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DYNAMICS OF A MULTIPLE BUILDING BASE ISOLATED SYSTEM

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Abstract

In multiple-building real state complexes, where seismic protection needs to be delivered to all structures, individual isolation may bring a series of construction difficulties. An alternative, is to create a large isolated concrete slab, on which all structures are built, delivering seismic protection to all of them, including common areas and connections. This concept has already been implemented and delivers diverse construction benefits; however, the behavior of each structure differs greatly from its response with individual isolation and this aspect has not been studied in proper depth. The objective is to characterize the dynamic behavior of a multiple-building base-isolated system subject to spatial motion by identifying its equivalent modal properties and analyzing its non-linear response. To do this, a simplified case of two structures was adopted and several configurations were simulated through a 3D numerical model, which considered the non-linear hysteresis of isolators and the possibility of structures undergoing non-linear incursions in addition. All simulations were complemented with a modal analysis of the system. Results indicate that there is a significant interaction between the two structures, caused mainly by the influence of higher modes, in which each structure has an effect on the kinematic of the isolation system. That is to say, the modal response of one structure depends on the parameters of adjacent buildings. As a consequence, common isolation of two dissimilar structures could lead to a significant increase in their displacements or interstory drift. The magnitude of this interaction depends principally on building distribution, structure properties (mainly their period and mass difference) and analysis direction.

Keywords: multiple-building; common isolation; fragility.

1. Introduction

To meet the growing demand for different public services, some civil engineering projects are evolving towards the emplacement of multiple structures as a single-building complex. Examples of this are hospitals, universities, large resorts, government or public buildings, data-centers, etc., which, by their nature, should probably be considered as essential buildings, whose operational continuity must be ensured for vital or economic reasons; they are also likely to contain high-end machinery or expensive content. A conventional design approach does not provide protection for the content, installations or architectural elements, which can easily account for up to 80% of the cost of the initial investment [1]; nor does it ensure the structure's operational continuity, leading to possible indirect costs due to goods and services which will not be produced or provided as a consequence of seismic damage. For example, 30% of the economic losses caused by the 2010 Maule earthquake in Chile were occasioned by assets that were no longer produced due to damaged structures [2]. These aspects can easily exceed the initial costs of the infrastructure itself and therefore a higher standard of seismic protection must be provided for the whole complex. This objective is best achieved with base-isolation which has proven to be very effective in controlling both structural damage and its acceleration, thus achieving both goals: protection of the structure's content and guaranteeing its operational continuity. However, isolating each structure with its own independent system may present a series of construction difficulties [3]. To overcome this, a new construction technique has recently been applied, referred to in the literature as multiple-building base-isolated structures. It basically consists of a large seismically-isolated concrete slab on which all structures are built, delivering seismic protection to all of them, including common areas and connections between buildings. An example of this are the Kamikuzawa Condominiums [4] – [5] (Fig.1 - right) at Sagamihara (Tokio), a twenty-one six to fourteen story buildings complex built on a common r-c isolated slab (125 x 250 meters) which involved several Lead Rubber Bearings (restoring force devices), Sliding Devices (energy dissipation devices) and Ball Bearings devices (support devices). Other examples of this construction technique are presented on [6] and [7].

Nevertheless, care must be taken in developing this type of structure, since its dynamic behavior differs greatly from its alternative, individual isolation. In a multiple-building base isolated system (MB-BIs), each structure depends not only on their properties, but also on the properties of all adjacent buildings, due to an indirect bond generated through the common slab. This was first noticed by Tsopelas *et al.* [8] – [9], but has not been broad by any recent investigation, except by Zhengguo and Huanding [10] who addressed the subject by comparing the differences between the alternatives in a series of individual case studies. To date, no investigation has made emphasis on characterizing the dynamic of the system, nor the interaction between its structures. Furthermore, the aforementioned researchers considered linear behavior of the structures, which are likely to experience non-linear behavior as consequence of interaction with adjacent buildings; and this performance goes against isolation design objective.

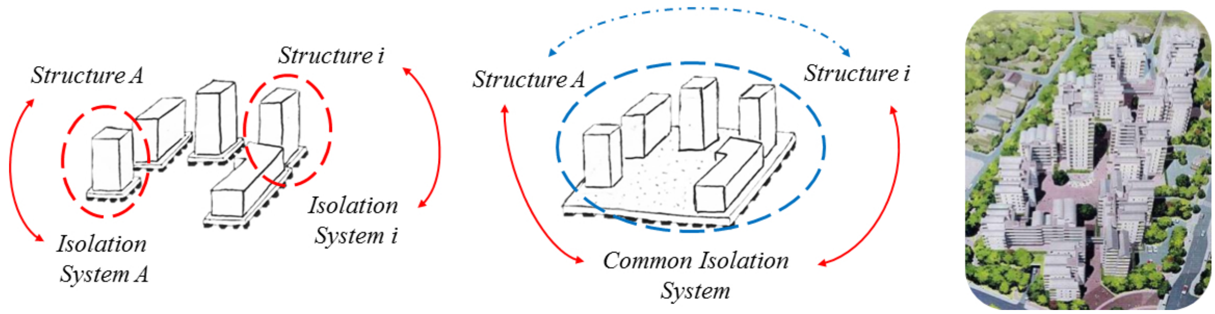


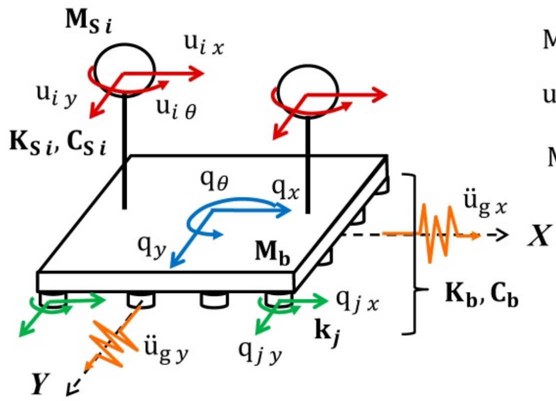
Fig. 1 – Multiple building – common base interaction schematized (left). Kamikuzawa Condomiums [4] (right).

