Effects of Bi-directional Motion on a Structural System Isolated with DCSS Devices with Laying Defects

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SUMMARY
In the present work, a tridimensional model of double concave surface slider with non-articulated slider has been studied, in order to model the response of the isolator subjected to a generic earthquake motion. The geometric model simulates the possible construction laying defects in terms of inclination of both the sliding surfaces with respect to the horizontal plane, while the hysteretic response has been modeled as a function of the applied vertical load and of the sliding velocity. The model has been employed to evaluate the performance of a reinforced concrete building of three stories, located on a slab layered on a grid of isolators. Particular attention has been focused on the influences of construction laying defect on the response of the whole system, such as the maximum number of contemporary detached devices, the variation of vertical load applied on each device, the variation of the dynamic friction coefficient for each device, and, in general, localized effects on the base slab.

Keywords: DCSS, Laying Defects, Friction Pendulum, Dynamic Friction Coefficient, Bi-Directional Motion

1. INTRODUCTION

The increasing research effort of the last years on friction pendulum systems has underlined a number of issues related to the response of such devices. The horizontal behaviour has been widely studied for the unidirectional motion of single and double concave surface sliders (SCSS and DCSS, respectively), both from the modelling and experimental point of view (e.g. D. Fenz, M. C. Constantinou, 2006). Regarding the bi-directional motion, a limited number of numerical studies is available, and tests on full scale devices have been carried out, but the accessible data are limited. Moreover, from a design point of view, devices are always assumed to be installed in ideal conditions, without accounting for the actual installations, which may imply construction laying defects such as the uneven inclination of the sliding surfaces with respect to the horizontal plane.
A recent study on complex system isolated with DCSS devices has been carried out (A. Pavese et al., 2011), using a plane (radial) model of the DCSS device, accounting for the possible construction laying defects. In such work the horizontal response of a case study has been computed, applying a unidirectional sinusoidal displacement time history at the base isolated slab of a three storey building. Since the isolator model was plane, the motion could be applied only parallel to the isolator direction of motion. Results were analyzed in terms of the effective contribution of each device to the global response, the contemporary number of detached devices during the simulated motion, the consequent increasing of the bending moment in the slab, and the redistribution of the vertical reactions, i.e. the vertical loads graving on the isolators. Results proved to be interesting, showing a relatively small influence on the global response of the system and more relevant effects at a local level.
In the current endeavour, a tridimensional model of DCSS with non-articulated slider has been studied. The model is based on the geometric definition of the DCSS components coordinates, used to study the device response when installed within complex systems, coupled with an hysteretic model which rules the horizontal response for a generic non-radial motion. The geometric model simulates the possible construction laying defects in terms of inclination of both the sliding surfaces with respect to the horizontal plane, while the hysteretic response is a function of the applied vertical load and of

the sliding velocity.
A case study is presented, in which the model has been employed to evaluate the performance of a reinforced concrete building of three stories, located on a slab layered on a grid of isolators.
Particular attention has been focused on the influences of construction laying defect on the response of the whole system, such as the maximum number of contemporary detached devices, the variation of vertical load applied on each device, the variation of the dynamic friction coefficient for each device.

2. DCSS DEVICE: TRIDIMENSIONAL MODEL

In what follows, the geometric model of the DCSS with non-articulated slider is illustrated, followed by a description of the hysteretic model.

2.1 Geometric model

The tridimensional model of the DCSS device accounts for three degrees of freedom, which are the two horizontal translations u and v and the rotation α about the vertical axis (Fig. 1).
The construction laying defects have been considered as arbitrary inclinations of the sliding surfaces. The inclination of each surface has been analyzed following the geometrical scheme shown in Fig. 2, defined by two reference systems: the former is global with origin at the center of the laying base of the device, while the latter is local with the center at the top laying surface of the device. Hence, for each sliding surface, two parameters are given, ψ_i and β_i (Fig. 2), characterizing the inclination of the surface with respect to the horizontal plane.
Thus, considering the geometrical sizes of all the components, and given the values of each degree of freedom, the total height of the device is obtained by means of a mathematical procedure.

