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The mass-reduction design concept in earthquake engineering

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Outline

- Introduction
- Equations of motion of a 5-story building model
- Strong motion records
- Investigation of a five-story structure with:
    - Floating Slabs on all floors
    - Floating Slabs on two consecutive floating slabs
    - Floating Slabs on two floating slabs separated by a single conventional floor
- Conclusions

PASSIVE STRUCTURAL CONTROL

Conventional Damage Control Design

Supplementary Energy Dissipation Systems

Seismic Isolation

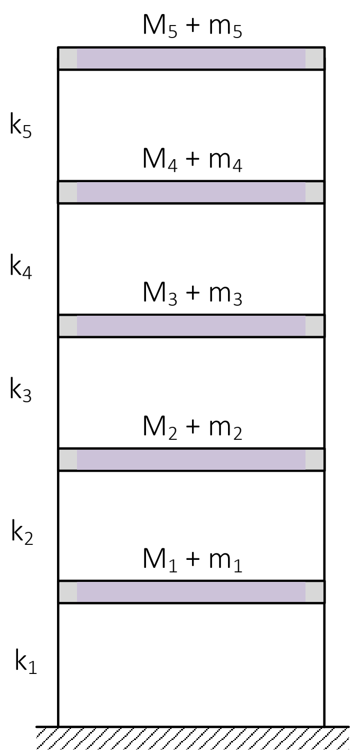
$$Ku + C\dot{u} + F_s = -M(\ddot{u} + \ddot{u}_g)$$

Mass Reduction Design-Concept

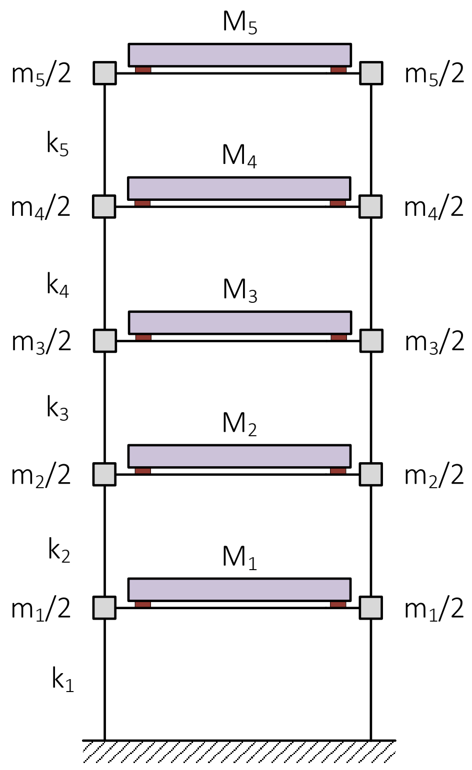
utilized by using FLOATING (or Gliding) SLABS, i.e. slabs “detached” from the Structural Skeleton of low- or high-rise buildings on some, or all of their floors.

This approach has been termed “mass-reduction design concept”.

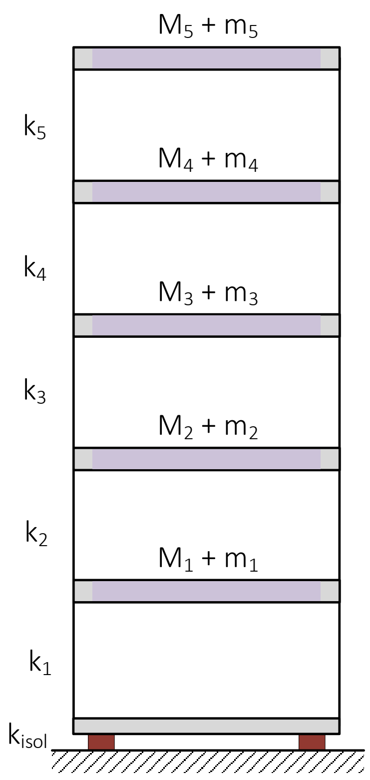
Mass Reduction Design-Concept - Floating Slabs



Conventional Structure



Floating Slabs Structure



Seismic Isolated Structure

- The behavior of FLOATING SLABS or ISOALTED SLABS depends on the selected Isolation Period, which is subject to design:
  - 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.

Introduction

Implementation of the mass-reduction design concept utilizing friction based isolators (FPS) in the floating slabs.

(previous work by Charalampakis et al. 2020, used visco-elastic Isolators)

- Four different cases of velocity-dependent friction (from 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 floating slab configurations along the height of the structure are examined.
- Design recommendations are given regarding the optimal placement of the floating slabs in the structure.

Equations of motion

- for the **Structural Skeleton**:

$$m_1\ddot{u}_1 + (k_1 + k_2)u_1 - k_2u_2 + (c_1 + c_2)\dot{u}_1 - c_2\dot{u}_2 - \boldsymbol{F_{IS1}} = -m_1\ddot{u}_g$$

$$m_2\ddot{u}_2 - k_2u_1 + (k_2 + k_3)u_2 - k_3u_3 - c_2\dot{u}_1 + (c_2 + c_3)\dot{u}_2 - c_3\dot{u}_3 - \boldsymbol{F_{IS2}} = -m_2\ddot{u}_g$$

$$m_3\ddot{u}_3 - k_3u_2 + (k_3 + k_4)u_3 - k_4u_4 - c_3\dot{u}_2 + (c_3 + c_4)\dot{u}_3 - c_4\dot{u}_4 - \boldsymbol{F_{IS3}} = -m_3\ddot{u}_g$$

$$m_4\ddot{u}_4 - k_4u_3 + (k_4 + k_5)u_4 - k_5u_5 - c_4\dot{u}_3 + (c_4 + c_5)\dot{u}_4 - c_5\dot{u}_5 - \boldsymbol{F_{IS4}} = -m_4\ddot{u}_g$$

$$m_5\ddot{u}_5 + k_5(u_5 - u_4) + c_5(\dot{u}_5 - \dot{u}_4) - \boldsymbol{F_{IS5}} = -m_5\ddot{u}_g$$

- for the **floating slabs**:

$$M_i\ddot{u}_{i+5} + \boldsymbol{F_{ISi}} = -M_i\ddot{u}_g$$

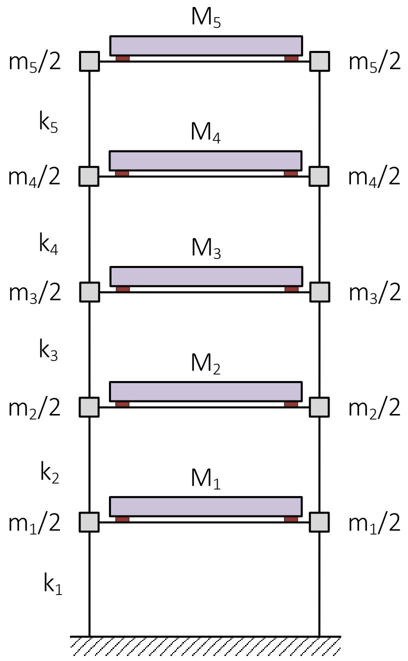
Where: M_i= slab mass

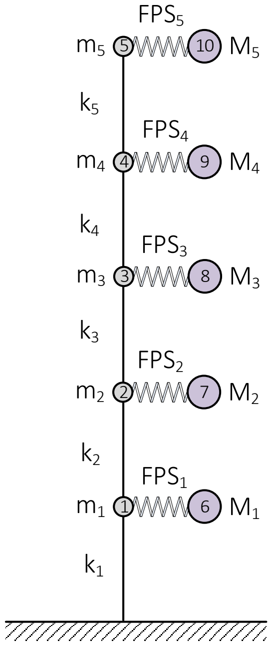
m_i,= skeleton node mass, $(i = 1,2, \dots, 5)$

k_i, = stiffness

$c_i = 2\xi(k_i m_i)^{1/2}$, = damping ($\xi = 5\%$ is the damping ratio)

u_i =lateral displacement of the i^{th} story of the building





Equations of motion

- forces of the **FPS isolators** take the form:

