the present work is much stronger on average than those in Charalampakis et al. (2020).
  - Several structural configurations of floating slabs placed along the height of the structure are examined.
  - Design recommendations are given regarding the optimal placement of the floating slabs in the structure.

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Equations of motion

- A five-story shear building is tested against strong earthquake motions.
- The coefficient of friction μ_s is a function of the sliding velocity $\dot{u}$, and is typically approximated by the exponential relation proposed by Constantinou and Mokha (1989):

$$\mu_s = \mu_{fast} - \left(\mu_{fast} - \mu_{slow}\right)\exp(-a|\dot{u}|) \qquad (1)$$

where μ_{slow} and μ_{fast} are the values of the friction coefficient for almost zero ($|\dot{u}| \rightarrow 0$) and large velocity ($|\dot{u}| \rightarrow \infty$), respectively.

Equations of motion

- Friction parameters and material types

Experimental study	Friction case	Material Type	μ_{slow}	μ_{fast}	a (s/mm)
Tsopelas et al. (Tsopelas et al. 1996)	I	PTFE-based composite typically used in FPS bearings (No. 1)	0.040	0.104	0.834
	II	High bearing capacity and low wear composite (No. 2)	0.058	0.058	-
Fenz & Constantinou (Fenz and Constantinou 2008)	III	Lubricated PTFE composite low friction material (Double 1)	0.0093	0.03	0.015
	IV	Lubricated PTFE composite intermediate friction material (Double 2)	0.07	0.14	0.0079

Equations of motion

- A Bouc-Wen-type hysteretic model is employed to estimate the restoring force of the friction isolator:

$$F_{IS}(t) = \mu_s W z(t) \quad (2)$$

- where W is the load carried by the sliding interface and $z(t)$ is a dimensionless hysteretic variable which is governed by the following differential equation:

$$\dot{z} = D^{-1}(1 - (\beta \,\mathrm{sgn}(z\dot{x}) + \gamma)|z|^n)\dot{x} \quad (3)$$

- where, $\dot{x}(t)$ is the sliding velocity, $D = 0.005$ is the yield displacement, $n = 2$ is the exponential parameter controlling the transition between pre- and post-yield response, and $sgn(\cdot)$ is the signum function.
- The dimensionless parameters $\beta = 0.9$, and $\gamma = 0.1$ control the shape and size of the hysteretic loop.
- Variable z takes values in the range $[-1,1]$, with ± 1 meaning full yield in the positive/negative direction.

Equations of motion

- The equations of motion for the skeleton:

$$m_1\ddot{u}_1 + (k_1 + k_2)u_1 - k_2 u_2 + (c_1 + c_2)\dot{u}_1 - c_2\dot{u}_2 - F_{IS1} = -m_1\ddot{u}_g \quad (4)$$

$$m_2\ddot{u}_2 - k_2 u_1 + (k_2 + k_3)u_2 - k_3 u_3 - c_2\dot{u}_1 + (c_2 + c_3)\dot{u}_2 - c_3\dot{u}_3 - F_{IS} = -m_2\ddot{u}_g \quad (5)$$

$$m_3\ddot{u}_3 - k_3 u_2 + (k_3 + k_4)u_3 - k_4 u_4 - c_3\dot{u}_2 + (c_3 + c_4)\dot{u}_3 - c_4\dot{u}_4 - F_{IS3} = -m_3\ddot{u}_g \quad (6)$$

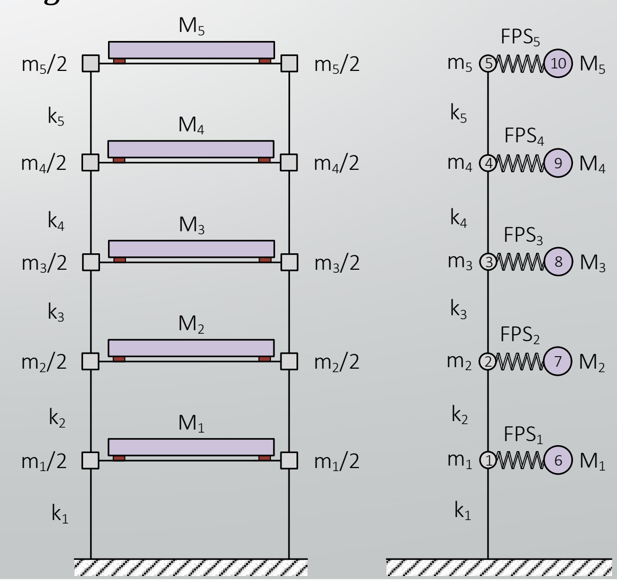
$$m_4\ddot{u}_4 - k_4 u_3 + (k_4 + k_5)u_4 - k_5 u_5 - c_4\dot{u}_3 + (c_4 + c_5)\dot{u}_4 - c_5\dot{u}_5 - F_{IS} = -m_4\ddot{u}_g \quad (7)$$

$$m_5\ddot{u}_5 + k_5(u_5 - u_4) + c_5(\dot{u}_5 - \dot{u}_4) - F_{IS} = -m_5\ddot{u}_g \quad (8)$$

- The equations of motion for the floating slabs:

$$M_i\ddot{u}_{i+5} + F_{IS} = -M_i\ddot{u}_g \quad (9)$$

where M_i, m_i, k_i, $c_i = 2\xi(k_i m_i)^{1/2}$, u_i are the slab mass, node mass, stiffness, damping, and lateral displacement of the i^{th} story of the building ($i = 1,2,\dots,5$), and $\xi = 5\%$ is the damping ratio.