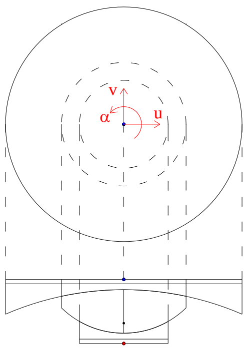

Figure 1. Degrees of freedom of the single device

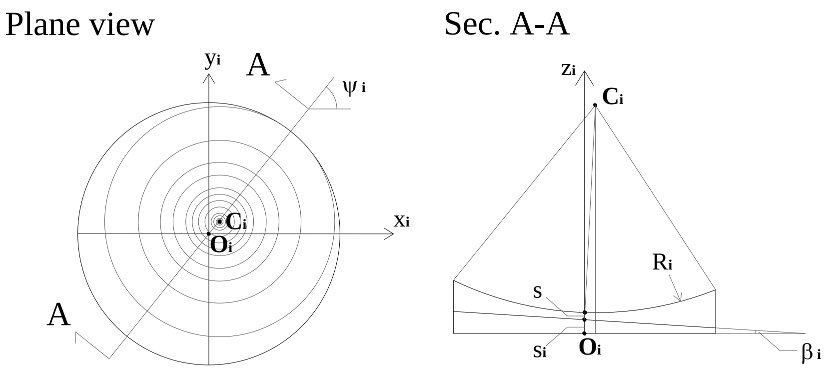

Figure 2. Laying defects: geometrical scheme

2.2 Hysteretic model

In order to model the generic bi-directional horizontal behavior of a DCSS, two contributions of the response have been considered, i.e. the radially oriented restoring force (F_r) and the frictional force (F_f), parallel to the trajectory of the motion, as shown in Fig. 3. differently from a radial plane model, the two forces are no longer parallel, and have to be vectorially summed up.

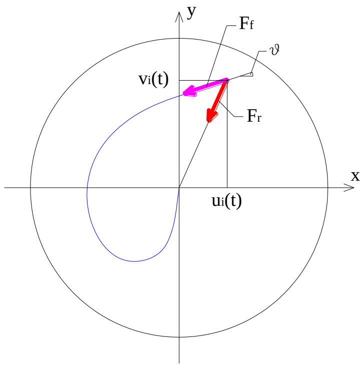

Figure 3. Contributes in the horizontal bi – directional response

The recentering force of the i-th device can be modeled by a linear spring as in the case of unidirectional motion.

$$F_{ri} = \begin{bmatrix} F_{rxi} \\ F_{ryi} \end{bmatrix} = \frac{W_i}{R_{eq-i}} \cdot \begin{bmatrix} u_i \\ v_i \end{bmatrix} \quad (2.1)$$

Wher W_i and R_{eq-i} are the applied vertical load and equivalent radius of curvature (according to the definition of D. Fenz, M. C. Constantinou, 2006), respectively.
Since the frictional force is parallel to the motion trajectory, it is necessary to define the direction of the motion of the upper surface, i.e. the direction of the velocity. The frictional force is expressed as a function of the directional cosines of the velocity of the device (Khoshnondian and Hadgonst, 2009 – Eroz and DesRoches, 2008):

$$F_{fi} = \begin{bmatrix} F_{fxi} \\ F_{fyi} \end{bmatrix} = \left|F_{fi}\right| \cdot \begin{bmatrix} \cos \vartheta_i \\ \sin \vartheta_i \end{bmatrix} = W_i \mu_i \tanh\left(\frac{\sqrt{\dot{u}_i^2 + \dot{v}_i^2}}{\dot{u}_s} \right) \cdot \begin{bmatrix} \dfrac{\dot{u}_i}{\sqrt{\dot{u}_i^2 + \dot{v}_i^2}} \\ \dfrac{\dot{v}_i}{\sqrt{\dot{u}_i^2 + \dot{v}_i^2}} \end{bmatrix} \quad (2.2)$$

Where $\dot{u}_i$ and $\dot{v}_i$ are the translational degrees of freedom of the considered device, and $\dot{u}_s$ is a parameter which describes the shape of the hysteresis loop, fixed equal to 0.01, as suggested by Dupont et al. (2000). The relation between the friction coefficient μ and the acting vertical load W_i has been based on the following equation (Soong and Constantinou, 1994):

$$\mu_i = f_{\max} - (f_{\max} - f_{\min}) \tanh(e \cdot W_i) \quad (2.3)$$

The equation parameters have been calibrated using the experimental results of dynamic tests performed at the EUCENTRE TREES Lab in Pavia, resulting in the curve shown in Fig. 4.