This research is based on the hypothesis that a multiple-building base isolated structure is controlled by different mechanisms from the alternative, the individual isolation; and this aspect has not been studied in depth. The objective is to characterize the dynamic behavior of a multiple-building base-isolated system, identifying the mechanisms that define and control its response - analyzing how are they affected by each structure properties - and furthermore to study the consequences of common isolation on the seismic demand of each structure. All conclusions are based on a modal analysis of the system, but have been verified through several non-linear simulations by means of self-developed software.

2. Simulation and analysis properties

To analyze a system of such properties, a numerical model was created and implemented in a Matlab [11] code routine capable of taking into account every significant aspect of the spatial dynamic of a multiple-building base-isolated system. Each building was defined as a three degrees of freedom (*dof*) equivalent structure i.e. a concentrated mass with two translational and one torsional *dof*; linked to a common three *dof* isolated base, that results from the motion of multiple two *dof* seismic elastomeric isolators (Fig.2). Each structure and isolator is represented by a non-linear element, defined by a Bouc-Wen (B-W) model of hysteresis [12]. The solution is obtained as a time history analysis, through a State Space procedure and the Dynamically Exact method [13]. The B-W hysteresis model is controlled by a set of parameters: A, β, γ and n. The first three parameters are algebraically redundant: if A is set equal to 1, β and γ control the shape of the hysteretic loop. "n" is a dimensionless parameter that controls the transition between the elastic and plastic phase: larger values of n give a sharp transition between the pre-yielding and the post-yielding stiffness. Based in the work present by Tsopelas *et al.* [8] and Vassiliou *et al.* [14], parameters $\beta = 0.9$, $\gamma = 0.1$ and $n = 2$ are chosen for elastomeric isolator, while $\beta = \gamma = 0.5$ and $n = 4$ are chosen to simulate 1 *dof* equivalent reinforced concrete frame structures. Further details of the numerical model and its parameters can be found on the full document [15]. The model and self-developed software were successfully validated by its comparison with commercial software's.

The research was simplified to a system with only two structures isolated on a common slab. One of them is denominated as the Control Structure (C.S.) and its counterpart is called the Adjacent Structure (A.S.). All results will be centered on what the C.S. experiences as different properties of the A.S. are modified. Furthermore, either of the two buildings can be defined as "Control Structure", so conclusions are valid for both buildings. For this to be possible, several combinations of properties in the two structures were analyzed.



$\mathrm{M}_{S\,i}$, $\mathrm{K}_{S\,i}$, $\mathrm{C}_{S\,i}$: Mass, Stiffness and Damping matrix for *i*th structure

$\mathrm{u}_{x\,i}$, $\mathrm{u}_{y\,i}$, $\mathrm{u}_{\theta\,i}$: *i*th structure traslational and torsional *dof*

M_b , K_b, C_b: Mass, Stiffness and Damping matrix for the common base

q_x, q_y, q_θ : common base traslational and torsional *dof*

$q_{i\,x}$, $q_{i\,y}$: elastomeric isolator *j*th traslational *dof*

k_i: elastomeric isolator *j*th stiffness

$\ddot{u}_{g\,x}$, $\ddot{u}_{g\,y}$: seismic motion on principal axes

Fig. 2 - Representation of a MB-BIs model.

Each equivalent structure is based on a concrete frame structure of dimensions 60 x 20 m and period $T_s = 0.7$ s. The equivalent mass of the structure (M_S) is equal to 3500 T and its resistance is 10% of its weight. Its post-yielding stiffness (αK_S) was defined as equal to 35% of its elastic stiffness (K_S). The isolation system is designed to deliver a period (T_b) of 3 s for a displacement of 0.25 m. The common base mass (M_b) is defined as a function of the superstructure mass ($M_{S.E.}$, i.e. both structures mass); it will be equal to 30% at first ($M_b/M_{S.E.}$ = 0.3), but will be modified to analyze its effect on the results. All properties were chosen based on the experience behind empirical data and previous investigations presented by other authors, as well as on the recommendation and specification from different design codes as is shown on the full document [15]. Torsional properties are derived directly from translational properties or, as the case may be, take similar values as them. Properties were not restricted to a certain configuration or set of parameters, but varied over a wide range of values, in order to generate general conclusions. This will be noticed on each analysis.

Table 1 - General properties for all simulations.

	Period (s)	**Mass (T)**	**f_y**	**Dimensions (m)**	**Non-linear parameters**			
					α	**β**	**γ**	**n**
Structures	0.7	3500	10% M_S g	60 x 20	0.35	0.5	0.5	4
Isolation System	3 s, D_D = 25 cm	30% $M_{S.E.}$	$0.02 \sum k_a = f(T_b)]$	(Table 2)	0.15	0.9	0.1	2

The Control Structure response will be presented always normalized to its individual isolation response (without an adjacent structure influence). By means of this standardization, and since it has only one story (or concentrated mass), the normalized response can be also interpreted as a modification of its inter-story drift or base shear. This will allow to establish - in the following plots - whether there was an increase or a decrease in the demand of the C.S. as a consequence of sharing an isolation system with a dissimilar A.S. and compared to its individual isolation demand.

The parameter "System Dispersion" (D_s) was created to act as a simple definition of the structure distribution on the common slab. It refers basically to the distance between both isolated structures, measured perpendicularly to the axis in which the response is registered (i.e. perpendicular to analysis direction). The dispersion degree (D_s) is calculated as a ratio of the distances between the C.M. of both structures (d_s) to the structures width measured on the same axis (L_S). This is schematized in Fig.3. Dispersion is equal to 1 when both structures are directly adjacent to each other; as they separate, the Dispersion value increases. Even though its numerical expression is valid only for this research, its conceptual definition can be extrapolated to other situations. Furthermore, system dispersion can take different values for a given system configuration, since it depends also on analysis direction (this will be addressed later in this document). In Table 2 system dimensions are assigned as function of D_s, considering an analysis on the principal axis *x*. On all cases 16 equal isolator devices are distributed uniformly under the common slab. This configuration delivered an adequate density of isolators without affecting results nor increasing software - processing cost.