Equations of motion

- The restoring forces of the FPS isolators take the form:

$$F_{ISi}(t) = \frac{W_i}{R_i}(u_{i+5} - u_i) + \mu_{si} W_i z_i(t) \quad (10)$$

where $W_i = M_i g$, R_i $(i = 1,2,\ldots,5)$ are the effective radii and

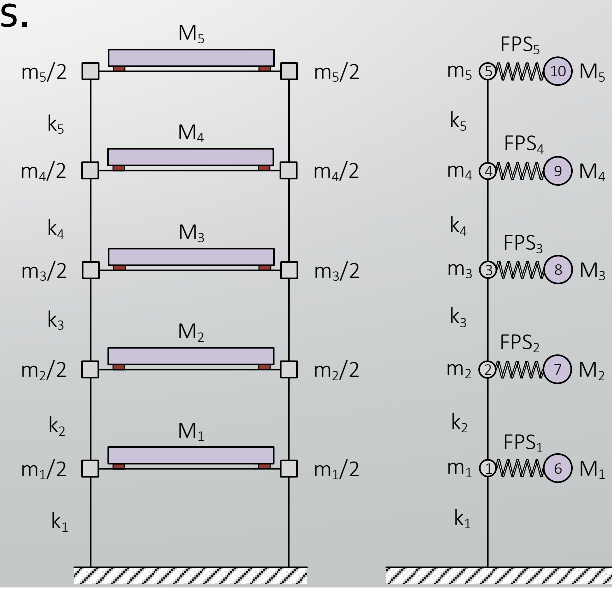
$$\mu_s = \mu_{fast} - (\mu_{fast} - \mu_{slow})\exp(-a|\dot{u}_{i+5} - \dot{u}_i|) \quad (11)$$

are the friction coefficients of the spherical sliding surfaces.

- Finally, $z_i(t)$ $(i = 1,2,\ldots,5)$ are dimensionless hysteretic variables that are governed by the following differential equation:

$$\dot{z} = D^{-1}(1 - (\beta\,\mathrm{sgn}(z\dot{x}) + \gamma)|z|^n)\dot{x} \quad (12)$$

with $\dot{x}_i = \dot{u}_{i+5} - \dot{u}_i$.



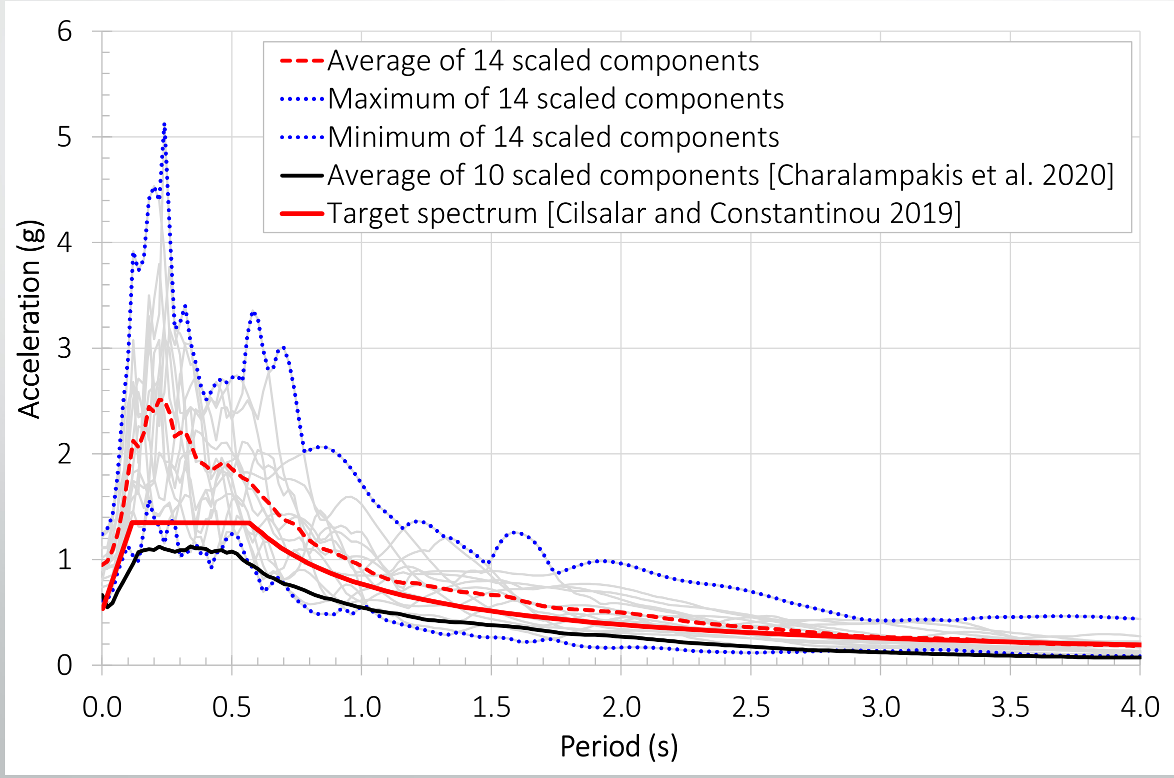
Strong motion records

- Seven pairs of scaled acceleration time histories from seven actual earthquakes with magnitudes larger than 6.7 and the closest distance of the recording site to the rupture surface $R_{rup} > 10$ km were considered.