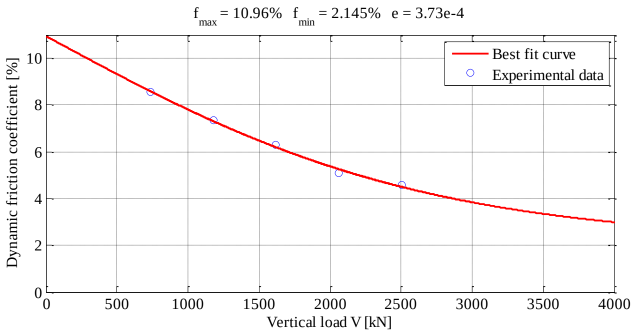

Figure 4. Dynamic friction coefficient versus vertical load: calibration of experimental results

In Fig. 5 and Fig. 6 an example of cloverleaf motion applied to the modelled DCSS device is reported, with the following parameters: dynamic friction coefficient $\mu = 0.1$, applied vertical load $W = 800$ kN and equivalent curvature radius $R_{eq} = 4$ m.

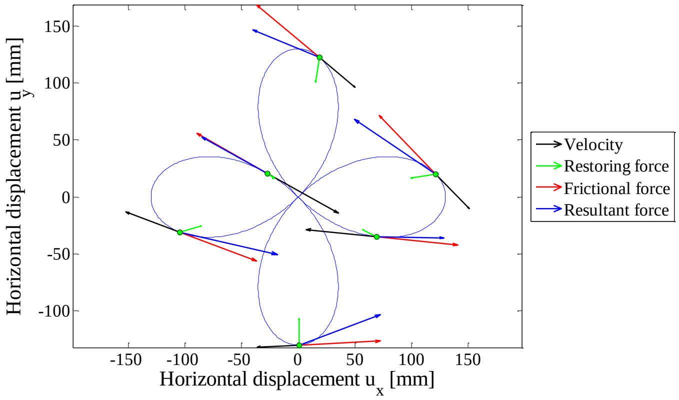

Figure 5. Bi – directional trajectory of the device

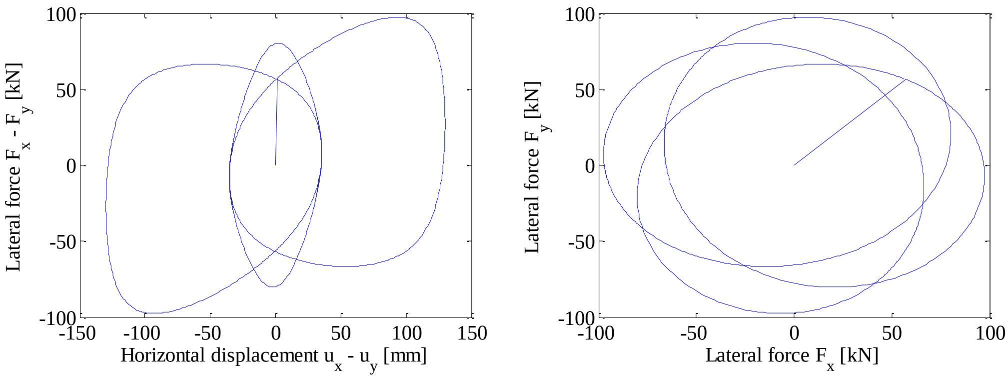

Figure 6. Bi – directional hysteretic behaviour of the device

Fig. 5 shows the force decomposition in frictional and restoring forces at different locations of the trajectory, as red and green vectors respectively, while Fig. 6 shows the hysteretic response in the two main direction of motion. The shape of the loops in x and y looks to be the same, due to the symmetric applied motion, however the two motions are not synchronous: Fig. 6 (right) shows the values of F_x plotted versus F_y. The bi-directional response of a DCSS device is significantly different from the case of radial motion: hysteretic loops are highly nonlinear, compared to the radial case, in which the horizontal response can be easily bi-linearized.

3. ANALYSIS OF ISOLATED SYSTEMS

The aim of the present endeavour is to analyze the response of a structural system isolated with DCSS devices, in order to quantify the consequences of possible laying defects of the isolators, which are likely to occur in actual installations. Particular attention has been focused on the consequences of such laying defects on the displacement response of the whole system, with respect to the ideal case, without any kind of laying defects.

