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BEHAVIOR OF RC FRAMES WITH HYSTERETIC DAMPERS CONSIDERING DYNAMIC SOIL STRUCTURE INTERACTION

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ABSTRACT: The amount of energy dissipated by hysteretic dampers depends on the magnitude of their drift, which in the most common arrangements is related to the story drift. In general for structures placed on soft soils Dynamic Soil Structure Interaction (DSSI) could modify the response of the structure. Variations on displacement distribution within the structure produced by DSSI may have an influence on dampers behaviour. In this work, the behaviour of hysteretic dampers placed on a 10 story RC-frame when considering DSSI is studied. Plane frames are considered and the DSSI is introduced as a set of springs at the base. The springs stiffness' correspond to the magnitude of the impedance functions of the soil-foundation system. Hysteretic dampers are placed on a Chevron braced system considering that frame and damper-brace systems have the same stiffness. Frame elements and braces are considered to behave elastically. A medium-soft soil record was used as input motion and four soils stiffness' were considered. The amount of energy dissipated by the hysteretic dampers is compared for different soil conditions. It is shown that base flexibility modifies the energy that dampers dissipate.

1. Introduction

Use of devices to control seismic response of structures has become more common in the last decades, as an alternative solution to reduce economical and social impact of earthquakes in structures and society. All around the world, a great amount of research, booth analytical and experimental, has been done related with this topic (Tena-Colunga 2000,Symans et al. 2008, Withaker et al. 1999, Soong and Spencer, 2002, among others). The main scopes of these researches is to establish under what scenarios and conditions, control devices are more effective in reducing different structural responses (displacements, velocities, accelerations, internal forces, etc.)

One of the most used devices is the hysteretic damper, in which the energy dissipation depends on the inelastic behavior of the device. The main goal of this kind of devices is to concentrate the damage and inelastic behavior in the damper, keeping the structure elastic and without damage. These devices may add stiffness or damping to the structures that may help to control structural response. The amount of energy dissipated depends on the magnitude of their drift and plastic deformations (Symans et al. 2008), which in the most common arrangements is related to the story drift.

A great number of studies about the effectiveness and behavior of hysteretic dampers on structures have been conducted considering a fixed base of the structure (Tena-Colunga 2000, Soong and Spencer 2002, Witthaker et al. 1999). This hypothesis is accurate if the soil-foundation stiffness is large enough to ensure no relative displacement between the ground and the base of the structure. However, in some cases, due to soil flexibility, consideration of a fixed base may not be correct and the influence of base flexibility must be considered. The effects produced by base flexibility on the dynamic behavior of structures are commonly known as Dynamic Soil Structure Interaction (DSSI).

Some of the most acknowledge modifications that DSSI produces to structural behavior are fundamental period lengthen and structural damping modification (Wolf 2005). However DSSI may change the distribution of displacements and deformations within the structure, mainly because the introduction of rigid body component produced by base translation u_0 and base rocking ϕ in addition to the displacements associated to structure deformation u (figure 1). Since the energy dissipated by the hysteretic dampers depends on the story drift, the variations on displacement distribution within the structure produced by DSSI may have an influence on dampers behavior. Previous works have proven that DSSI influence the displacement distributions in the structure (Aviles and Perez-Rocha 2003, Carbonari et al. 2011) and passive control devices efficiency (Stehmeyer et al. 2008, Wu et al. 1999).

In this work, DSSI is included using the concept of impedance function $\widetilde{K_m}(\omega)$. Impedance function relates a dynamic harmonic force $P_m(\omega)$, applied in m direction, to the dynamic displacement $U_m(\omega)$ produced in the soil-foundation system in m direction (frequency dependent dynamic stiffness). This relation is expressed in Eq 1, which considers a massless foundation, so the dynamic part of the problem is associated to soil mass. Impedance functions include also the additional damping produced by soil-foundation system. Additional damping is produced by two main sources, soil hysteretic behaviour and energy radiation from foundation to soil (Wolf 2005). Different impedance functions must be defined for each degree of freedom for the base, considered in the problem. Only horizontal and rocking impedance are used in the present study (m=h and r). Impedance function is expressed in terms of an equivalent spring stiffness (k_m) and equivalent dash-spot constant (c_m) as in Eq. 1.

$$\tilde{K}_m(\omega)=\frac{P_m(\omega)}{U_m(\omega)}=k_m+i\omega c_m \qquad (1)$$

where ω is the frequency of the harmonic force and displacement.