#	No.	Event	Year	Station	M	R_{rup} (km)	V_{s30} (m/s)	Scale factor	PGA (g)	PGV (cm/s)	PGD (cm)
01	68	San Fernando	1971	LA – Hollywood Store FF	6.61	22.77	316.46	4.10	0.92	89.00	65.22
02									0.80	69.41	52.77
03	169	Imperial Valley-06	1979	Delta	6.53	22.03	242.05	2.60	0.61	68.41	38.19
04									0.91	85.75	52.43
05	174	Imperial Valley-06	1979	El Centro Array #11	6.53	12.56	196.25	2.46	0.90	88.56	61.69
06									0.93	109.68	52.43
07	721	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.54	18.20	192.05	2.85	1.02	136.93	54.91
08									0.74	119.05	62.27
09	767	Loma Prieta	1989	Gilroy #3Array	6.93	12.82	349.85	2.22	1.24	80.56	24.05
10									0.82	100.80	53.49
11	960	Northridge-01	1994	Canyon Country – W Lost Canyon	6.69	12.44	325.6	2.35	0.95	104.25	26.46
12									1.11	96.60	34.23
13	1602	Duzce, Turkey	1999	Bolu	7.14	12.04	293.57	1.51	1.12	84.42	38.62
14									1.22	99.43	19.76

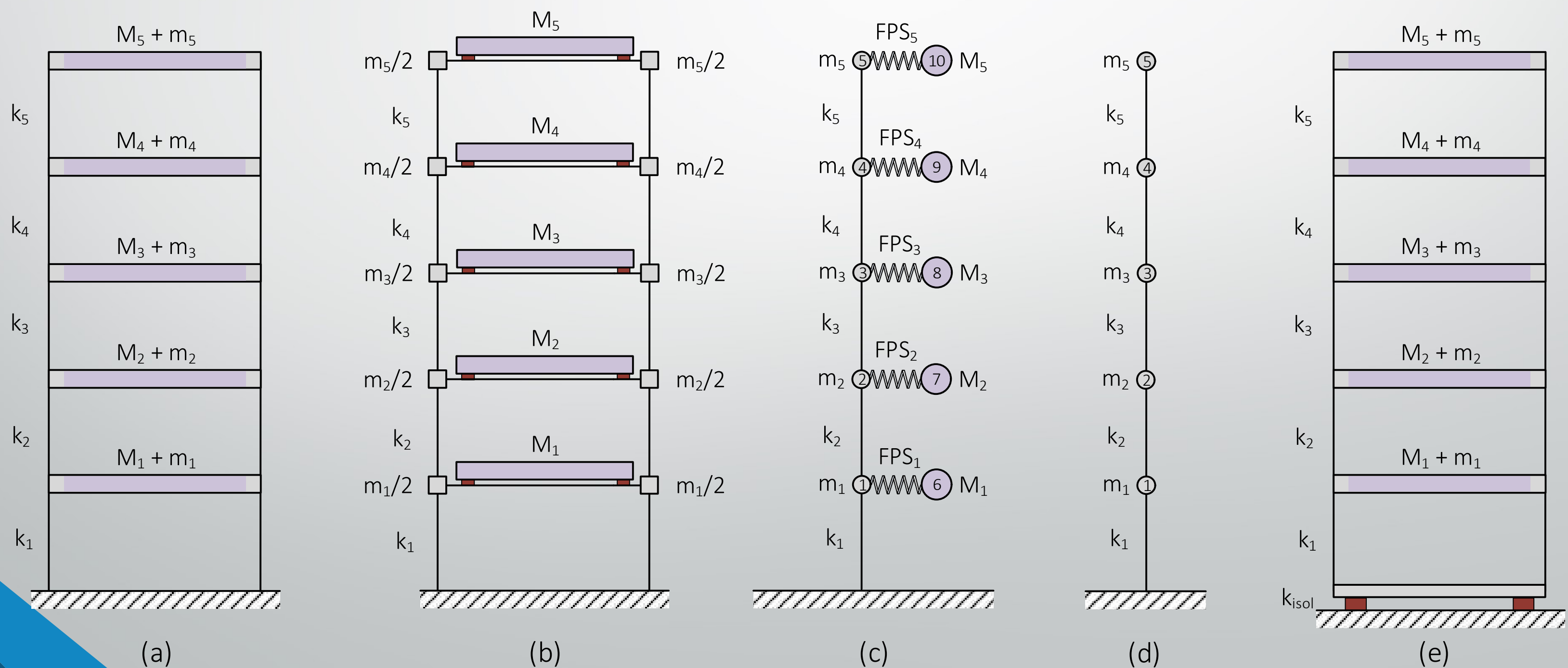
Strong motion records

- Seven pairs of scaled acceleration time histories from seven actual earthquakes with magnitudes larger than 6.7 and the closest distance of the recording site to the rupture surface $R_{rup} > 10$ km were considered.