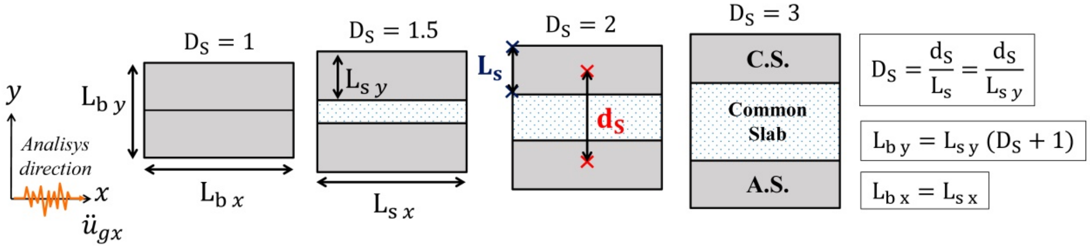


Fig. 3 - MB-BIs with different dispersion values measured on principal axis-*x*.

Table 2 - Dimensions assigned to each configuration as function of system dispersion.

D_s	$L_{s\,x}$ [m]	$L_{s\,y}$ [m]	Distance between C.M. of structures: $d_S = D_s * L_{s\,y}$ [m]	Base dimensions [m]:	
				$L_{b\,x} = L_{s\,x}$	$L_{b\,y} = L_{s\,y}\,(D_s + 1)$
1	60	20	20	60	40
2			40		60
3			60		80
4			80		100

The results showed an important dependency on the frequency content of the seismic motion. Therefore, to obtain more statistically reliable conclusions, all analyses were based on an average behavior for different Chilean ground motion records (Table 3). All of them present diverse frequency content [15], therefore it is essential to interpret analyses results only as trends, without much focus on specific magnitudes, since their purpose is to characterize the behavior of such systems and to create hypotheses about their action mechanisms. This will allow conclusions to be extrapolated to predict more complex cases.

Table 3 - Seismic ground motion records used in analysis

Earthquake - [M_w]	Maule (27-02-2010) – 8.8 M_w		Valparaíso (03-03-1985) – 8 M_w					
Station	San Pedro		Llolleo		Melipilla		Viña del Mar	
Direction	NS	EW	N10E	S80E	NS	EW	N20W	S70W

3. Modal analysis results

The spatial dynamic of a multiple-building base-isolated system can be mostly explained through a modal analysis of its linear behavior in plane motion. Such a modal approach has already been adopted to study the individual isolation of structures [13], in which a modal bond emerges between the structure's properties and its isolation system response. This bond is caused mainly by the second modal form, in which the structure displacement reaches an important magnitude related to its base displacement, modifying its behavior. In a multiple-building base-isolated system, this bond goes further: higher modes that present a similar structure-base bond emerge; subsequently, each structure affects the dynamic of the common isolated base as a function of their properties and distribution on the slab. As a consequence, an indirect bond between structures emerges, in which the modal properties and response of one structure depend on the parameters of adjacent buildings. This was called Multiple Building – Base Interaction or structure-structure interaction. To define this bond, a modal approach on the plane system will be briefly presented. Such system presents 3 modes summarized below and schematized in Fig.4.

The First modal form is very similar to the first mode of an individually isolated system. It is characterized by an important participation in global response (Γ_1) that decreases as the period of the two structures rises. It presents a modal period similar to the isolation period ($T_1 \approx T_b$) and therefore involves high modal displacements (S_{d1}); however they are concentrated as base deformation, since the structures' modal amplitude ($\phi_{1\,C.S./A.S.}$) is very low in relation to its base amplitude ($\phi_{1\,b}$). Subsequently, no important interaction between the structure properties and the base response occurs, and consequently no important interaction between buildings emerges. In other words, the modal response of one structure (e.g. Control Structure) is mainly a function of its own properties and those of the isolation system (as in individual isolation); i.e. $\Gamma_1\ \phi_{1\,C.S.}\ S_{d1} \approx f\ (\mathbf{T_{C.S.}}, T_b)$. This can be observed in Fig.5, in which the response of the Control Structure ($T_{\mathbf{C.S.}} = 0.7$ s) for each j modal form ($\Gamma_j\ \phi_{\mathbf{C.S.}\ j}\ S_{d\,j}$) is presented as a function of Adjacent Structure period ($T_{\mathbf{A.S.}} = 0.1 - 1.2$ s). This plot uses a displacement spectrum calculated as an average of 8 seismic motions (Table 3).

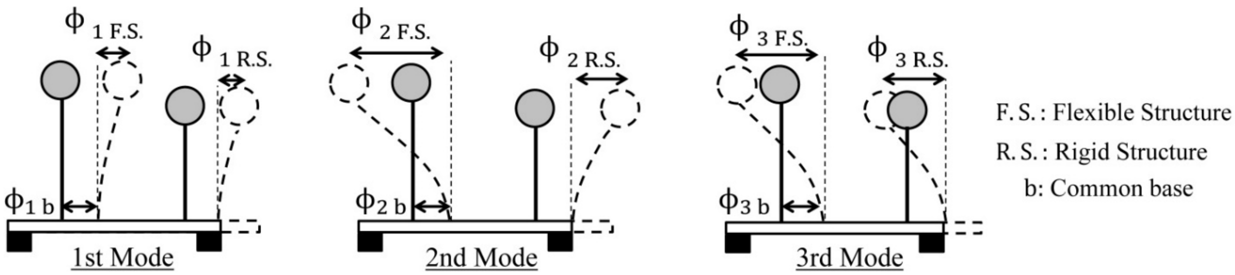


Fig. 4 - Two-structure base-isolated system modal forms in plane motion.

The second modal form consists of a differential motion between structures, in which the flexible building presents a deformation opposite to base displacement, whereas the rigid structure moves in the same direction as the base motion. Its modal participation factor (Γ_2) assumes importance as structures present differences in their periods. If the structures are similar to each other, this mode has no participation whatsoever ($\Gamma_2 = 0$) and the modal behavior of the system converges into that of two individually isolated structures. The modal period consists of a weighted average between the periods of the two structures, with a higher weighting for the flexible building. Therefore, this mode involves high modal displacement when one of both structures presents a high period. Unlike the first mode, the structures' modal amplitude ($\phi_{1\,C.S./A.S.}$) may be comparable or superior to its base amplitude ($\phi_{2\,b}$). Consequently, a high interaction between each structure and the isolated system is expected, in which each structure alters the dynamic behavior of the common base, therefore indirectly altering the dynamic behavior of the adjacent building; i.e. a large structure-structure interaction is expected, in which the modal response of one building its not function of its own period alone, but also of the period of the adjacent buildings, specifically a function of the period difference between them($\Delta T_{S.E.}$); i.e. $\Gamma_2\ \phi_{2\,C.S.}\ S_{d2} \approx f(\mathbf{\Delta T_{S.E.}}, T_b)$. This can be seen on Fig.5.