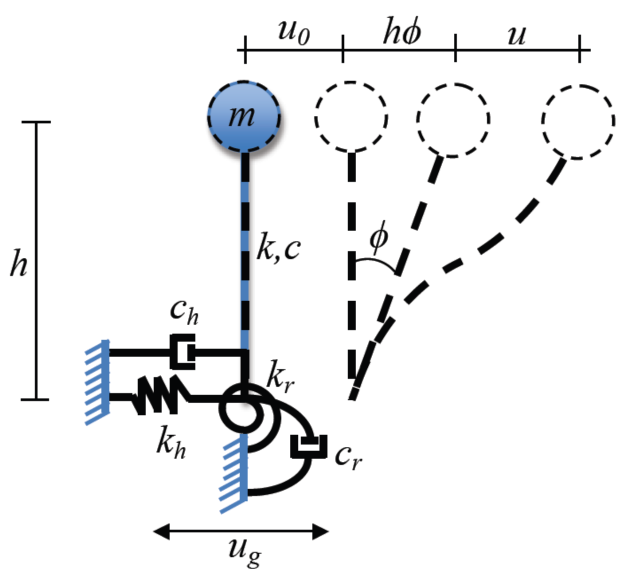

Fig. 1. Displacement components in a flexible base structure.

Since a non-linear time domain analysis is performed, the frequency dependence of impedance functions cannot be considered, so the value corresponding to the fundamental period of the structure with flexible base is used. In addition, soil non-linearity is taken into account by the use of its properties corresponding to the expected deformation levels (Rosset and Scalleti, 1979).

As mentioned before, the main objective of using hysteretic dampers is to dissipate energy by plastic behaviour of dampers material, so system effectiveness can be defined by computing the percentage of total energy dissipated by the hysteretic dampers. In this work, the energy concept established by Uang and Bertero (1990) is used. By the principle of conservation of energy, it can be established that the energy introduced to a building by an earthquake (input energy E_0) must be equal to the energy absorbed by the different mechanisms of dissipation (Eq. 2)

$$\mathrm{E}_0 = \mathrm{E}_\mathrm{E} + \mathrm{E}_\mathrm{K} + \mathrm{E}_\mathrm{H} + \mathrm{E}_\mathrm{D} \tag{2}$$

where E_0 corresponds to the total input energy, E_E is the energy dissipated by structures elastic deformation, E_K is the kinematic energy dissipated by structures displacement, E_H is the energy absorbed by material hysteretic behaviour and E_D is the energy dissipated by damping. The main idea of using hysteretic dampers is to concentrate the energy dissipation by material hysteresis in the elements designed for such end (hysteretic dampers).

Cumulative input energy can be computed at time t with Eq. 3 (Christopoulos and Filiatrault, 2006):

$$\mathrm{E}_0(t) = \mathrm{E}_0(t-\Delta t) + \frac{1}{2}\left(\left\{\ddot{x}_a(t-\Delta t)\right\} + \left\{\ddot{x}_a(t)\right\}\right)^T [M]\{r\}\left(\left\{x_g(t)\right\} - \left\{x_g(t-\Delta t)\right\}\right) \tag{3}$$

where $\mathrm{E}_0(t)$ is the cumulative input energy, $\{\ddot{x}_a(t)\}$ is the vector of absolute acceleration of the structure at time t, $[M]$ is structures mass matrix, $\{r\}$ is an unitary vector and $\{x_g(t)\}$ is the ground displacement vector at time t.