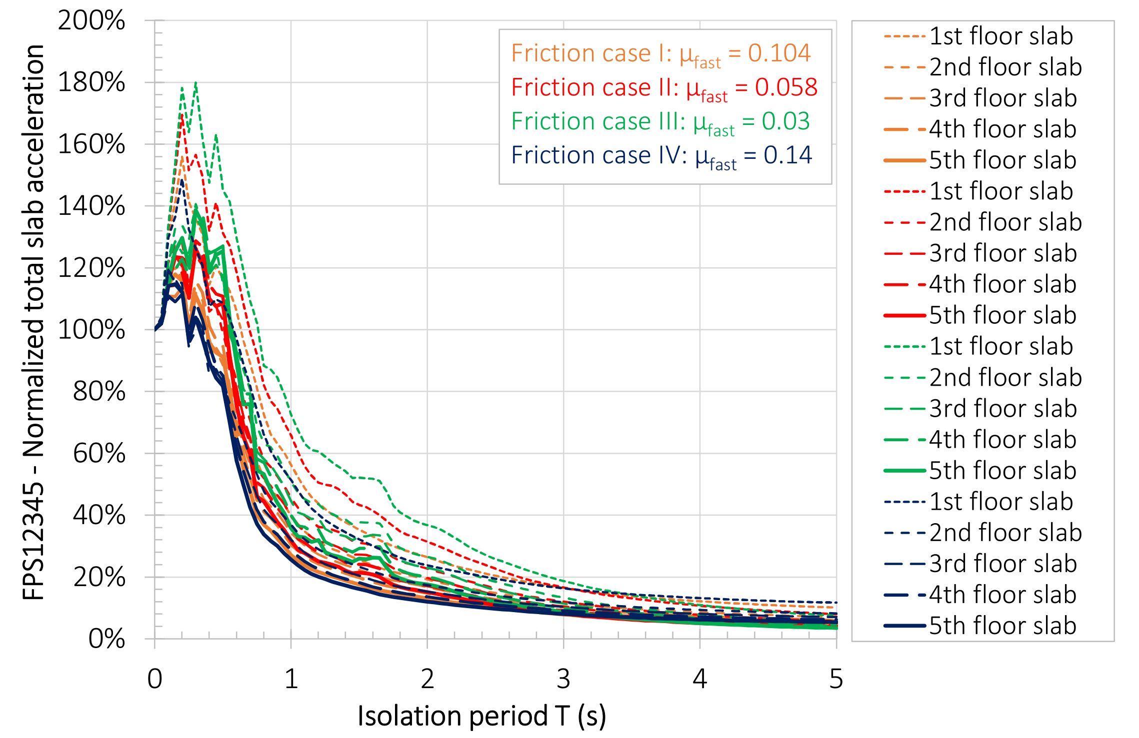
Floating slabs on all stories

- First, the structural configuration of all five slabs resting on spherical frictional isolators (FPS12345), is examined.
- All measured quantities are normalized with respect to the corresponding quantities of the conventional (elastic) structure.



Floating slabs on all stories

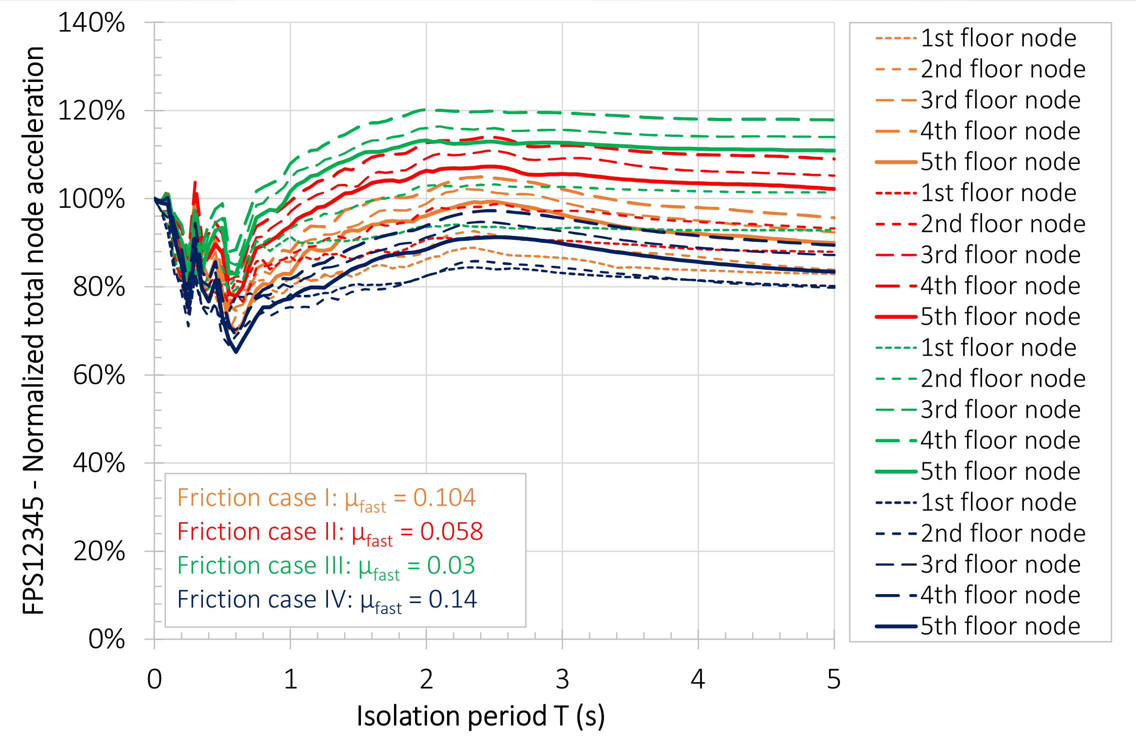
- Average of the normalized maximum total acceleration at the slabs for all four friction cases.
- For short isolation periods ($T < 0.75\ s$), the floating slabs act as mass dampers and experience large accelerations.
- For long isolation periods ($T > 2.5\ s$) the floating slabs are essentially decoupled from the skeleton (isolated).



- Values of T in the range of $0.75\ s - 2.5\ s$ might be attractive to the designer (smaller displacements). Disaggregation of the results is observed.