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

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

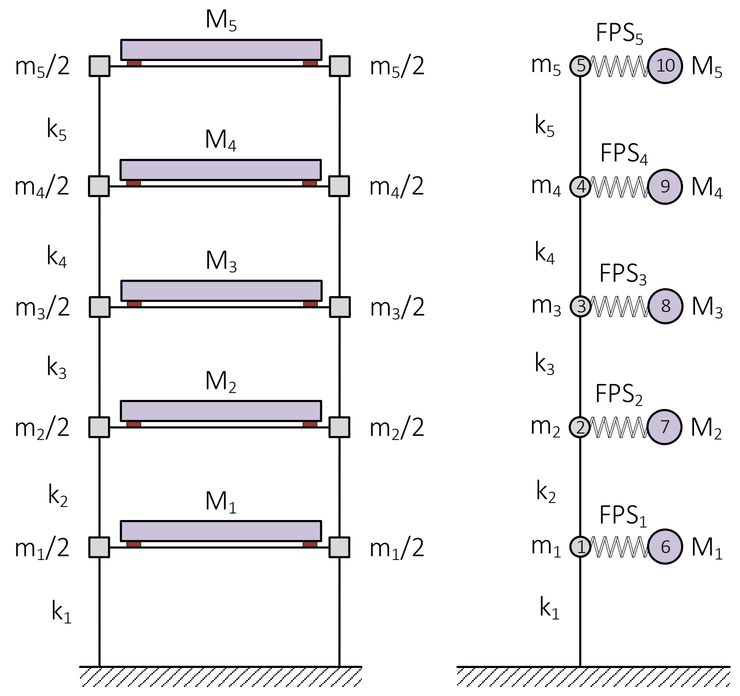
$$\mu_s = \mu_{fast} - (\mu_{fast} - \mu_{slow})\exp(-a|\dot{u}_{i+5} - \dot{u}_i|)$$

are the friction coefficients of the spherical sliding surfaces.

- Finally, $Z_i(t)$ $(i = 1,2,\ldots,5)$ are dimensionless hysteretic variables governed by:

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

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



FPS ISOLATORS

Friction parameters and material types

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

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

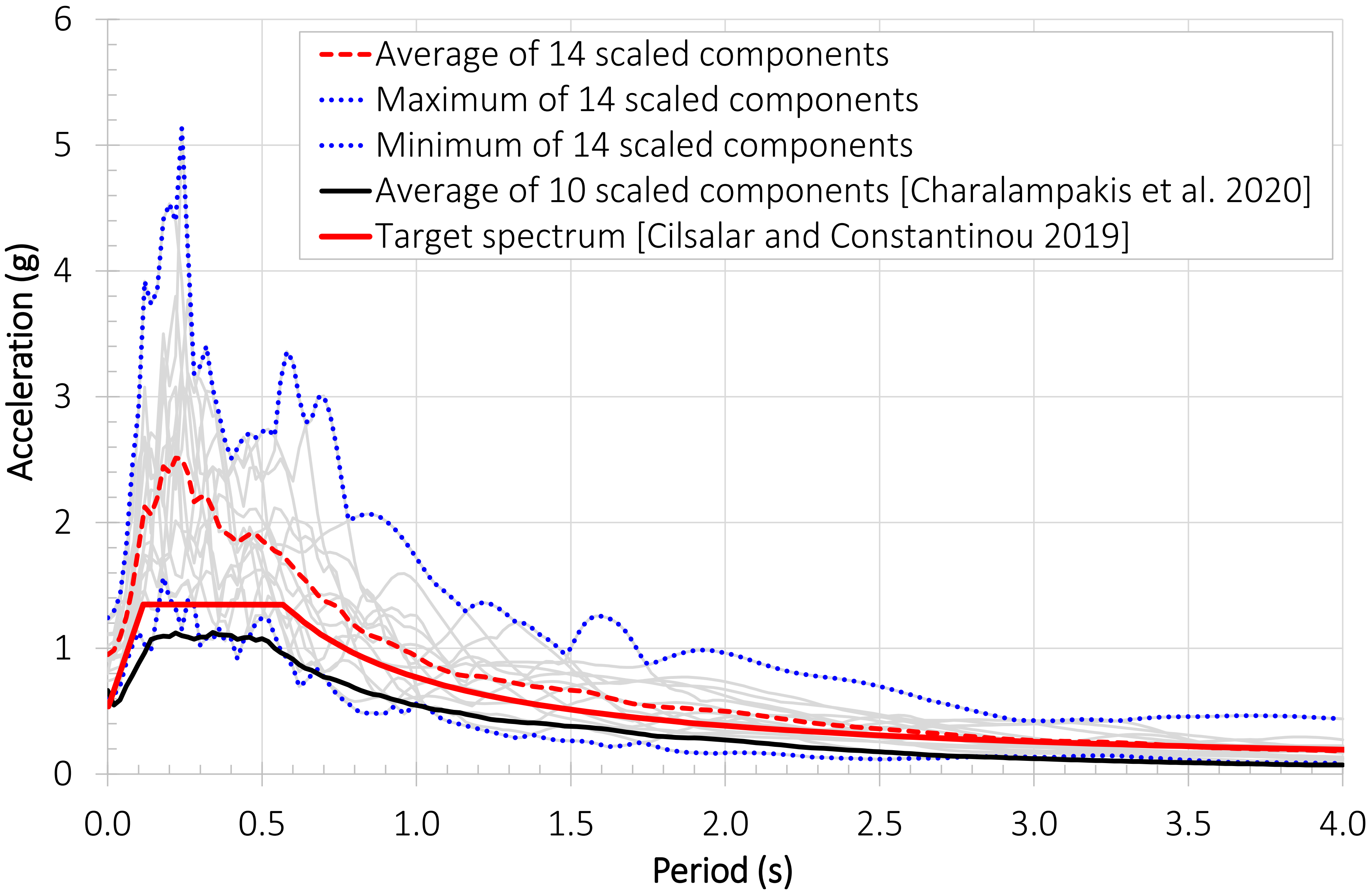
where μ_{slow} and μ_{fast} are the friction coefficient for almost zero ($|\dot{u}| \to 0$) and large sliding velocity ($|\dot{u}| \to \infty$), respectively

Seismic Motions

- 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 $R_{rup} > 10\ \mathrm{km}$ were considered from **Cilsalar and Constantinou 2019**.

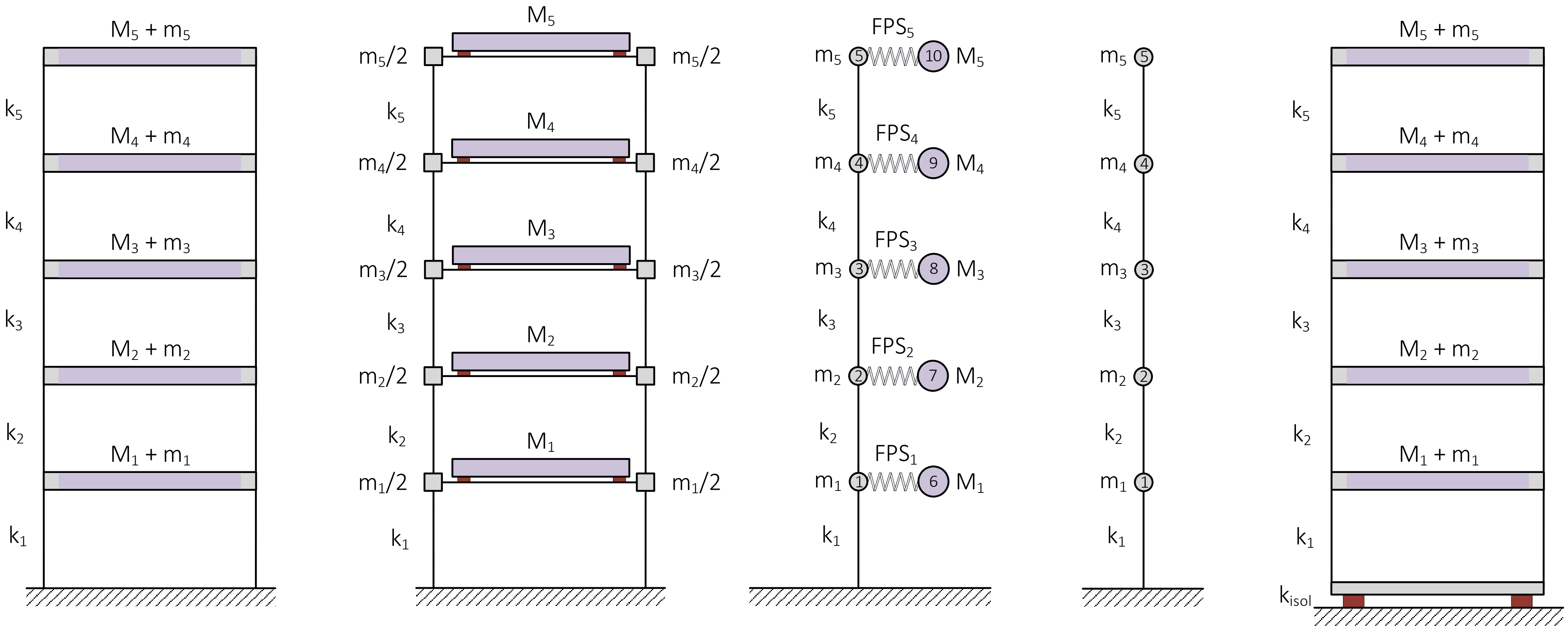
#	No.	Event	Year	Station	M	R_{rup} (km)	V_{s30} (m/s)	Scale factor	PGA (g)	PGV (cm/s)	PGD (cm)
01	68	San Fernando	1971	LA – Hollywood Store FF	6.61	22.77	316.46	4.10	0.92	89.00	65.22
02									0.80	69.41	52.77
03	169	Imperial Valley-06	1979	Delta	6.53	22.03	242.05	2.60	0.61	68.41	38.19
04									0.91	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