3.1 Modelling of the structure

A simplified structural system has been defined, as shown in Fig. 7. The isolated slab has been modelled with Kirchhoff shell elements for the vertical deformation, considering the whole translational mass M_p and the rotational mass I_p lumped at the centre of the slab CM_p. The building has been modelled as an equivalent linear single oscillator of given mass M_s for each direction of motion, with the natural period corresponding to the first mode: the actual position of the building with respect to the slab is considered, accounting for all the forces transmitted through the point CM_s to the slab, i.e. the base shear in both the directions (V_{sx} and V_{sy}), while the overturning moments are transferred to the slab as variation of vertical load at the actual building column locations. A damping ratio equal to 5% has been assumed.

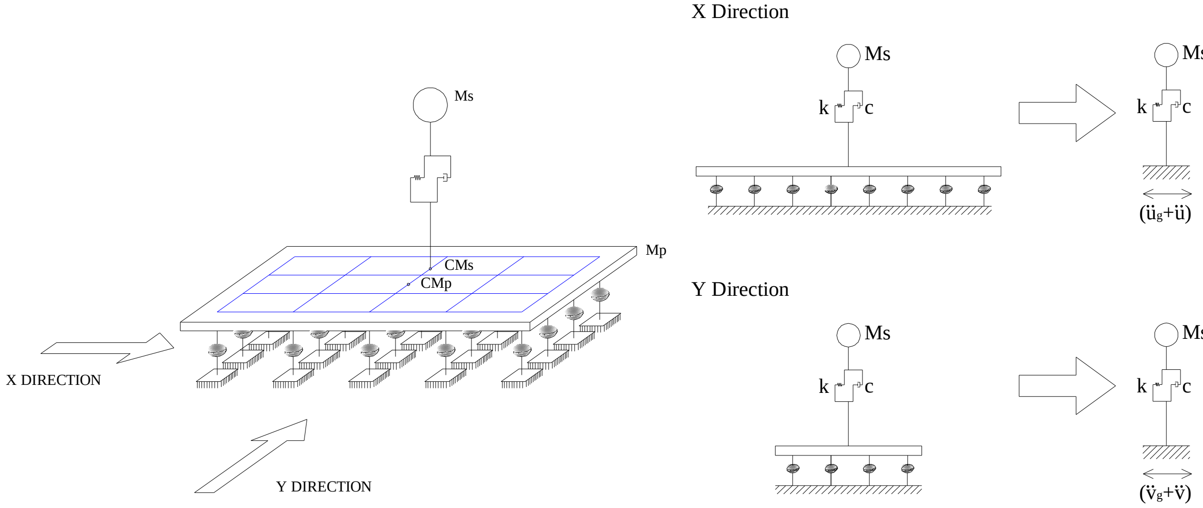

Figure 7. Modelling of the building using an equivalent SDOF per each direction

The displacements of each device, and their time derivatives, can be obtained at each time step as a function of the motion of the isolated slab. Hence, given the degrees of freedom of the slab u, v and α, and according to the assumption of small displacements, the local DOFs of the i-th isolator are computed as:

$$\begin{cases} \alpha_i = \alpha \\ u_i = u - \alpha_i y_i \\ v_i = v + \alpha_i x_i \end{cases} \quad (2.1)$$

The response of the building is found integrating the equation of motion in x and y, considering as external actions the sum of the ground and the slab acceleration, as shown in Fig. 7 (right).
The final equation of the motion of the isolated slab can be written as a function of its degrees of freedom and their time derivatives, of the mass matrix of the slab, of the forces transmitted by the building, of the ground accelerations for both the directions $\ddot{u}_g$ and $\ddot{v}_g$ and of the horizontal forces due to the hysteretic response of each isolator:

$$\begin{bmatrix} M_p & 0 & 0 \\ 0 & M_p & 0 \\ 0 & 0 & I_p \end{bmatrix} \begin{pmatrix} \ddot{u} \\ \ddot{v} \\ \ddot{\alpha} \end{pmatrix} + \begin{pmatrix} \sum_{i=1}^{N} F_{xi} \\ \sum_{i=1}^{N} F_{yi} \\ \sum_{i=1}^{N} \left(-F_{xi} y_i + F_{yi} x_i \right) \end{pmatrix} + \dots$$