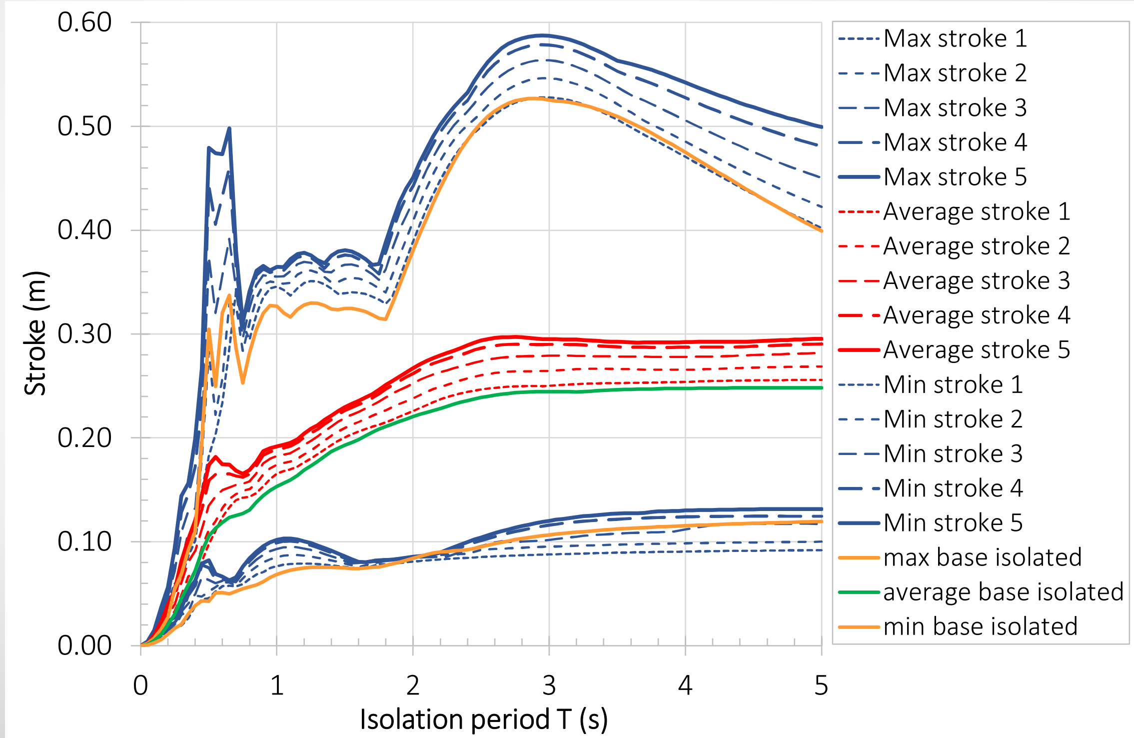
Floating slabs on all stories

- Average of the normalized maximum total acceleration at the skeleton nodes for all four friction cases.
- The accelerations are on average similar to the conventional floor accelerations (around 100%).
- The skeleton is essentially decoupled from the floating slabs and thus responds as a conventional structure with a smaller fundamental period.
- Disaggregation of the results is observed, with higher skeleton floor accelerations corresponding to smaller levels of friction.



Floating slabs on all stories

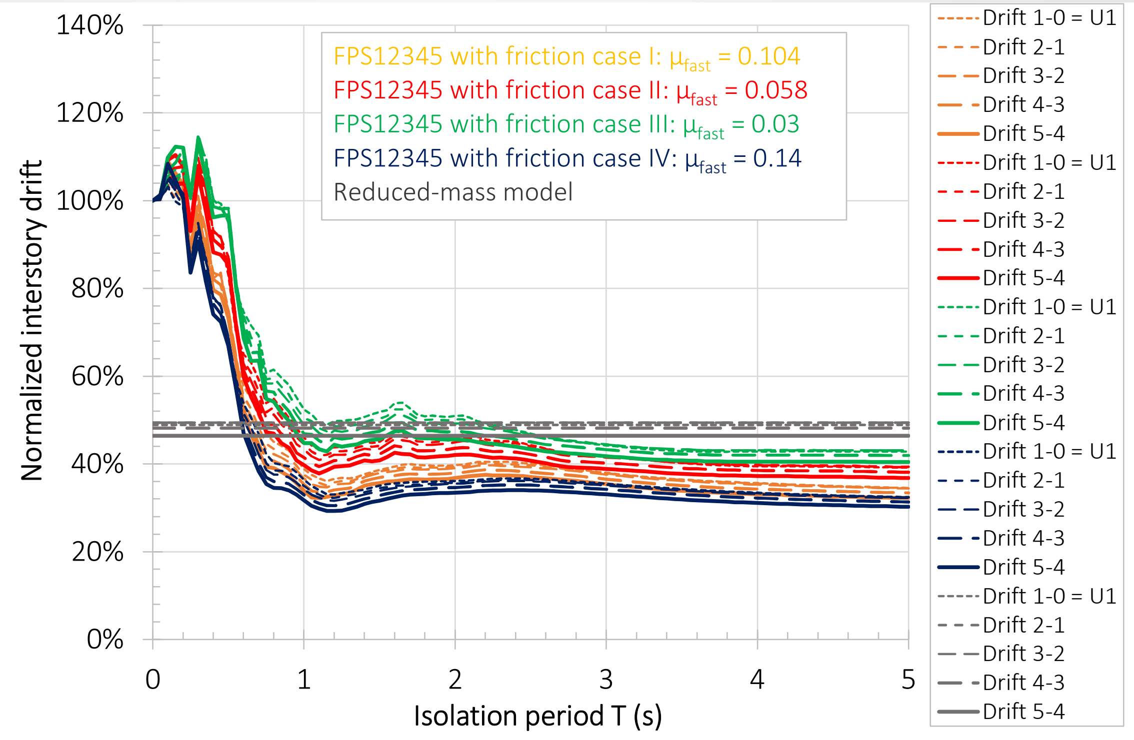
- Maximum, average, and minimum (over fourteen strong motions) of the maximum isolation stroke (FPS12345 and base isolation, both with friction case IV).
- The isolation displacements of the floating slabs are quite similar to the isolation displacement of the base in the conventional isolation design.