Seismic Motions



Floating slabs on all stories

- First, the structural configuration of all five slabs resting on spherical frictional isolators (FPS12345), is examined.
- FIXED Base Structure - eigenperiods $\{\mathbf{0.363},\ \ \mathbf{0.124},\ \ \mathbf{0.079},\ \ \mathbf{0.061},\ \ \mathbf{0.054}\}\ s$
- All Response quantities are normalized w.r.t. the corresponding Response quantities of the conventional (elastic) structure.



(a) **Conventional Structure**

(b) **Floating Slabs Structure**

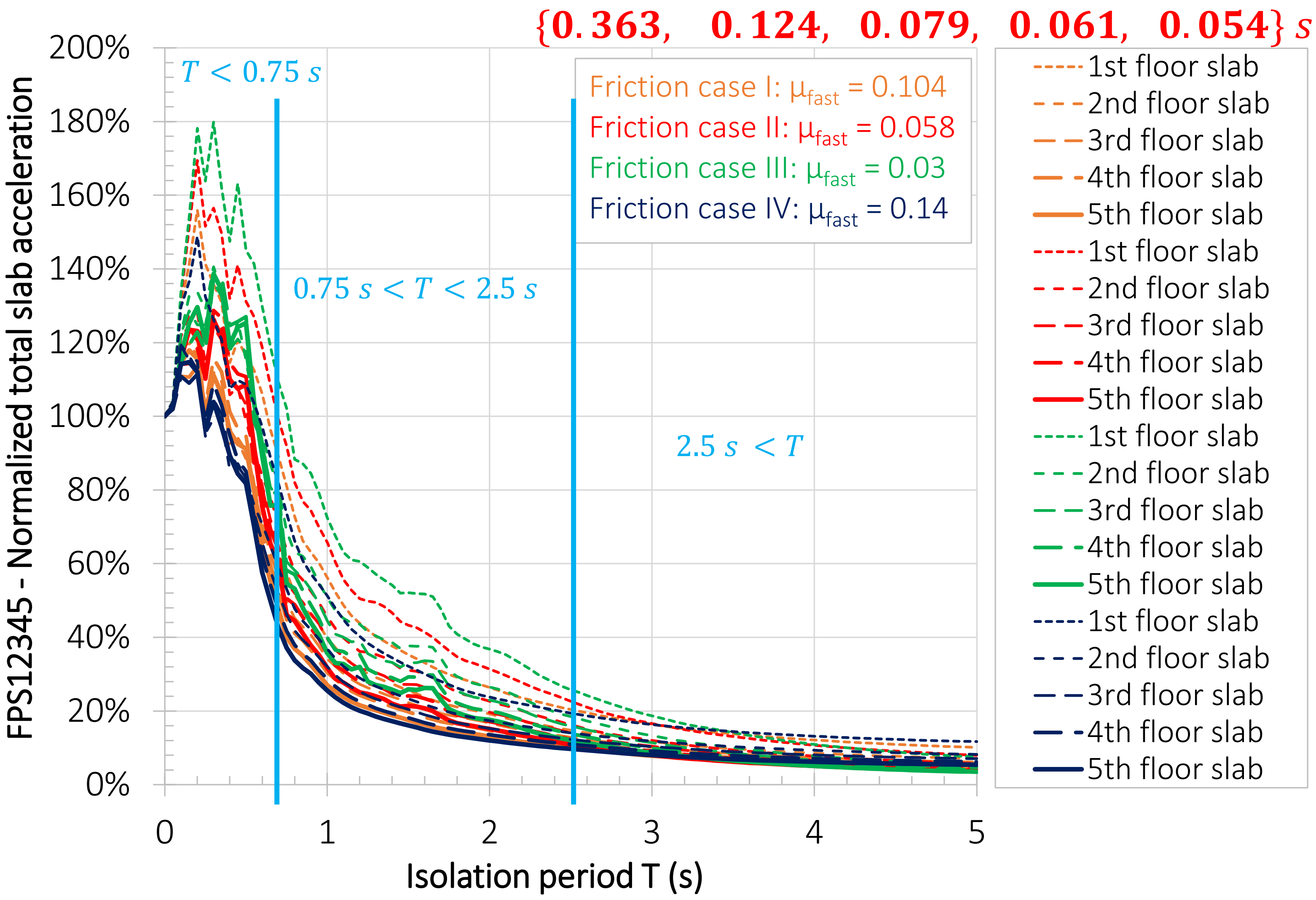
(c)

(d) Reduced Mass Model

(e) **Isolated Structure**

Floating slabs on all stories

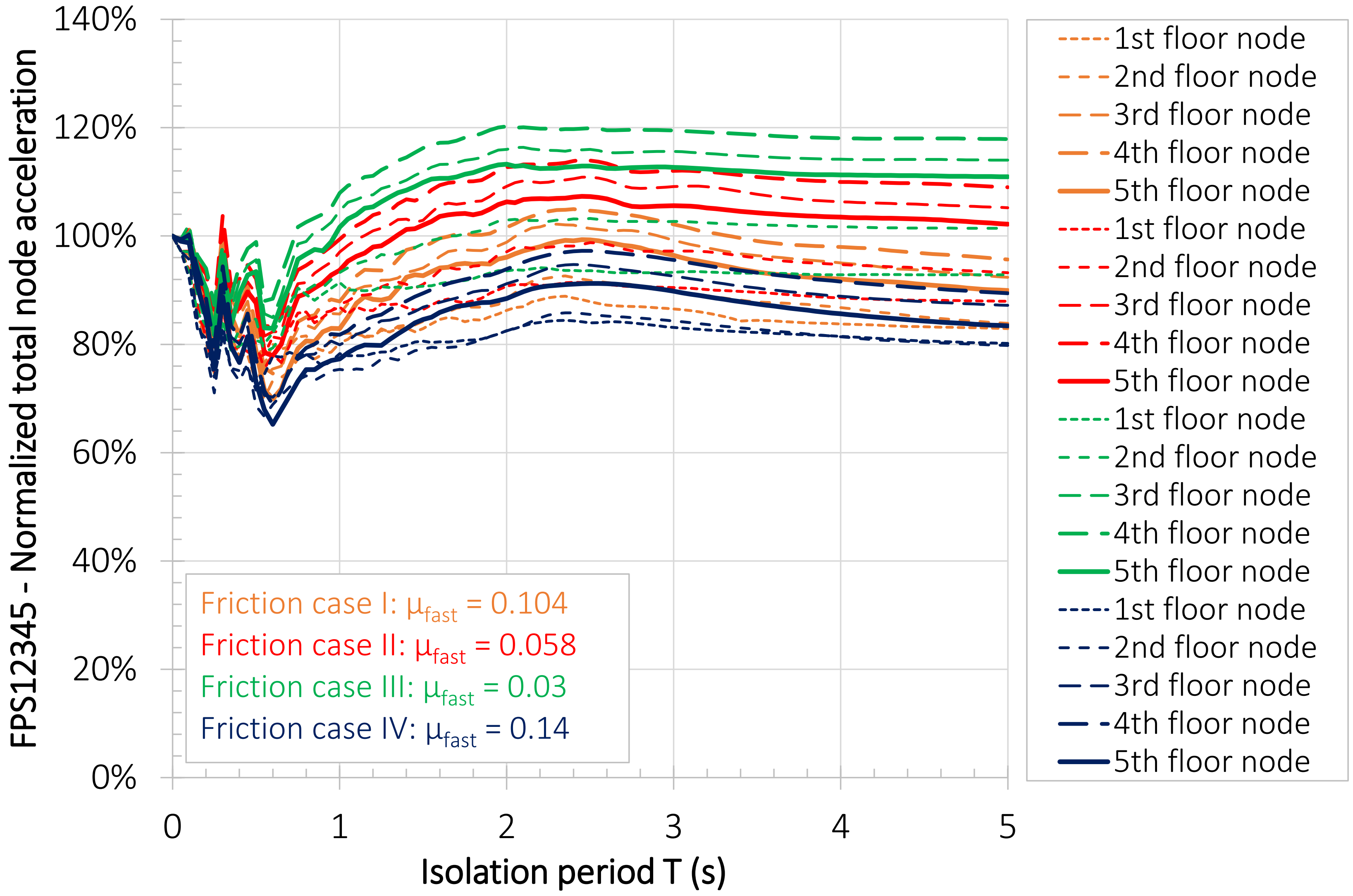
- Average of the normalized maximum total acceleration at the **Slabs** for all four friction cases.
- For short isolation periods ($T < 0.75\ s$), the floating slabs act as mass dampers and experience large accelerations.
- For long isolation periods ($T > 2.5\ s$) the floating slabs are essentially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