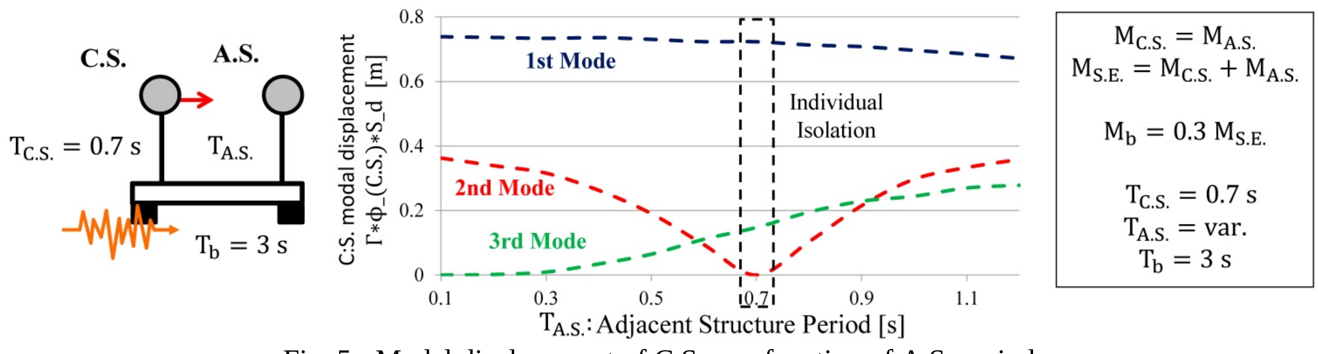


Fig. 5 - Modal displacement of C.S. as a function of A.S. period.

The third modal form is similar to the 2nd mode of an individually isolated structure: it involves low displacement of isolators and high structure modal deformation, which occurs contrary to the motion of the base. An effect of each structure over the isolation system behavior is expected and an indirect modal bond arises between the properties of one structure and the response of adjacent buildings. Modal participation grows with the period of both buildings, but it usually presents a low modal period, always lower than the period of the rigid structure, therefore involving low modal displacements. The deformation of each structure increases with its own period as much as with the period of the adjacent building. If the two structures are similar, this mode converges into the 2nd mode of an individually isolated structure. On the other hand, if the period of one structure (e.g. Control Structure) is reduced or increased, modal deformation in the Adjacent Structure will respectively decrease or increase. i.e. $\Gamma_3\ \phi_{3\,C.S.} \approx f(T_{C.S.}, T_{A.S.}, T_b)$. This is shown on Fig.5.

As shown above, unlike an individually isolated structure, the modal response of one structure (C.S.) in a multiple-building base-isolated system does not depend on its own properties alone, but also on the properties of the rest of the structures isolated on the common slab. This occurs to a different degree in each modal form and is mainly a function of structure periods (although seismic frequency content also plays an important part). It can be seen that when both structures are equal ($T_{A.S.} = T_{C.S.} = 0.7$ s) the 1st modal form controls most of the response, with a small contribution of the 3rd mode and no participation of the 2nd mode, converging to an individual isolation model. However, if the A.S. period is modified, an indirect effect is observed on the C.S. whose period wasn't modified. This bond arises as a consequence of two mechanisms summarized below:

- As the A.S. period moves further away from the C.S. period, modal deformation of the C.S. associated with the 2nd mode increases. This effect is called the **M2** mechanism due to its relation with the second modal form. In other words, the **M2** effect consists of an increase in seismic demand of both structures in the common isolation system as they present a difference in their period.

- As the A.S. period rises (higher than the C.S. period), modal deformation of the C.S. associated with the 3rd mode increases, while the opposite occurs when the A.S. period drops (lower than the C.S. period). That is to say, when two structures share a common isolation system, the rigid structure will experience a higher seismic demand and the flexible structure a lower seismic demand compared to their demand when individually isolated. This effect is called the **M3** mechanism due to its relation with the 3rd mode.

As the combined effect of both mechanisms, when the C.S. is isolated together with a more flexible adjacent structure, it will present an increase the 2nd and 3rd modes displacements; hence its global seismic demand will increase in comparison to individual isolation. This **I**ncrease in its **D**emand caused by a more **F**lexible adjacent structure is called **IDF effect**. On the other hand, when the C.S. is isolated with a more rigid structure, it will experience an increase in the 2nd mode response, but attenuated by a decrease in 3rd mode displacements. As result, the C.S. will experience an **I**ncrease in its seismic **D**emand caused by a more **R**igid adjacent structure - this is called the **IDR effect -** whose effect is slighter than the **IDF effect** due to the attenuation caused by the M3 mechanism. In other words, in plane motion, whenever two structures of different periods share an isolation system, their seismic demand will increase. The more rigid structure will experience a more intense effect, called the **IDF effect**, while the more flexible structure will experience a slighter consequence called the **IDR effect**. Both effects increase with the period gap between buildings and their intensity will also depend on the frequency content of the seismic motion.

4. Plane System Analysis

The behavior presented above was verified through several non-linear time-history simulations. The maximum response in time of the C.S. was registered for eight seismic motions; results are shown in Fig.6 as a function of the period gap between structures ($\Delta T_{S.E.}$). All results are normalized to the case of individual isolation of the C.S. A positive value on *x*-axis means the A.S. is more flexible than the C.S. and a negative value means it is more rigid.

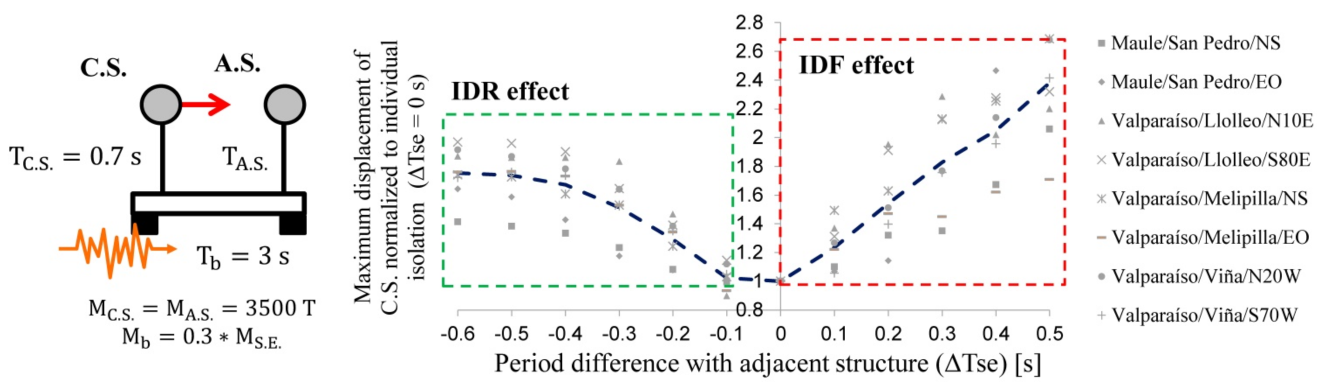


Fig. 6 - Displacement of C.S. as a function of A.S. period, normalized to individual isolation.