- The larger isolation displacements at the top floating slabs can be explained considering that each floating slab is being excited by the accelerations experienced at their floor level, which are amplified as compared to the ground acceleration.

Floating slabs on all stories

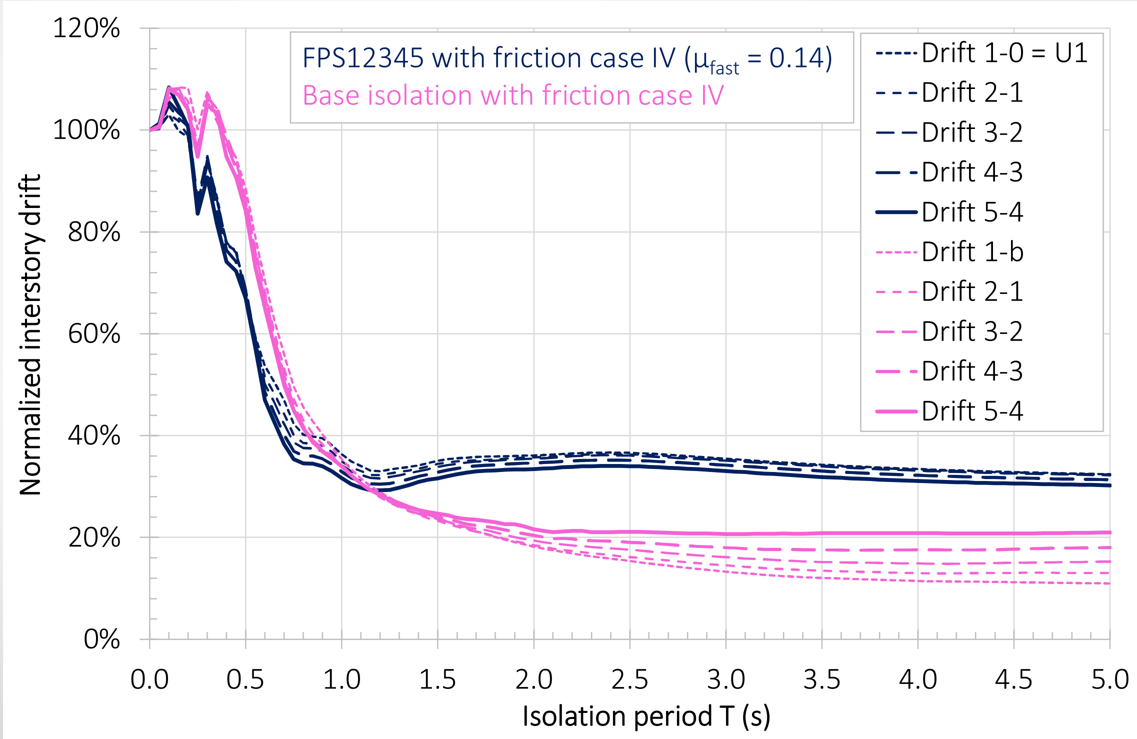
- Average of the normalized maximum interstory drifts for all four friction cases.
- The grey lines correspond to the reduced-mass model (i.e., the linear response of the structure without the masses of the floating slabs), in which the drifts of the elastic model converge.
- The FPS12345 model performs even better.



- Disaggregation of the results is observed, with large values of μ_{fast} lead to increased damping and diminished drift response of the structural skeleton.