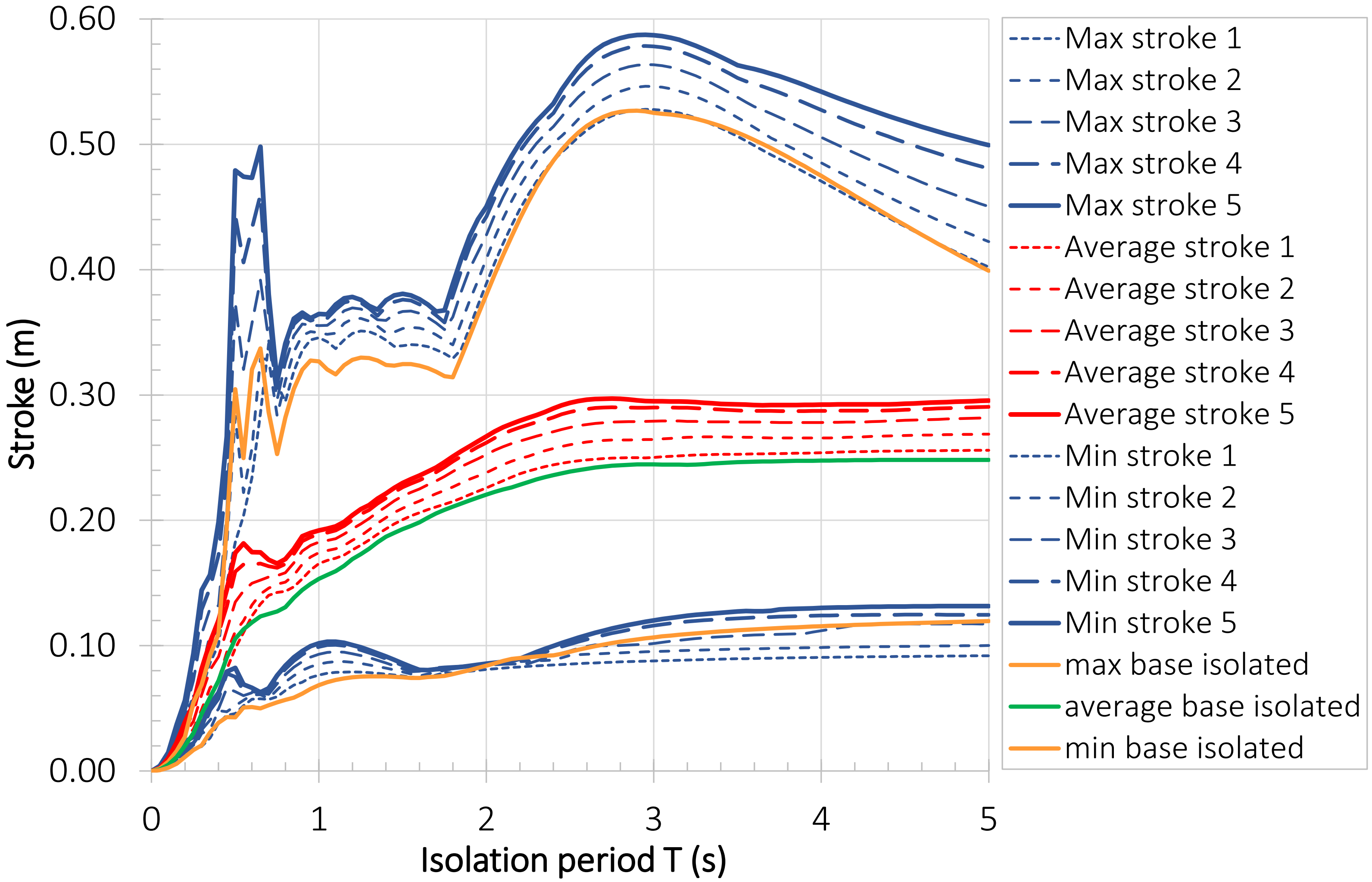
- Average of the normalized maximum total acceleration at the **Skeleton Nodes** for all four friction cases.
- The accelerations are on average similar to the conventional floor accelerations (around 100%).
- The skeleton is essentially decoupled from the floating slabs and thus responds (accelerations) 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

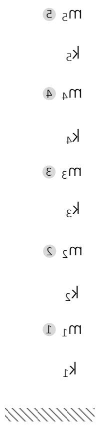
- Maximum, average, and minimum (over fourteen strong motions) of the maximum Isolation Stroke (FPS12345 and base isolation, both with friction case IV).
- The isolation displacements of the floating slabs are quite similar to the isolation displacement of the base in the conventional isolation design.