Effects on the C.S. due to common isolation with a dissimilar structure are clearly proven: an increase in its demand as a consequence of a more flexible adjacent structure (**IDF** effect, positive *x*-axis) and idem with a more rigid adjacent structure (**IDR** effect, negative *x*-axis). In addition, **IDF** effect was shown to be more intense than **IDF** and both effects increase with $\Delta T_{S.E.}$. The same analysis was recreated for different period of the C.S.; the same behavior and similar magnitudes were observed. This allows the definition of either of the structures as the C.S., as long as they are not extremely flexible or extremely rigid, since considerably lower effects were registered in such structures. This occurs due to the irregularities of the displacement spectrum, which causes extremely mild M2 and M3 mechanisms in very rigid Control Structures and low M2 mechanism in very flexible C.Ss. This behavior will not be discussed further in this document and can be found on [15].

On another subject, isolating two structures together involves a larger isolated area in relation to the built area. That is to say, more free (common) spaces will exist on the artificially isolated ground, entailing a higher $M_b/M_{S.E.}$ ratio. As the 3rd mode period is directly related to this parameter, a higher $M_b/M_{S.E.}$ ratio will translate into a higher 3rd mode period, entailing higher structural modal deformation (associated to 3rd mode). In Fig.7, similar curves to those presented in Fig.6 are plotted, but considering different $M_b/M_{S.E.}$ ratios. All the curves are normalized to individual isolation of the C.S. ($M_b/M_{S.E.} = 0.3$). It can be seen that higher $M_b/M_{S.E.}$ ratios involve higher seismic demand on the C.S. (IDF and IDR effects are increased), independently of the A.S. period; i.e. both structures will present higher seismic demand as $M_b/M_{S.E.}$ ratio increases.

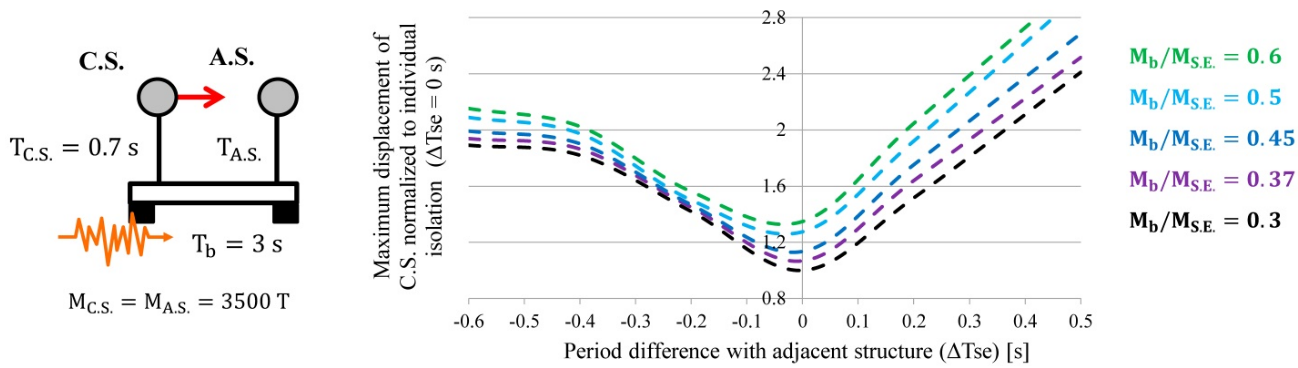


Fig. 7 - Influence of $M_b/M_{S.E.}$ ratio on structure–structure interaction.

5. Spatial System Analysis

When a torsional *dof* and spatial behavior are included in the previously defined system, new modes emerges. This lead to new consequences on structures, which are controlled by the new mechanisms summarized below:

- Modes 1 and 3 are not significantly modified in spatial motion since both modes involve a very low torsional participation factor (less than 1%). Accordingly, both modes deliver a similar interaction to that presented in plane analysis, with similar effects on structures. In other words, mechanism M3 described in plane motion remains unaffected in spatial motion.

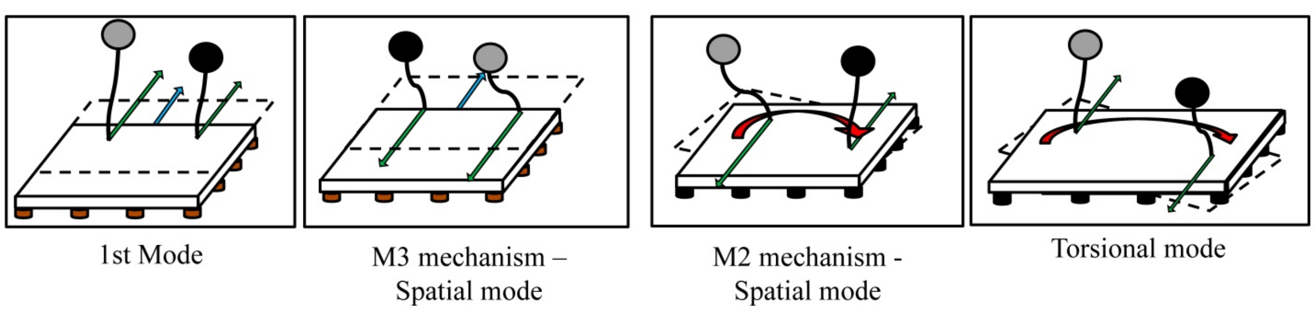


Fig. 8 - Two-structure base-isolated system modal forms in spatial motion.