On the other hand, the energy absorbed by the hysteretic damper at time t, can be computed with Eq. 4 (Christopoulos and Filiatrault, 2006)

$$\mathrm{E}_\mathrm{H}^i = \mathrm{E}_\mathrm{H}^i(t-\Delta t) + \frac{1}{2}\left(F_r^i(t-\Delta t) + F_r^i(t)\right)\left(u^i(t) - u^i(t-\Delta t)\right) \tag{4}$$

where $F_r^i(t)$ and $u^i\ (t)$ are the internal force and relative displacement of the i-th damper at time t.

2. Model description

A 10-story reinforced concrete (RC) frame, with three bays is studied. Hysteretic dampers are placed at the top of a Chevron bracing configuration. Damper-brace system has the same lateral stiffness than the simple frame (Figure 2) in each story. Yield force of dampers in each story was established as a fraction of the story shear as proposed in Christopoulos and Filiatrault (2006). Brace-damper system provides 50% of lateral stiffness. Fundamental periods with fixed base are shown in table 2 (FB). More details of frames design and properties can be consulted in Martinez-Galindo (2014). Frames were designed as part of a complete regular building with four parallel frames. The building has a square footprint of 18 x 18 m.

Time domain non-linear analysis is performed with OpenSees software (Mazzoni et al. 2006). Frame elements (beams and columns) were modeled as elastic elements, as well as the braces, considering that the whole inelastic behavior will be concentrated in the hysteretic devices. In the design of frames with hysteretic dampers, a detailed design and collapse mechanism check must be done to ensure that actually all inelastic behavior will be concentrated on the damper (Tena-Colunga and Nangullasmu 2014). In the present study is supposed that the design of dampers was done under these considerations, so desired collapse mechanism is ensure. Braces develop only axial force. Hysteretic damper was modeled as an element with no length, the non-linear behavior was considered with in the inelastic force-displacement relation of the device. A perfectly elasto-plastic behavior was considered. Dampers and structure model were calibrated with previous analytical solutions. Details of calibration can be consulted on Martinez-Galindo (2014).

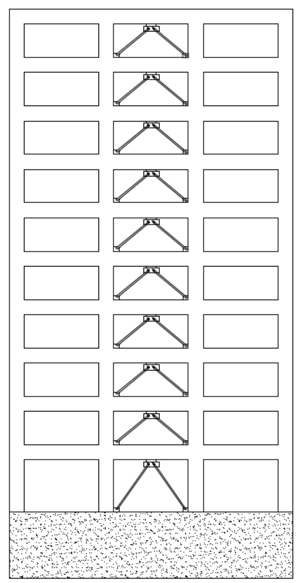

Figure 2. Scheme of damped braced frame.

Foundation consists on mat foundation overlaying a homogenous soil layer of 40 m depth. The foundation is embedded 5 m. Four soil types with different shear wave velocities for flexible base cases were considered. Shear wave velocity is a measure of soil stiffness. Previous studies had used similar values for soil shear wave velocities (Carbonari *et al*. 2011). Shear wave velocities (V_s), mass densities (ρ) and Poisson ratios (ν) of used soil types are reported on table 1. For all soil types, the same ground motion was used, neglecting the modifications of site effects produced by soil stiffness differences. Site effects variations are neglected to establish in a better way the variability introduced only by base flexibility. Ground motion corresponds to Viveros station record of the 09/19/1985 Mexico City earthquake (BMDSF), which corresponds to a medium-soft soil with dominant periods around 0.6-0.8 s (figure 3). Kinematic interaction also is neglected. In order to achieve a full non-linear behavior of dampers, excitation was scaled to meet spectral pseudo accelerations around 1 g for structures fundamental periods with fixed and flexible base.