$$\dots - \begin{pmatrix} V_{sx} \\ V_{sy} \\ -V_{sx}\left(y_s - y_{CM,p}\right) + V_{sy}\left(x_s - x_{CM,p}\right) \end{pmatrix} = - \begin{bmatrix} M_p & 0 & 0 \\ 0 & M_p & 0 \\ 0 & 0 & I_p \end{bmatrix} \begin{pmatrix} \ddot{u}_g \\ \ddot{v}_g \\ 0 \end{pmatrix} \quad (2.2)$$

Whereas for the building, only the translational degrees of freedom u_s and v_s have been considered, accounting for the stiffnesses and the damping coefficients in both directions:

$$\begin{bmatrix} M_s & 0 \\ 0 & M_s \end{bmatrix}\begin{pmatrix} \ddot{u}_s \\ \ddot{v}_s \end{pmatrix} + \begin{pmatrix} c_x \dot{u}_s \\ c_y \dot{v}_s \end{pmatrix} + \begin{pmatrix} k_x u_s \\ k_y v_s \end{pmatrix} = -\begin{bmatrix} M_s & 0 \\ 0 & M_s \end{bmatrix}\begin{pmatrix} \ddot{u} + \ddot{u}_g \\ \ddot{v} + \ddot{v}_g \end{pmatrix} \tag{2.3}$$

The two systems (the slab and the building), i.e. the two equations, are coupled: in fact, the response of the slab is a function of the forces transmitted by the building, whereas the response of the building is a function of the absolute acceleration of the slab. Such a formulation has been chosen since the most suitable for the time integration procedure defined in the next paragraph.

3.2 Nonlinear time history analysis procedure

Given the high nonlinearity of the system, an explicit time integration method has been implemented, i.e. the Backward Euler method, according to which all the derivatives are expressed with the difference quotient, and all the other quantities are referred to the previous time step. Such a method does not provide the equilibrium stepwise (Butcher, John C., 2003): however, if the time step is small enough, the values of the residual sum of all the forces are closer to the zero mean value, with a reduced standard deviation. The implemented procedure is shown in Fig. 8.

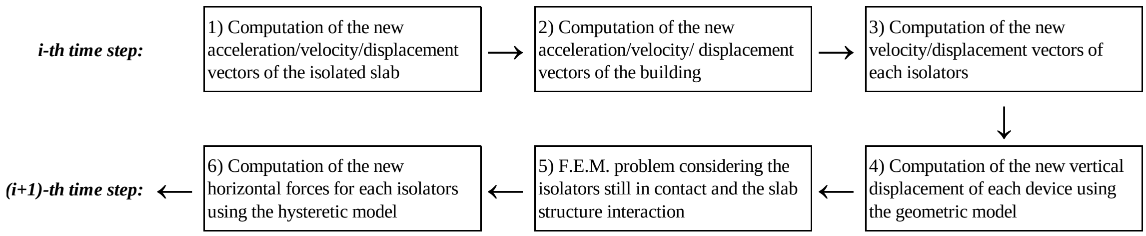

Figure 8. Non-linear time history analysis procedure

The F.E.M. procedure is able to recognize if each device is in contact, either removing from the boundary conditions all those isolators which start to experience a tensile reaction, or adding all those points of the slabs, where there is compenetration between slab and device. At each time step the stiffness matrix is accordingly updated.

4. CASE STUDY

The case study consists of a three storey RC building (Fig. 9), built on an slab, isolated with forty DCSS devices, and having sliding surfaces with equal curvature radii (A. Pavese et al., 2011). The building mass is 2058 tons, lumped at 67% of the total height; the stiffness and the viscous damping coefficient have been computed considering the value of the first period, equal to 0.48 sec and a damping ratio of 5%. The devices have two sliding surfaces with a curvature radius of 2 m, with the friction coefficient as previously described (Fig. 4).