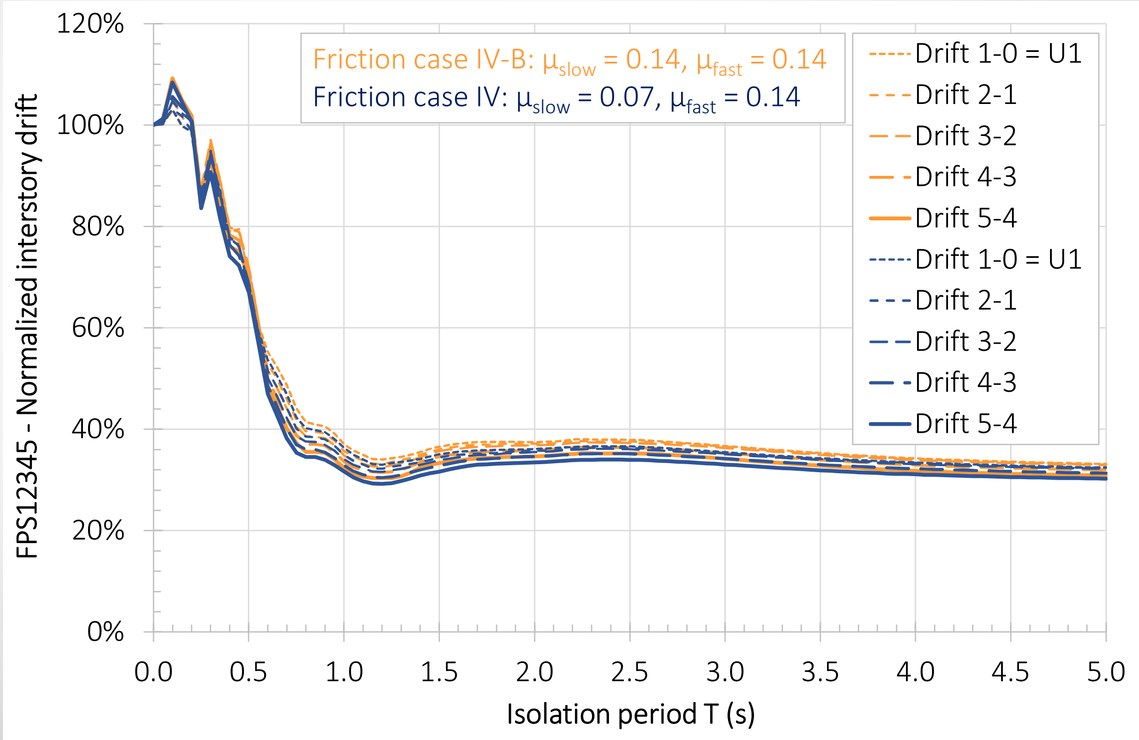
Floating slabs on all stories

- Average of the normalized maximum interstory drifts for FPS12345 and the base-isolated structure (friction case IV).
- The drifts are smaller for FPS12345 for $T < 1\ s$, while the opposite is true for longer isolation periods.
- This counter-intuitive response can be explained by the tuned mass damper action of this system in the vicinity of the fundamental period of the structure.



Floating slabs on all stories

- Average of the normalized maximum interstory drifts for FPS12345 with friction case IV and the corresponding Coulomb friction model (IV-B).
- Small differences in the response are observed.



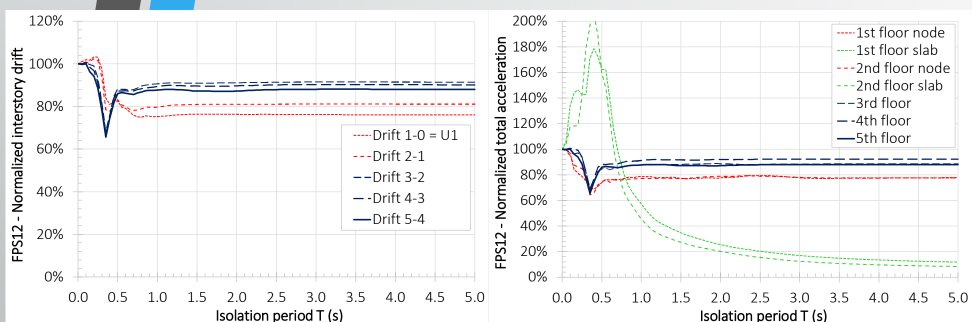
Floating slabs on two consecutive stories

- Next, four different structural configurations with floating slabs in two consecutive stories are examined:
  - FPS12 (floating slabs on floors 1 and 2),
  - FPS23 (floating slabs on floors 2 and 3),
  - FPS34 (floating slabs on floors 3 and 4), and
  - FPS45 (floating slabs on floors 4 and 5).

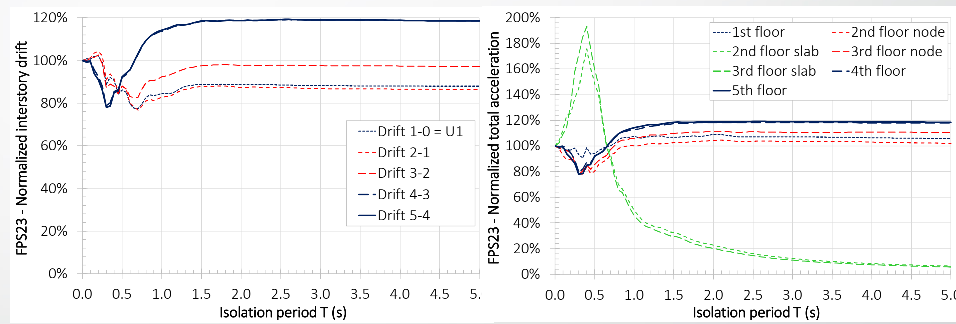
Floating slabs on two consecutive stories

- Average of the normalized maximum interstory drifts (of the skeleton nodes) and normalized total accelerations (at the slabs).