Table 1. Soil properties

Soil type	V_s (m/s)	ρ (t/m^3)	ν
S4	400	1.6	0.49
S3	250	1.6	0.49
S2	100	1.6	0.49
S1	70	1.6	0.49

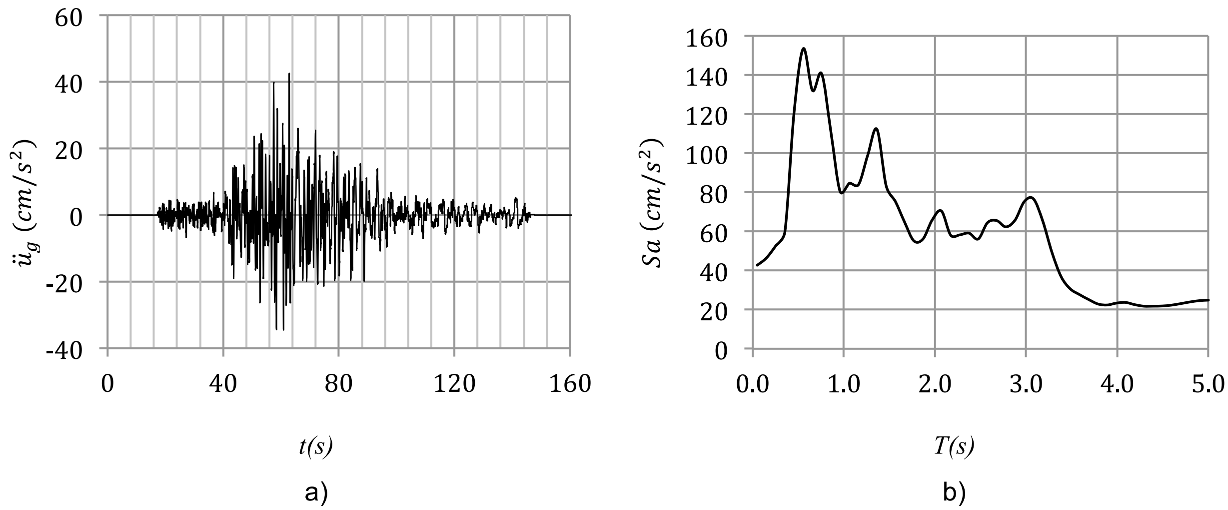

Figure 3. 1985 Mexico City earthquake, Viveros station a) ground acceleration b) pseudo acceleration response spectrum.

Software DYNA6 (Novat *et al.* 2012) was used to estimate horizontal and rocking impedance functions. Mat foundation of the whole building was considered. As mentioned before, impedance function values are frequency dependent. Since a time domain analysis was performed, only the value corresponding to the fundamental frequency of the structure was used. Given that the period of the structure with flexible base ($\tilde{T}_e$) and base flexibility are mutually dependent, it is necessary to perform an iterative process to establish the definitive values of impedance functions. Soil-foundation system stiffness' (k_h and k_r) and periods of the structure with fixed and flexible base are presented on table 2. Additional damping introduced by DSSI is taken into account by using an effective damping ratio. Effective damping ratio was computed with the procedure included on Mexican building code (NTCDS-04):

$$\tilde{\zeta}_e = \zeta_e\left(\frac{T_e}{\tilde{T}_e}\right)^3 + \frac{\zeta_h}{1+2\zeta_h^2}\left(\frac{T_h}{\tilde{T}_e}\right)^2 + \frac{\zeta_r}{1+2\zeta_r^2}\left(\frac{T_r}{\tilde{T}_e}\right)^2 \qquad (5)$$

where ζ_e and T_e are the damping ratio and fundamental period of the fixed base structure, T_h and T_r are the fundamental period of the structure vibrating as rigid body in translation and rocking respectively and ζ_h and ζ_r are equivalent damping ratios of the energy dissipated by base translation and rocking. Equivalent damping ratios and effective damping ratios for all soil types are presented on table 2.