- The second mode of the plane system (differential structure displacement) is significantly modified in a spatial analysis. It ceases to present a translational motion and changes into a torsional mode, whose rotation center tends to be below the rigid structure. The Nevertheless, the modal amplitude of each structure is similar to the amplitude observed in the 2nd mode of the plane analysis: the rigid structure deforms in the same direction as the base movement, while the flexible structure deforms opposite to the isolation system rotation (see "Mode associated to M2 mechanism" in Fig.8). Consequently, this mode involves a "force transmission" - or a structure-structure interaction - very similar to that presented in the plane system; i.e. it consists of the same M2 mechanism, but through a torsional motion.
- In addition to mode 1 and the spatial modes associated with the M2 and M3 mechanisms, a new mode emerges, which will be called the **Torsional Mechanism**. This mode consists of a mostly torsional motion, in which both structures deform in the same direction as the base rotation, without a significant influence over it, neither affecting the adjacent building dynamics (see "Torsional mode" in Fig.8); i.e. it does not imply any structure – structure interaction or "force transmission".

If the structures are close to each other (lower D_S), the spatial mode associated with the M2 mechanism tends to involve a rotational participation factor close to 100%, with low or null participation of the Torsional mechanism. Therefore, as $D_S \rightarrow 0$, only the M2 and M3 mechanisms define structure – structure interaction. Since both mechanisms aren't affected by the inclusion of the spatial *dof*, multiple building – base interaction on systems with low D_S will tend to that in the plane motion case. On the other hand, as structure separation increases (higher D_S), the modal participation factor of M2 decreases, increasing the participation of the Torsional mode, which involves no interaction between structures. In such cases, only interaction due to the M3 mechanism takes place. From another perspective, as structure separation increases, forces due to differential motion of structures are not transmitted directly to each other, but through a torsional motion that acts as an absorber, attenuating the M2 interaction effect.

This behavior can be observed in Fig.9, where maximum displacement over time of the C.S. is registered as a function of A.S. period considering different system dispersions (D_s, Table 2). As in Fig.6, all responses are normalized to the individual isolation response and the M_b/M_{SE} ratio is taken as 0.3 for all simulations. It can be seen that when structures are far apart (high D_S) their interaction is defined solely by the M3 mechanism (see Fig.5) and therefore a low IDF effect is expected, the IDR effect tends to disappear and a low **D**iminution of the structure's seismic **D**emand as consequence of a more **R**igid structure occurs instead; this was called the **DDR effect**. On the other hand, when structures are close to each other (low D_S), their interaction is controlled by both the mechanisms previously defined (M2 and M3) with intense IDR and IDF effects, tending to the behavior seen on plane interaction. Rotation is low enough for it to be practically irrelevant for isolator displacements.

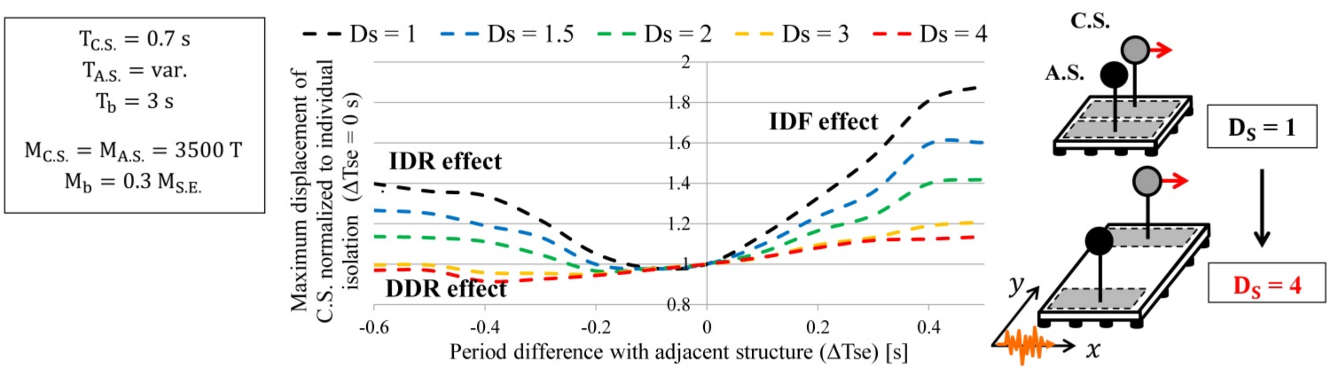


Fig. 9 - Structure–structure interaction as a function of system dispersion.

Although higher dispersion attenuates interaction effects, it also implies a larger isolation slab and therefore a higher M_b/M_{SE} ratio. As noted previously in Fig.7, this generates an increase in seismic demand on all structures isolated on the common slab. If system dispersions described in Table 2 are linked to a M_b/M_{SE} ratio, the curves shown in Fig.10 are delivered. These are similar to the curves presented in Fig.9, but considering the variation of the common base mass with its dimensions. Similar to previous analysis, all results are normalized to the individual isolation case with a $M_b/M_{SE} = 0.3$.

It can be seen that as a consequence of these two effects (structure interaction and an increase in the M_b/M_{SE} ratio), whenever two structures are isolated in a common system, an increment in their seismic demand is expected; that is higher drifts and base shear. The magnitude of this depends mostly on structure distribution and period difference, but also on the frequency content of the seismic motion, aspect which will not be discussed further in this document. Is worth noting that, similar tendencies and magnitudes were observed when the total energy dissipation over time was used as the measured response of the C.S.

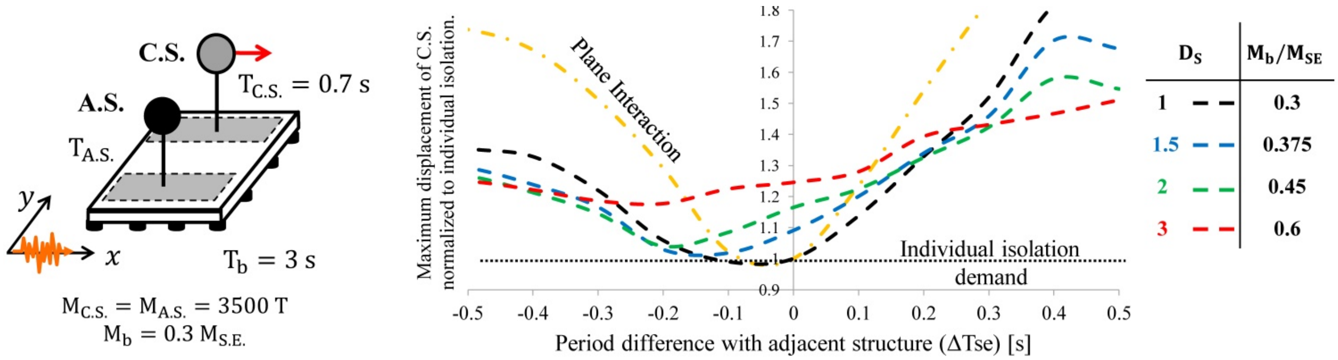


Fig. 10 – Structure–structure interaction as a function of system dispersion with variation of M_b.