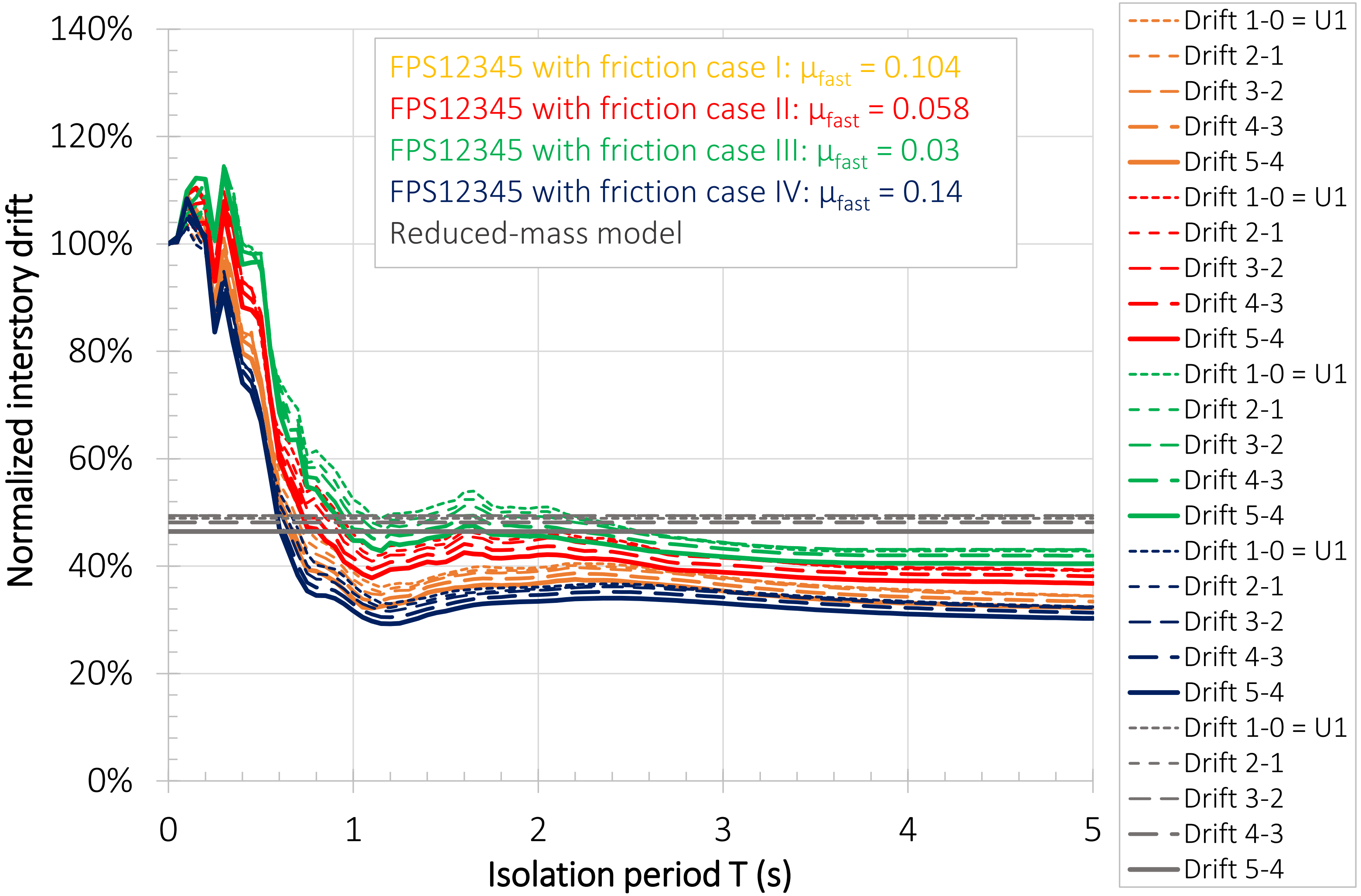
- The larger isolation displacements at the top floating slabs can be explained considering that each floating slab is being excited by the accelerations experienced at their floor level, which are amplified as compared to the ground acceleration.

Floating slabs on all stories

- Average of the normalized max Inter-story 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.



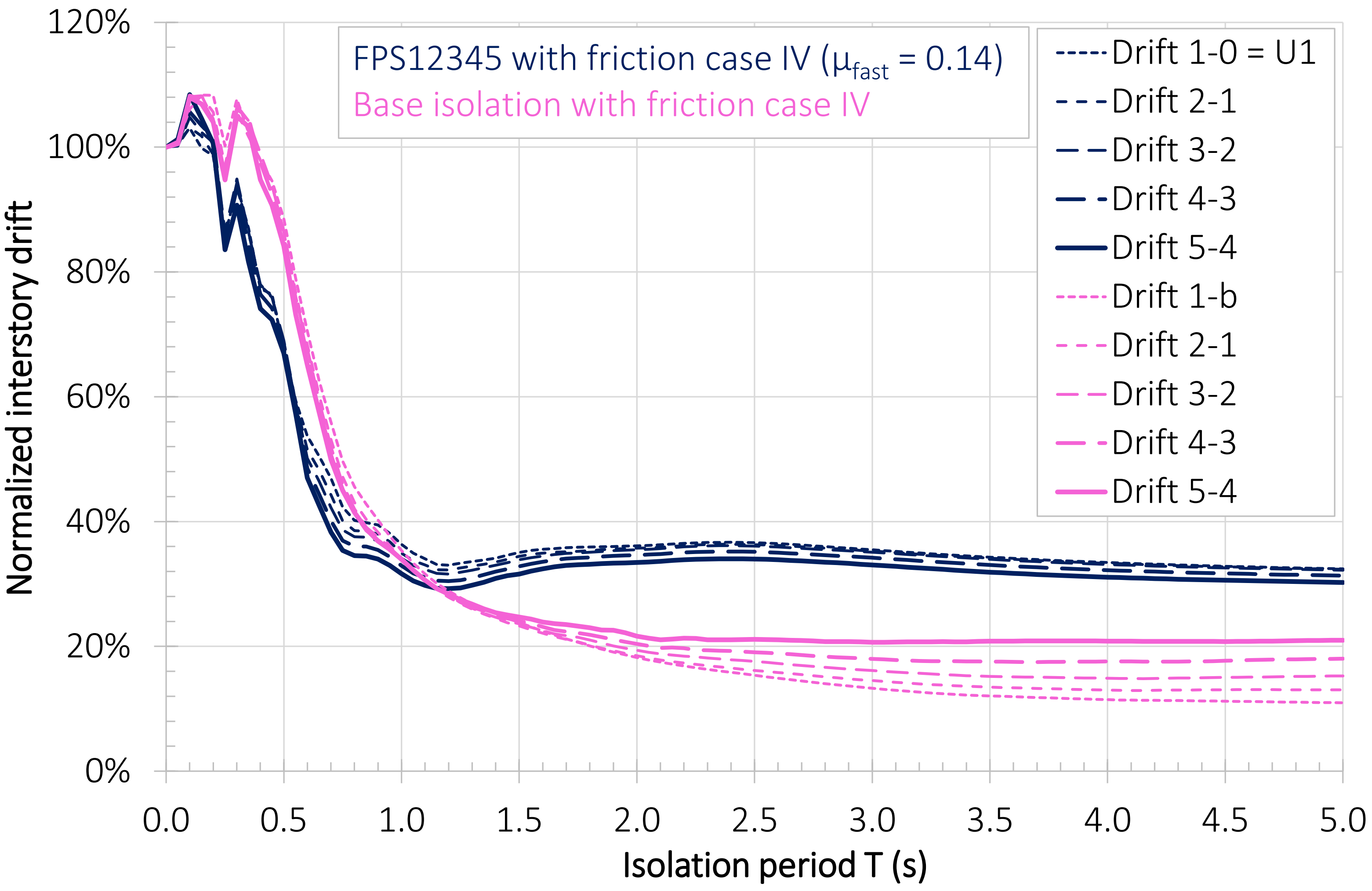
(b)