Since impedance functions computed correspond to the complete foundation, and only individual frames were analyzed, the total soil-foundation stiffness was distributed in to each frame. This distribution was done proportional to the lateral stiffness of each frame and considering that foundation system is rigid. Since all frames had the same lateral stiffness, there is no eccentricity. Under these conditions, corresponding base stiffness of each frame is 25% of the total soil-foundation stiffness reported on table 2. With frame base stiffness computed, a set of two springs (horizontal and rotational) was included at the middle of frames base (figure 4).

Table 2. Flexible base properties of the structure

Soil	$\tilde{T}_e\ (s)$	$k_h\ (t/cm)$	$k_r\ (t\text{-}cm)$	$\zeta_h (\%)$	$\zeta_r (\%)$	$\tilde{\xi}_e (\%)$
FB	0.74	∞	∞	0	0	5
S4	0.75	$6.83\text{x}10^3$	$8.91\text{x}10^9$	2.6	2.5	4.9
S3	0.78	$2.37\text{x}10^3$	$3.02\text{x}10^9$	3.1	2.5	4.6
S2	1.00	$3.72\text{x}10^2$	$4.50\text{x}10^8$	22.1	2.6	4.9
S1	1.23	$1.77\text{x}10^2$	$2.09\text{x}10^8$	25.6	0.23	4.6

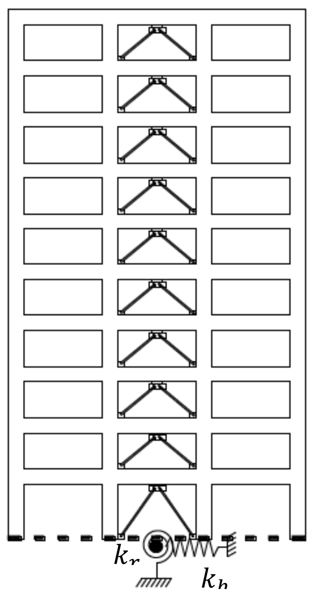

Figure 4. Model of base flexibility

3. Numerical results

To establish the behavior of hysteretic dampers, non-linear analysis in time domain was performed. On figure 5, the hysteretic curves of control devices are shown. Curves of lateral force vs drift relation are presented. Damper drift was computed as the relative lateral displacement of the corresponding story. It is important to mention that because of base flexibility, floor displacement includes components introduced by rigid body behavior of the structure. To compute story and damper drifts, these rigid body components must be subtracted from lateral displacement, since rigid body behavior does not contributes to structures deformation.

From figure 5, it can be seen that for all soil types, tenth story dampers develop smaller drifts and hence dissipates less energy. It is clear that FB damper develops the largest hysteretic curves. As soil becomes softer, fifth story damper dissipates a smaller amount of energy, except for S1. Dampers for S2 soil are the ones that develop the less energy dissipation of all.

The modification of the amount of energy dissipated by hysteretic dampers due to soil types can be associated to a two main effects. First, base flexibility produces a fundamental period shift that may lead to different spectral accelerations. This variation may change the input energy introduced to the system, and so the demand on the whole structure, including the dampers. On the other hand, base flexibility introduces rigid body components to lateral displacement, as mentioned before. These components can change displacement distribution along the structure, producing some modifications on structures deformation and story drifts. Since energy dissipated by dampers is function of story drifts, differences on hysteresis curves can be associated with this effect.