6. Analysis Direction and Structure Fragility

The numerical definition of the system dispersion parameter (D_S) was designed to be applied in this research only, however its conceptual definition - the degree of separation between structures measured perpendicular to the analysis direction - can be applied to more general situations. Consequently, a given system can present different values of D_S according to the analysis direction, since the distance between structures varies when measured along each principal axis. Furthermore, when analyzing the global fragility of a system, there will always be a direction in which structures are aligned and will experience a significant interaction due to a low D_S - almost similar to plane interaction - if they present a difference of period.

To address this subject, and as a method for attaching an order of magnitude to the conclusions reached in the previous analyses, a series of more complex, statistically reliable analysis was made using fragility curves. These are constructed for a C.S. of a fixed period 0.7 s and mass equal to 3500 T. Each curve represents a certain property assigned to the A.S. (in particular, the period will be varied). All remaining properties of both the structures and the isolation system were detailed in Chapter 2. Nineteen Chilean seismic records were used, rotated through 0°, 30°, 60° and 90°, giving a total of 76 different bidirectional seismic motions [15]. PGA was chosen as a simple seismic intensity parameter; an average of 0.5 g and standard deviation of 0.25 g was registered. All records were normalized and scaled following the procedure presented in [16]. Inter-story drift was chosen as the structure damage parameter, using the method presented in [17] to convert the equivalent structure global drift to the real structure inter-story drift. According to recommendations and conclusions presented in [18] and [19], all curves were constructed for an inter-story drift of 3‰, which represents a slight-damage state and also a limit state for structure design according to [20].

Fig.11 shows the modification of Control Structure fragility caused by common isolation with a period-dissimilar Adjacent Structure. It can be seen that in the analysis direction in which structures are aligned (in this case, the *y*-axis), structure fragility is deeply affected by the A.S. period, almost similar to what would occur in plane motion interaction; that is to say, the global fragility of the Control Structure would be highly modified when isolated with a period-dissimilar adjacent structure, regardless of system dispersion. The magnitude of the modification depends on the period difference and frequency content of the seismic motion, but fragility can easily achieve twice its initial "individually isolated" magnitude (especially if the C.S. consists in the rigid structure). This effect is independent of structure separation, since interaction magnitude is determined by the direction in which the two buildings are aligned.

On the other hand, if fragility along global axis *x* is analyzed, the distance between structures assumes an important role. As the two structures are placed further apart, slighter modifications to the fragility curves were registered, especially when the C.S. is isolated with a more rigid adjacent building.

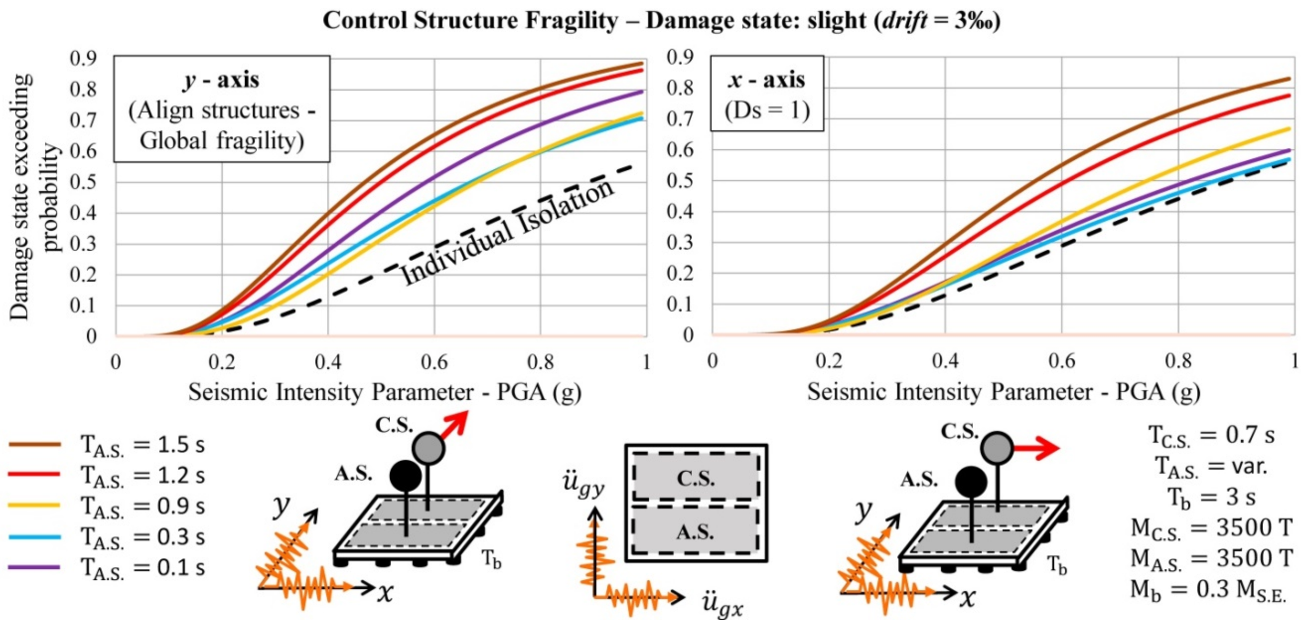


Fig. 11 - Control Structure fragility as a function of the Adjacent Structure period.