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

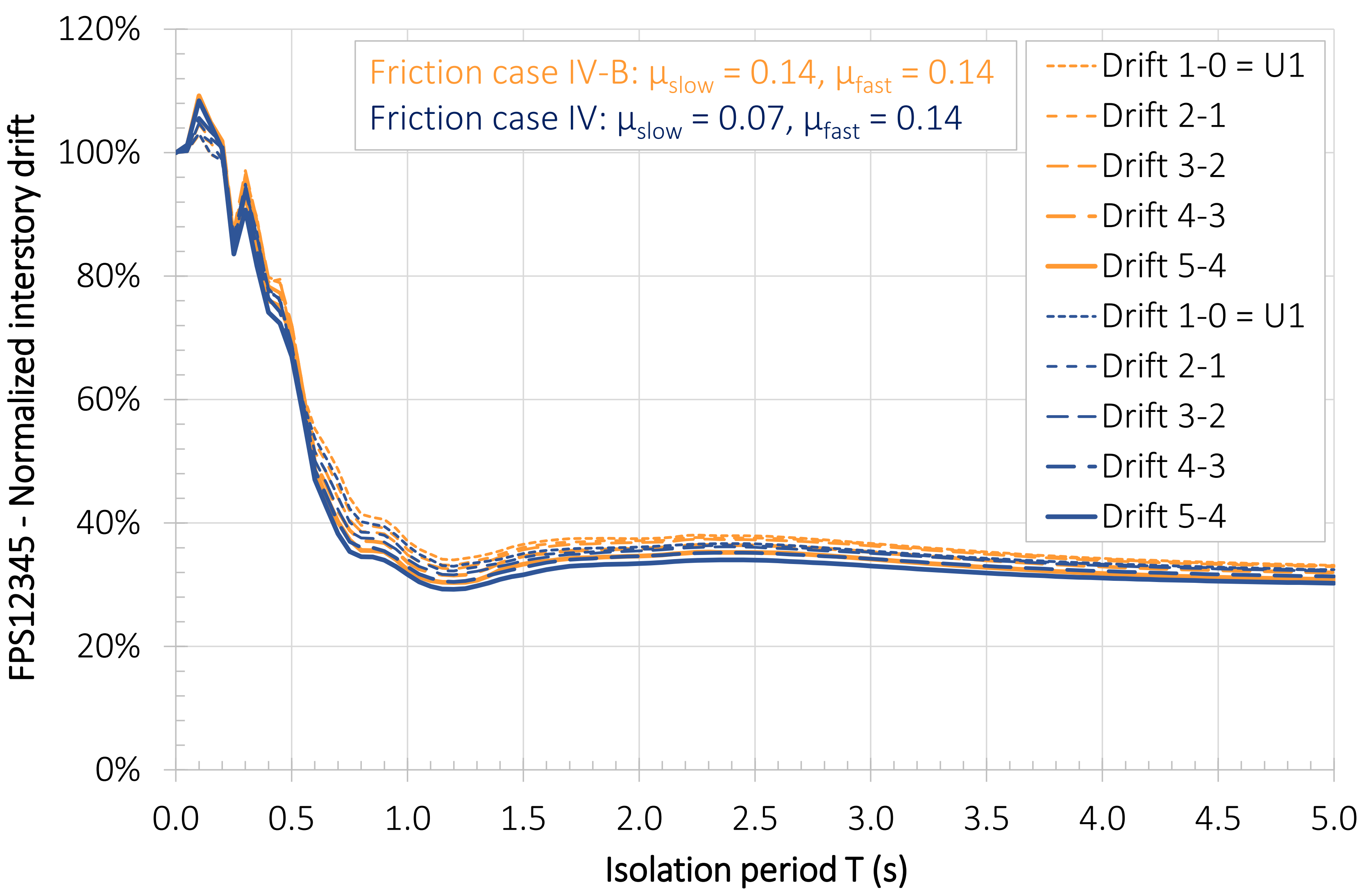
Floating slabs on all stories

- Average of the normalized max 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.

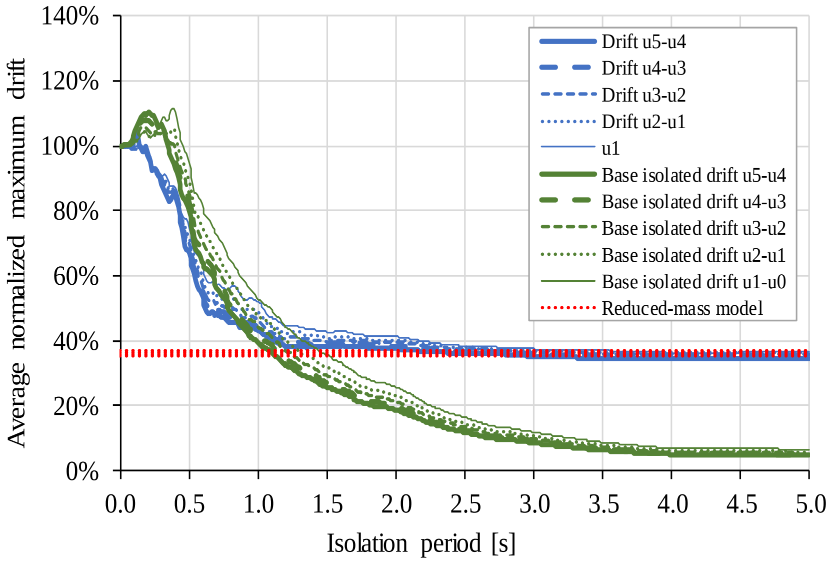


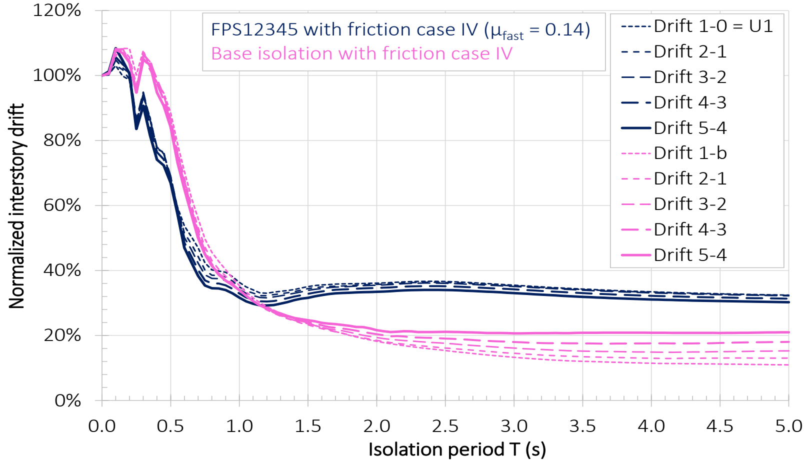
Floating slabs on all stories

- Average of the normalized max Inter-story Drifts for **FPS12345 with friction case IV** and the corresponding **Coulomb friction** model (IV-B).
- Small differences in the response are observed.



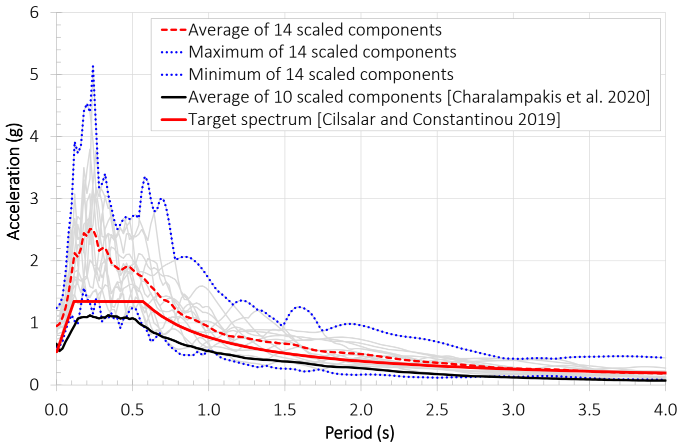
Visco-Elastic vs FPS Isolation Systems of 5 floating slabs





Floating Slab Isolation System : Visco-Elastic | FPS (Friction)

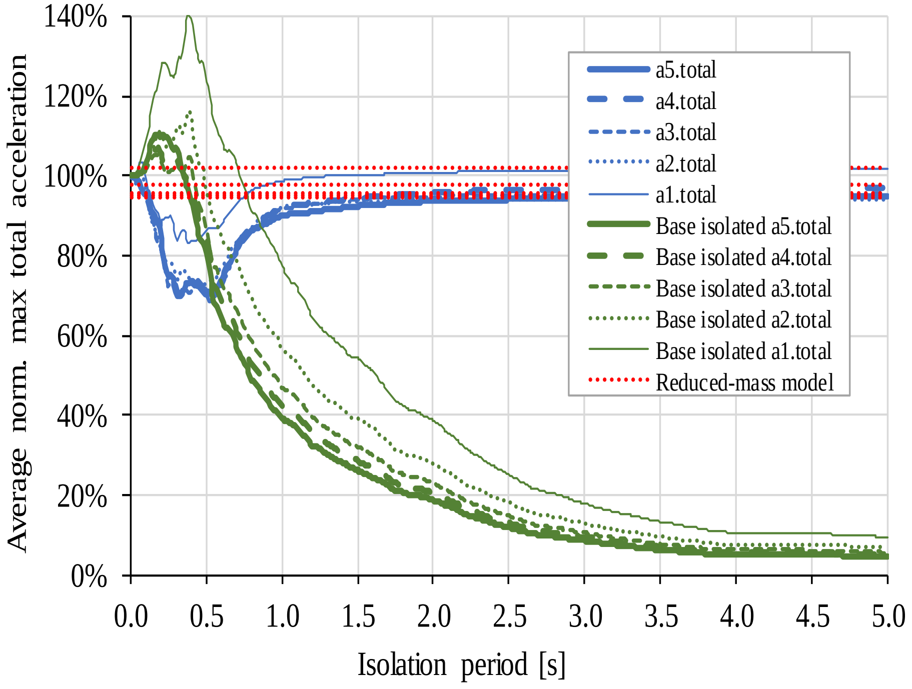
- For $T_{isol} < 1s$ the average maximum interstory drifts of the structure with floating slabs are **smaller** than those of the base-isolated structure.
- For $T_{isol} > 1.5s$ the average maximum interstory drifts have **converged** to **the values of the reduced-mass model**. In this case, $\mu = 63.04\%$.
- The behavior of the structure can be derived from the reduced-mass model.
- Average max. inter-story drifts of base-isolated fall below 30% of the fixed base