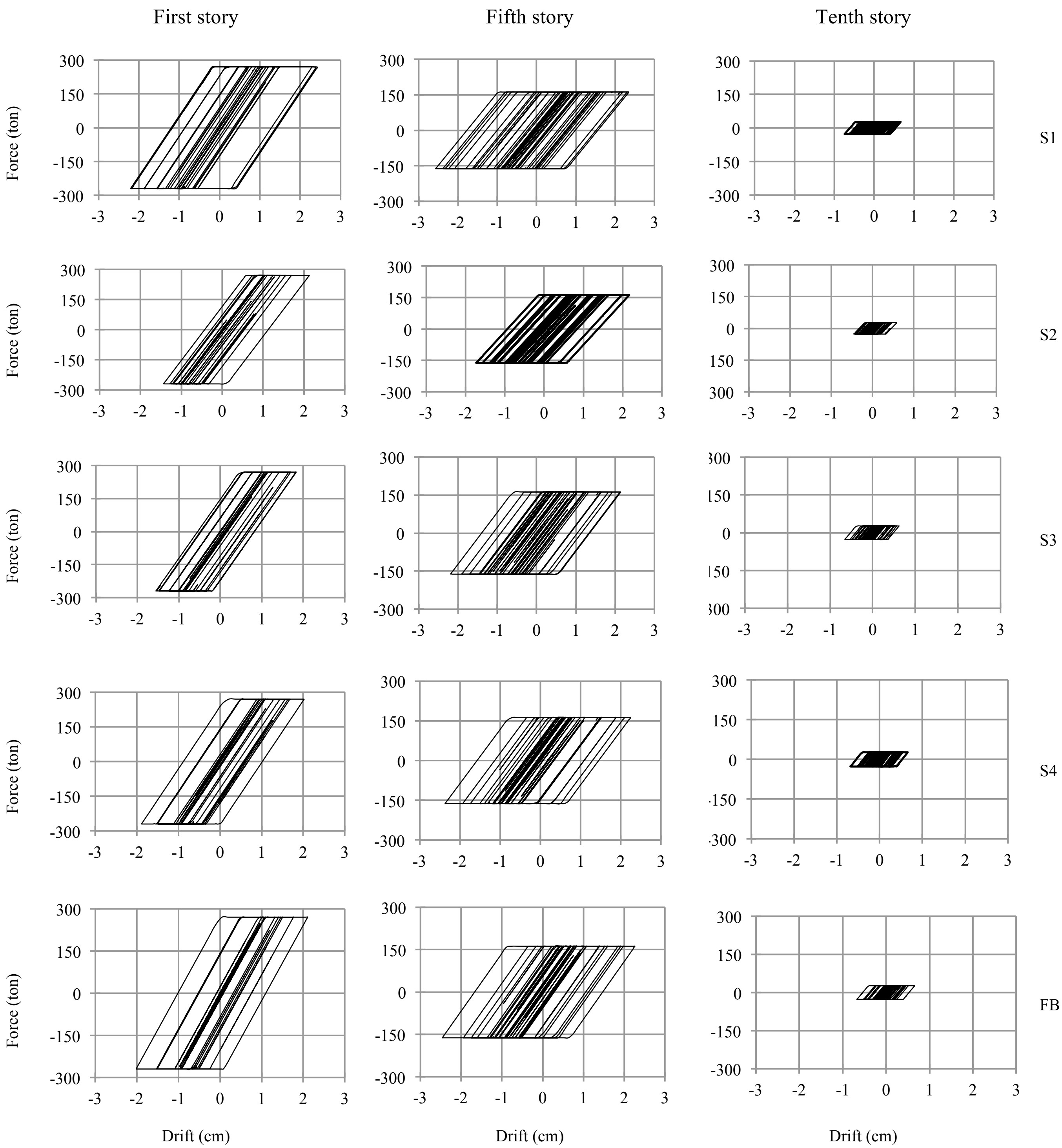

Figure 5. Hysteretic curves of dampers on story 1, 5 and 10, for all soil types.

To assess how damper efficiency is modified by displacement distribution and not because period shift, the comparison of systems input energy and dampers absorbed energy is made. Input energy and dampers absorbed energy are computed with equations 3 and 4. In figure 6, two types of results are shown. On the left side, it is shown the ratio of the energy dissipated by dampers in the system with flexible base respect to the energy dissipated with fixed base for all stories. Values of this ratio below the unit represent that dampers in systems with flexible base dissipate less energy than dampers in the system with fixed base. On the right side, the curves of normalized cumulative input energy and cumulative energy absorbed by all dampers of the frame are shown (E'_0). In these curves, the percentage of total energy absorbed by hysteretic dampers can be observed.