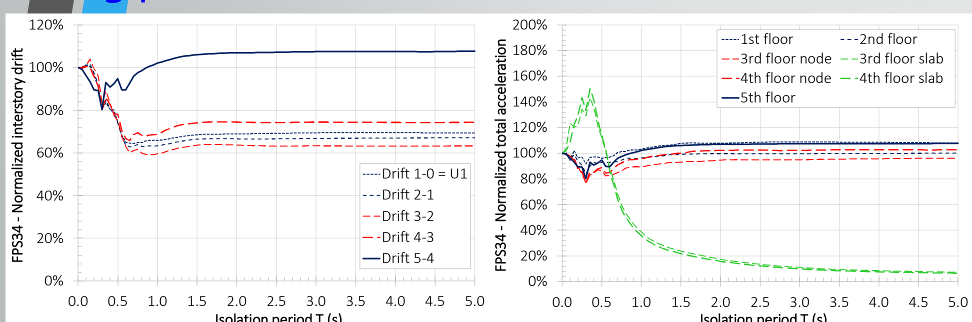
FPS12



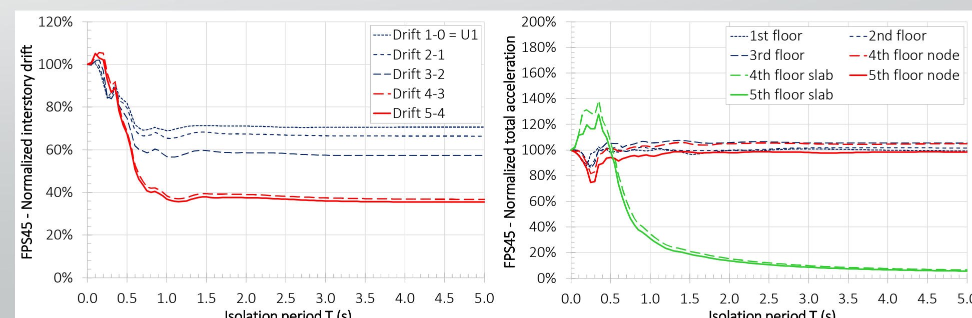
FPS23



FPS34



FPS45



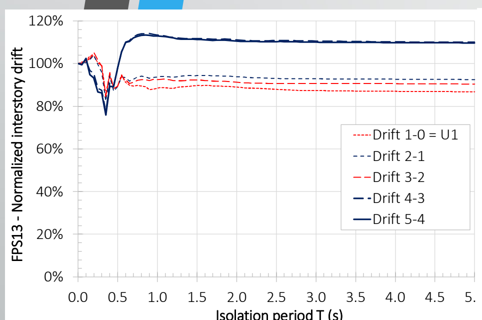
Floating slabs on two stories separated by a conventional story

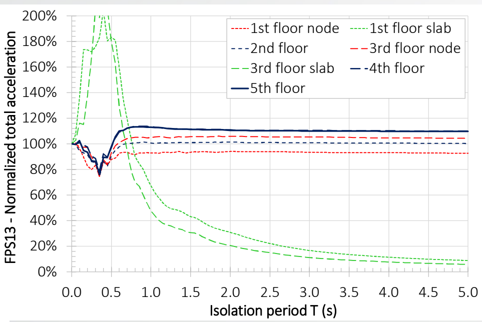
- Next, three different structural configurations with floating slabs in two stories separated by a conventional story are examined:
  - FPS13 (floating slabs on floors 1 and 3),
  - FPS24 (floating slabs on floors 2 and 4), and
  - FPS35 (floating slabs on floors 3 and 5).

Floating slabs on two stories separated by a conventional story

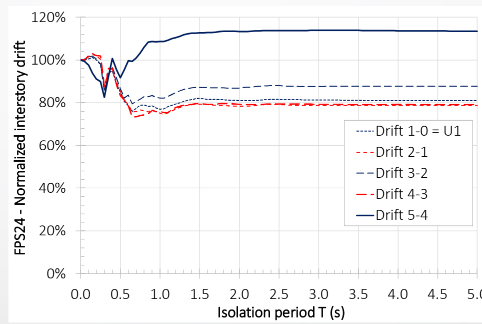
- Average of the normalized maximum interstory drifts (of the skeleton nodes) and normalized total accelerations (at the slabs).

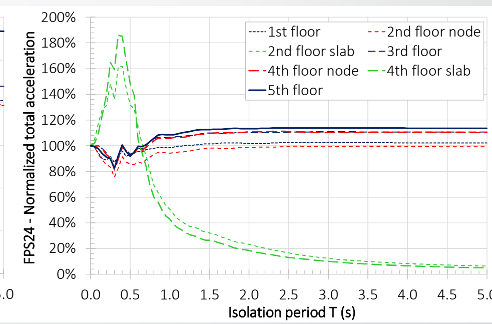
FPS13



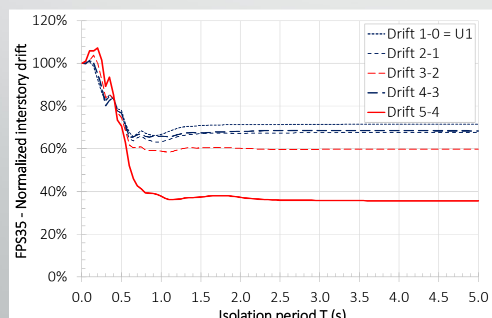


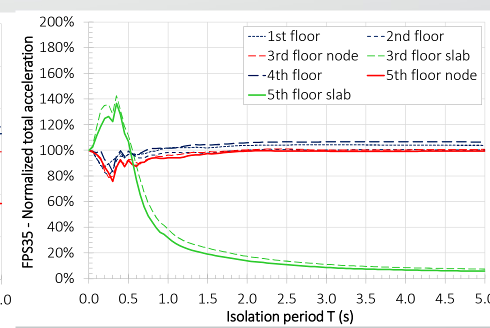
FPS24





FPS35





Conclusions

The following conclusions can be drawn from the analyses:

- For the FPS12345 model and the four different sliding material types (μ_{fast} between 0.03 and 0.14), it is shown that the response (interstory drifts, slab accelerations, skeleton node accelerations) is relatively insensitive to the level of friction, yet higher levels of friction perform slightly better. Regarding the velocity-dependent property of the frictional law, parameter μ_{fast} is dominant. However, its effect, as compared to the corresponding Coulomb law, is small.
- The variability of the FPS12345 model's response due to the variability of the seismic motions is significant over the whole period range. However, for long isolation periods, even if one accounts for this variability, the interstory drifts are still smaller than those of the conventional structure.

Conclusions

The following conclusions can be drawn from the analyses:

- The isolation displacements of the floating slabs in the FPS12345 model are quite similar to the isolation displacement of the base-isolated structure. Moreover, the interstory drifts are smaller for $T < 1\ s$, as compared to the base-isolated structure, while the opposite is true for longer isolation periods.
- For the case of partial floating slab installation (FPS12, FPS23, FPS34, FPS45 and FPS13, FPS24, FPS35 models) the conventional floors above the top floating slab will experience larger drifts and accelerations as compared to the elastic conventional structure.
- As a final design recommendation, when the architectural design constraints impose a limited number of isolated slabs, those should be configured consecutively towards the top floors.

Thank you for your attention!