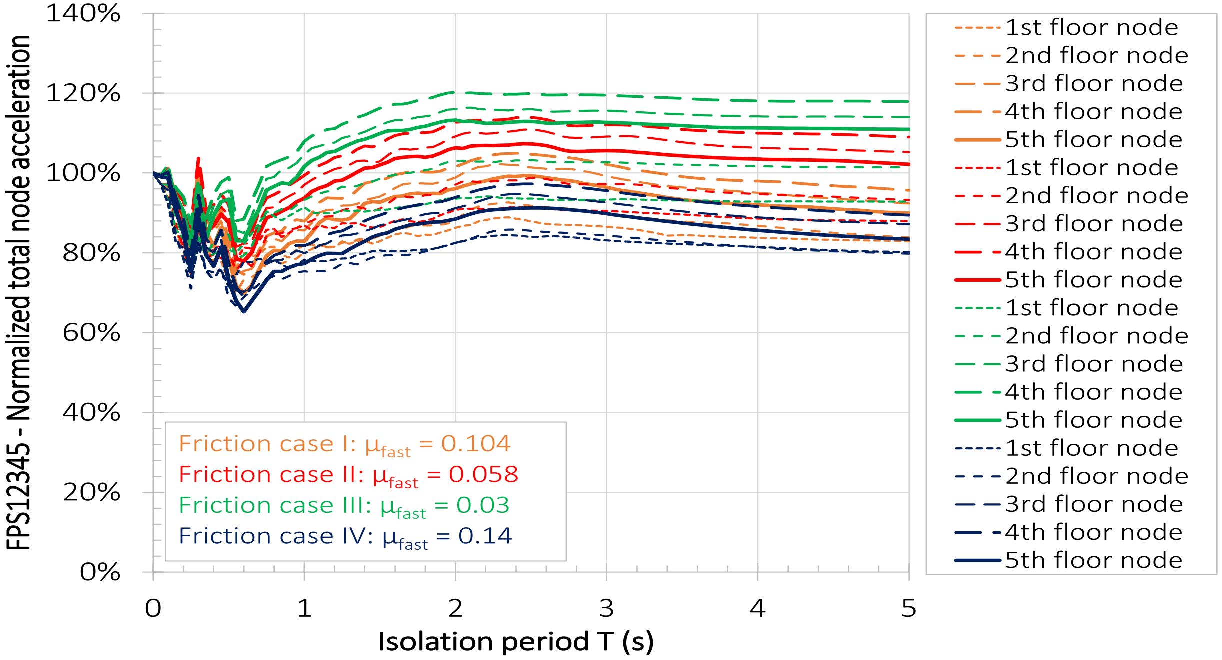


Average (over the 10 or 14 ground motions) normalized maximum interstory drifts.

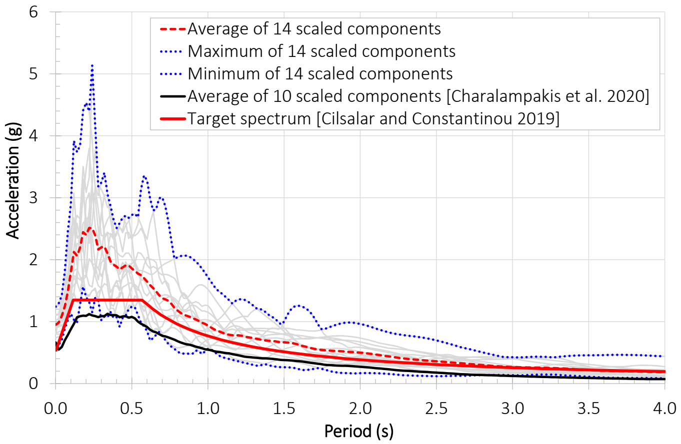
Normalization w.r.t. fixed base conventional structure (therefore all lines stem from 100% when $T_{isol} = 0s$).

Visco-Elastic vs FPS Isolation Systems of 5 floating slabs





Floating Slab Isolation System: Visco-Elastic FPS (Friction)



- For $T_{isol} > 1.5s$ the average max. total accelerations of the skeleton nodes converged to the reduced-mass model values. These are **much higher** than the base-isolated structure, because of the skeleton smaller period.

Average (over the 10 or 14 ground motions) normalized maximum interstory drifts.

Normalization w.r.t. fixed base conventional structure (therefore all lines stem from 100% when $T_{isol} = 0s$).

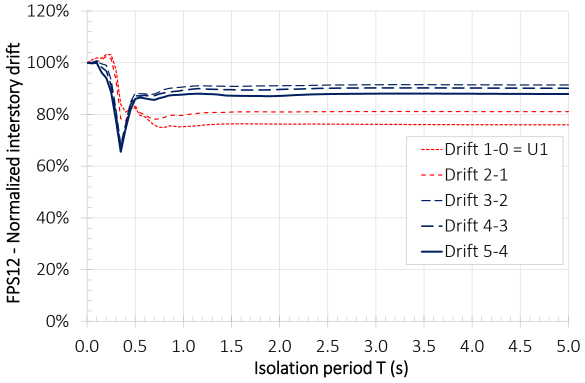
Floating slabs on two consecutive stories

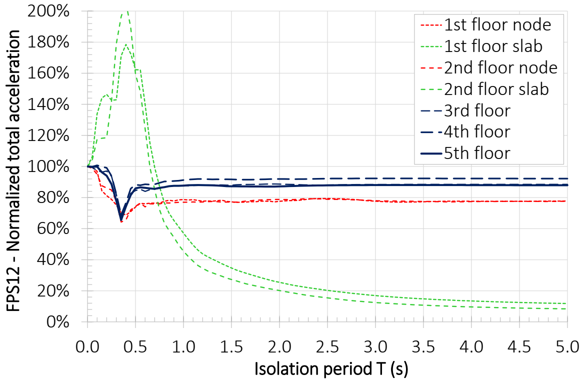
- Next, four different structural configurations with floating slabs in two consecutive stories are examined:
  - FPS12 (floating slabs on floors 1 and 2),
  - FPS23 (floating slabs on floors 2 and 3),
  - FPS34 (floating slabs on floors 3 and 4), and
  - FPS45 (floating slabs on floors 4 and 5).

Floating slabs
on two consecutive stories

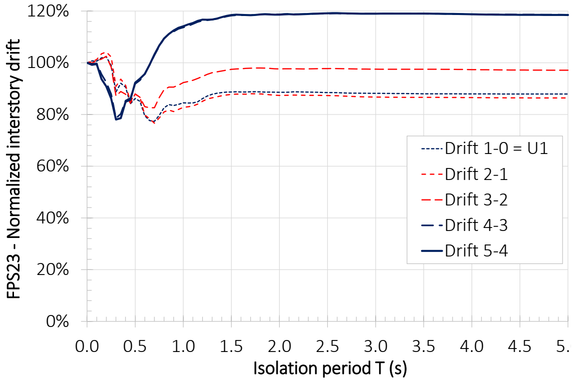
- Average of the normalized maximum interstory drifts (of the skeleton nodes) and normalized total accelerations (at the slabs).