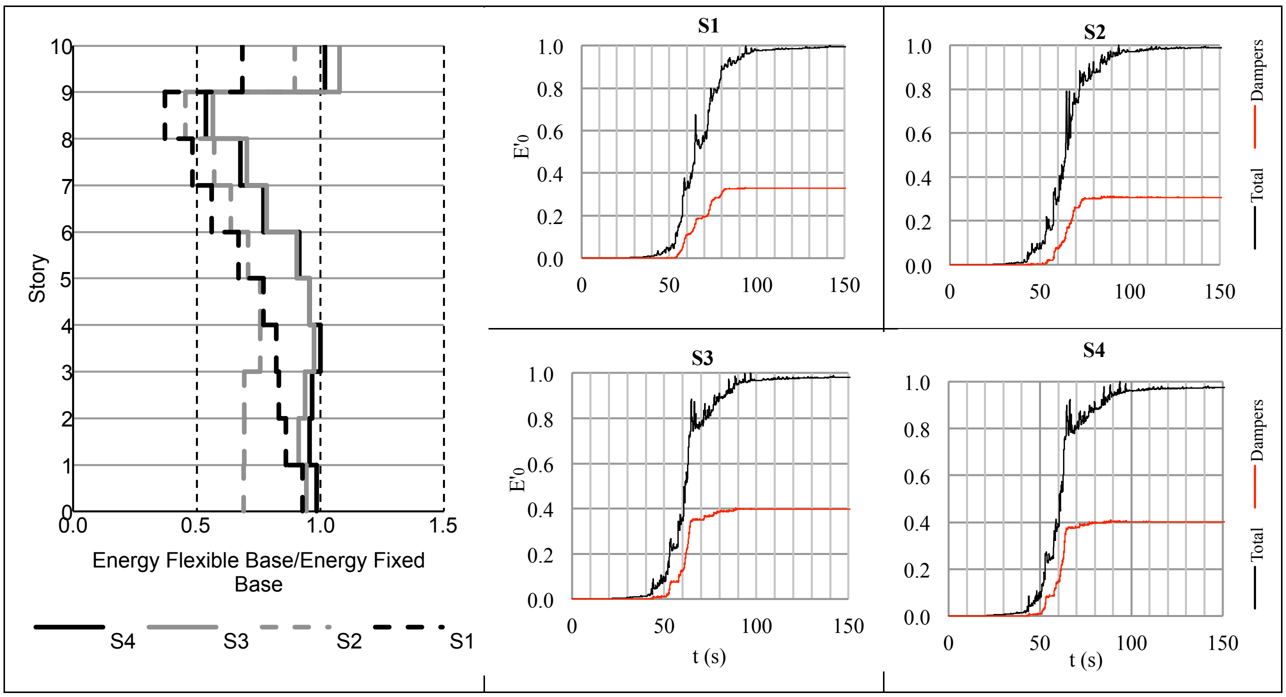

Figure 6. On the left, ratios of the energy absorbed by dampers in systems with flexible and fixed base. On the right, cumulative total and dampers absorbed energy.

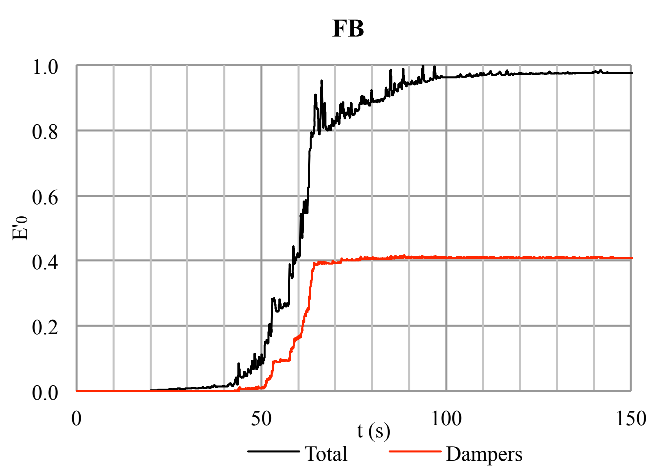

Figure 7. Cumulative total and dampers absorbed energy for fixed base.