7. Superstructure Mass Eccentricity

Mass difference between structures has also been broad on this research, but due to extension limitations it won't be discussed in this document, yet introduced briefly: when two structures placed symmetrically on a symmetrically isolated system present a difference in their mass, a differential displacement between the isolators under each structure occurs. In particular, isolators under the heavier structure will experience higher displacements than those under the lighter structure. Isolators displacement relates directly with the seismic demand transmitted to the superstructure: high isolator displacement delivers a high period and therefore high energy reflection will take place. On contrary, if displacements are low, devices will deliver a low isolated period and more energy will be transmitted to the superstructure, leading to higher seismic demand. Therefore, higher seismic demand will be transmitted to the lighter structure and lower demand to the heavier structure (in comparison to their individually isolated demand).

Contrary to what occurs with a period difference between buildings, mass difference is practically irrelevant when the structures are close together (or in plane motion), as the displacements of all isolators will tend to level out. However, it gains importance as structures tend to be further apart (higher system dispersion), in which case the effects over each building are proportional to $M_{A.S.}/M_{C.S.}$ ratio. In such a case, it should be corrected by placing the isolation system center of stiffness ($e_{K\,b}$) near the superstructure center of mass ($e_{M\,S.E.}$), that is to say, a stiffness eccentricity in the isolation system of a similar magnitude and direction as the mass eccentricity of the superstructure should be provided. As this occurs, torsion decreases considerably, the demand on the structures tend to equalize and they tend to behave, to some degree, like individually isolated structures, but will never reach this situation completely. This behavior can be observed in Fig.12, where maximum displacement of C.S. is plotted as a function of the mass of the A.S. represented by the ratio $M_{A.S.}/M_{C.S.}$. Results are normalized to individual isolation. All cases consider $M_b/M_{S.E.} = 0.3$.

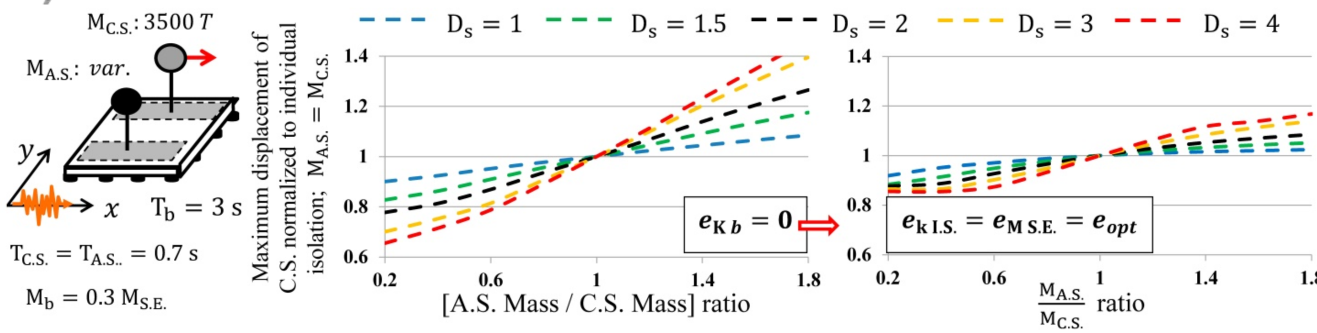


Fig. 12 - Structure–structure interaction caused by mass difference between structures.

8. Main Conclusions

The dynamic behavior of a multiple-building base-isolated system has been characterized using a simplified case of two structures on a common isolation system. An important interaction was found between the properties of one structure and the response of the other. This happens as a consequence of higher vibrational modes, in which each structure affect the dynamic of the common isolation base as a function of their properties and distribution on the slab. Consequently, an indirect bond between both structures emerges, in which the modal properties and response of one structure (e.g. its seismic demand) depend on the parameters of the adjacent building (s). This was called Multiple Building – Base Interaction or structure-structure interaction.

In particular, when structures present a difference in their flexibility, the seismic demand of both buildings is expected to increase. This is mostly function of their period difference, building separation and analysis direction. Particularly, on the axis in which structure are aligned (in the case of two buildings) - or when both structures are close to each other - a significant structure-structure interaction will occur and both structures will experience an important increase in their seismic demand. This translates into a higher inter-story drifts (or base shear) and it is proportional to period difference, but stronger in the more rigid structure. On contrary, when structure are further away from each other, and if analysis is made perpendicularly to structure separation, structure-structure interaction is highly diminished and both structures tend to act (or to be seismically demanded) as two individually isolated structures.

When structures global fragility is analyzed, it is not an overstatement to say that, for a given system, if structures present significant dissimilarities in their period, they will always experience an increment on their seismic demand, since interaction magnitude is determined by the direction in which they are aligned. This interaction cannot be corrected through a stiffness eccentricity on the isolation system.

In addition, as structures are placed further away from each other, higher seismic demand will be transmitted to each/all building, as consequence of a higher isolation system mass (higher M_b/M_{SE} ratio), due to larger dimensions of the common slab and an increase of free/common isolated spaces over the slab.

On the other hand, if structures present a difference in their mass, but isolators stiffness is not distributed accordingly, the heavier structure will induce a higher translational displacement demand to the isolators under it. On the contrary, isolators under the lighter structure will experience less translational displacement. I.e. a torsional motion will occur, leading to differential displacement between the isolators under each building. Consequently, a higher seismic demand will be transmitted to the lighter structure and a lower demand will be transmitted to the heavier structure (in comparison to their individually isolated demand). In simple words, the heavier structure will experience a “higher isolation period” than the lighter structure. This situation gains importance as structures are further apart, since each structure tends to individualize from its counterpart, and should be corrected by a stiffness eccentricity in the isolation system of a similar magnitude and direction as the mass eccentricity of the superstructure. As this occurs, the demand on the structures is equalized and they tend to behave, to some degree, like individually isolated structures, but never achieving this situation completely.

All analyses were based on a modal analysis of the plane system and in several non-linear simulations of both the plane and the spatial system. All conclusions were verified through a series of more complex and statistically reliable analyses, using fragility curves. The results indicate that, according to mass or period differences, the global fragility of a structure can be easily doubled if isolated with a structure of dissimilar properties on a same common system. The magnitude of this effect will depend on the seismic motion, since each modal form effect can be increased or reduced according to its modal period and the seismic frequency content. However, this aspect was not fully broad on this research.

In addition to mass and period difference between buildings, other parameters were analyzed to observe if they generate structure – structure interaction or if they affect the presented structure–structure interaction. These parameters include isolator's distribution and density; yield displacement of both isolators and structures; post-yielding / pre-yielding stiffness of both isolators and structures; isolation period; among others. However, results are not presented on this document, as they are less significant and require more extension to be introduced.

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