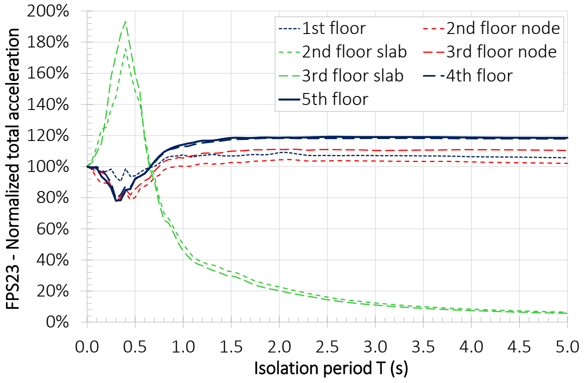
FPS12



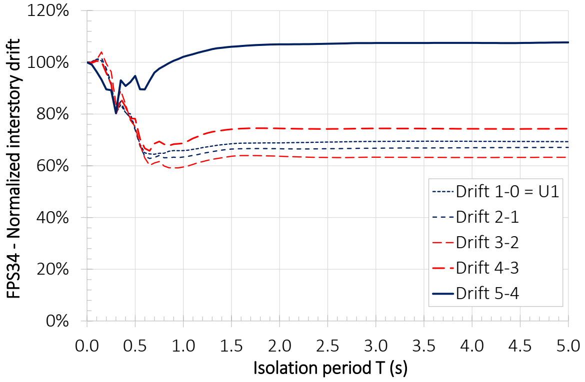


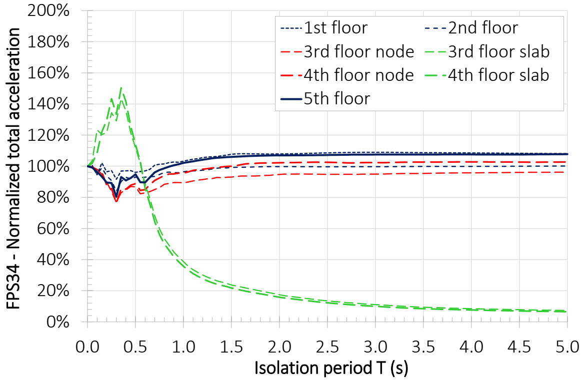
FPS23



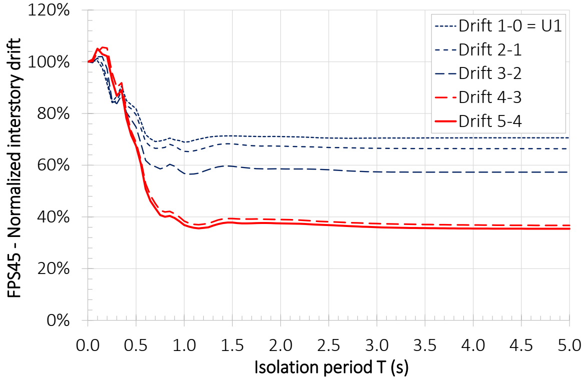


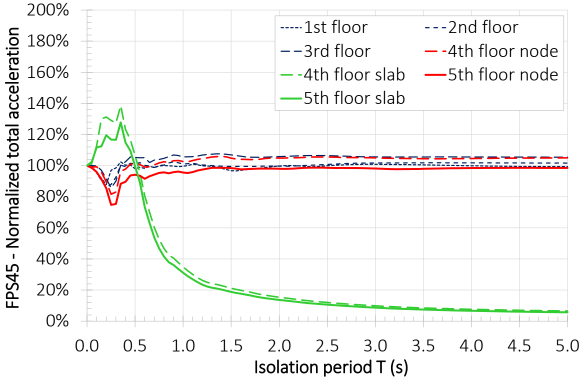
FPS34





FPS45





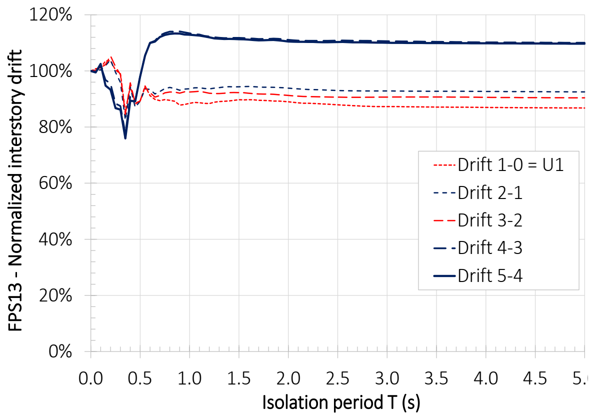
Floating slabs on two stories separated by a conventional story

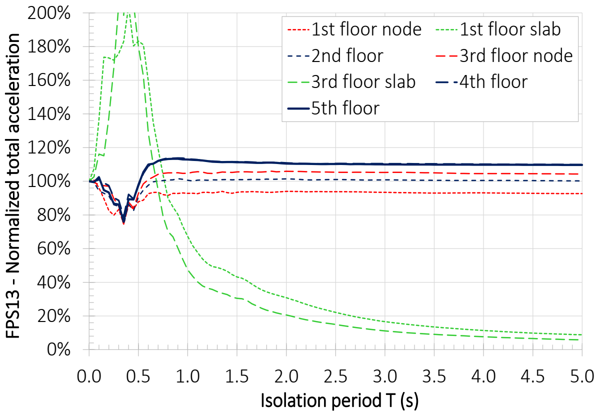
- Next, three different structural configurations with floating slabs in two stories separated by a conventional story are examined:
  - FPS13 (floating slabs on floors 1 and 3),
  - FPS24 (floating slabs on floors 2 and 4), and
  - FPS35 (floating slabs on floors 3 and 5).

Floating slabs on two stories separated by a conventional story

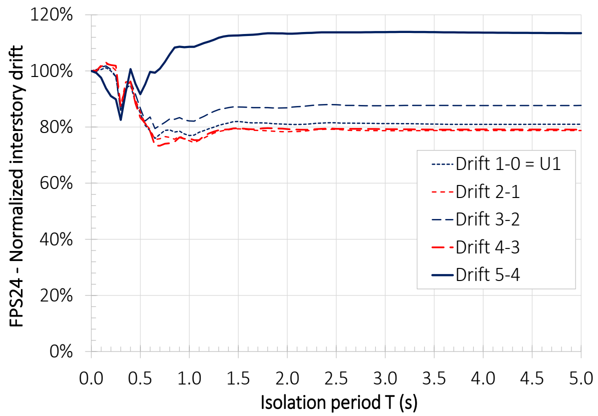
- Average of the normalized maximum interstory drifts (of the skeleton nodes) and normalized total accelerations (at the slabs).

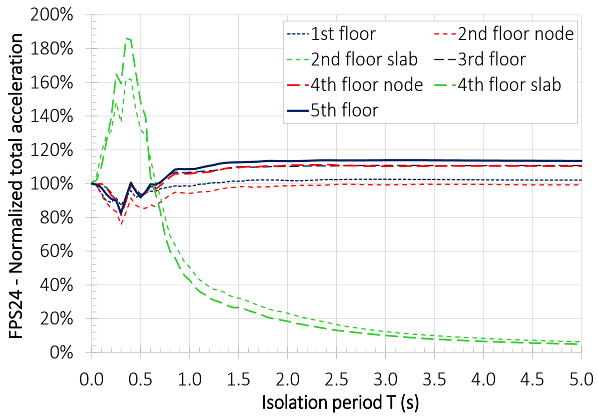
FPS13



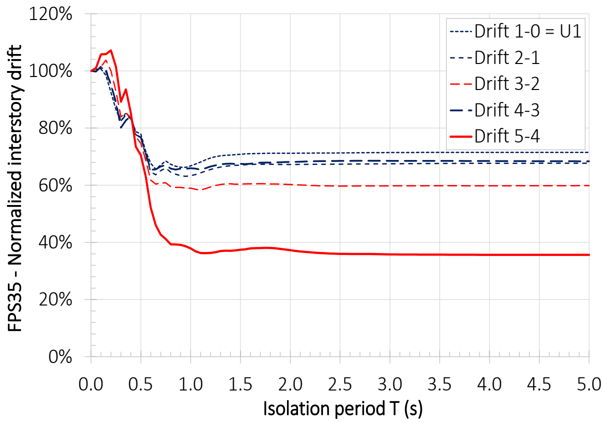


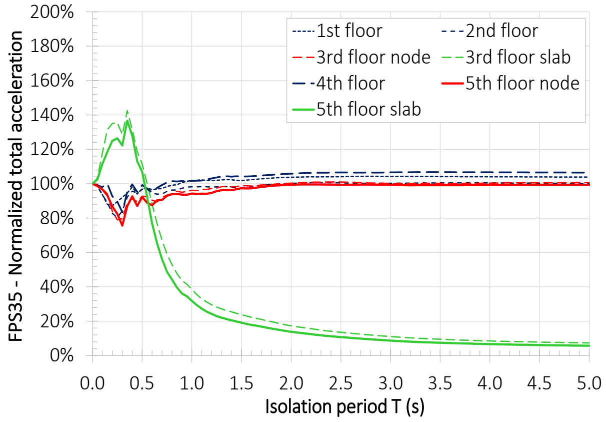
FPS24





FPS35





Conclusions

- 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 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!