From energy ratios shown in figure 6, it is clear that for S1 and S2 soils, all dampers dissipate less energy than in the fixed base structure. For dampers in stories 1-4, the S2 soil produces the less energy dissipation. Dampers in stories 5-10, develop less energy dissipation when soil S1 is considered. For soils S3 and S4, dampers placed on lower levels (1-4) show almost no differences on energy dissipated with respect to fixed base system. However, for upper levels (5-9), a reduction in dissipated energy can be observed. With this, it can be seen that DSSI not only modifies the amount of dissipated energy by dampers, it also changes the relations of how much energy dissipate each damper along structure. This can be established since energy ratios are no constant in frames height. In general, except for the last story, as the damper is placed in upper levels, the reduction in the energy dissipation produced by flexible base consideration becomes larger. In fact, these profiles of energy ratio vary for different soil types, for example S1 and S2 profiles are completely different.

In the cumulative energy curves of figure 6, it can be observed how the percentage of energy dissipated by all dampers in each frame is modified by base flexibility. For S4 and S3 soils, dampers dissipate 40% of total input energy. In the fixed base frame, dampers dissipate 41% of total energy (Figure 7). This amount of dissipated energy is achieved in a slightly larger time period for S3 than for S4 soil (around 20 s after). In the case of S2 soil, dampers dissipate the 31% of total energy. This corresponds to a reduction of 25% of dampers efficiency. Dampers considering soil S1 dissipate 33% of the total energy, a value similar to S2 case. It is worth to notice that since dampers placed on lower levels dissipate the most of the energy, reduction of energy dissipation on upper levels produces almost no change on the global behaviour (S3 and S4). On the other hand, S2 soil produces the greater reductions on lower levels, which is traduced on the biggest efficiency reduction on overall system. This condition produces that, even when S1 soil produces the greater reductions on upper levels, does not produces the greater overall reductions.

4. Conclusions

Modification of hysteretic dampers behaviour introduced by DSSI is explored. The analysis is performed considering 10-story RC frames. Hysteretic dampers are placed at the top of Chevron bracing system. Only lateral displacement and forces are considered in the dampers. Frame elements and braces are supposed to behave elastic; so all inelasticity is concentrated on dampers. Foundation is defined by a mat foundation overlaying a homogeneous layer. Base flexibility is introduced using springs at the base, which represent the impedance functions of the soil-foundation system. Four types of soil with different stiffness' are considered.

Non-linear analysis in time domain is preformed. Dampers efficiency is established by the amount of energy that they dissipate. The hysteresis curves of each damper are also studied, for all base conditions. It is studied the individual and global behavior of the hysteretic dampers.

From individual analysis of the hysteretic curves, it is shown that the energy dissipated by each damper is modified by base flexibility. In his study, it can be seen that as base becomes more flexible, hysteretic curves of dampers are smaller, with the exception of the softer soil where apparently period shift produces an increase in the input energy and in the energy absorbed by dampers.

Comparing the amount of energy dissipated by dampers in a fixed base and a flexible base system, it can be seen that, in general base flexibility produces greater reductions in the energy dissipated in dampers placed on upper levels. These reductions are not constant; they vary depending the base flexibility. This situation may have influence on design decisions.

In the global behaviour, it is shown that when energy dissipated by dampers placed in lower levels has small reductions, the percentage of energy dissipated by all dampers respect to the total energy shows minimum modifications. On the other hand, when the energy dissipated by this set of dampers (1-4 story) is reduced, the percentage of total energy that dampers will dissipate is reduced too. For the most drastic case (S2 soil), base flexibility reduces in 25% the dampers efficiency.

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