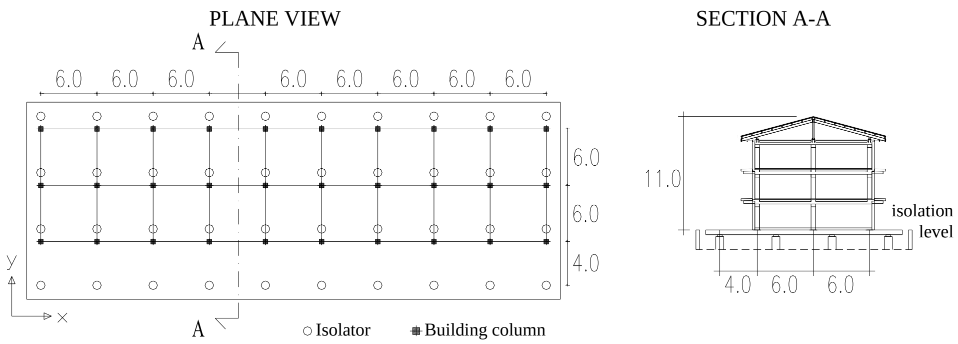

Figure 9. Case study: main characteristics

It can be noted that the building is eccentric with respect to the centre of mass of the slab: assuming unidirectional motion (in the x direction), this aspect, together with considering the dynamic friction coefficient as a function of the vertical load, is expected to cause a small amount of torsional rotation and negligible transversal displacements of the slab even with perfectly installed devices; on the other hand, if the construction laying defects are modelled, the uneven redistribution of the vertical load caused by the detachment of the devices is expected to induce bi-directional motion.

The system has been subjected to the most severe component of the mainshock of the IRPINIA earthquake (1980), scaled to a PGA value of 0.36 g (Fig. 11), applied firstly along the x direction (case a), then with an angle of 35° with respect to the x direction (case b), as shown in Fig. 10.

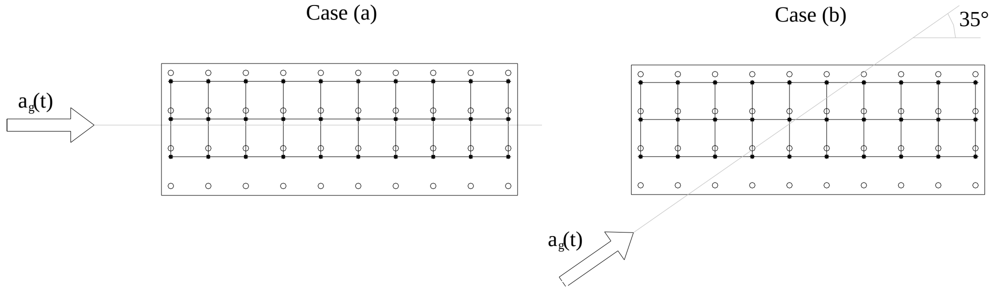

Figure 10. Considered directions of earthquake occurrence

The former case is studied to understand if the construction laying defects alone can induce displacement in the y direction and torsional rotation of the slab, compared to the reference case with ideally layered isolators. Case b can underline if the torsional effects are amplified with a different occurrence direction of the earthquake.
The construction laying defects have been simulated by considering for each device the sliding surface inclinations as varying parameters randomly selected up to a maximum absolute value equal to 1.5°, in order to analyze the system under extreme conditions. Five analysis per case have been carried out, together with the ideal reference case, with ideally co-planar isolators.

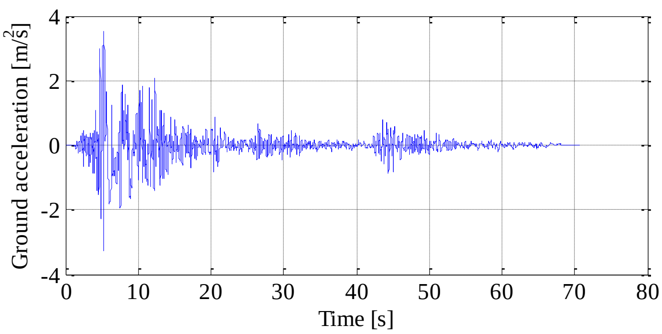

Figure 11. Input signal of the analysis

4.1 Results

In what follows, the results of the analyses are reported. Fig. 12 shows the displacement response of the isolated slab: it can be noted that the peak displacement increases significantly (about 80 mm) accounting for the construction laying defects in the unidirectional motion (case (a)), causing few millimetres of transversal displacement in y direction; whereas in the case (b) the difference between peaks is not relevant. In both the cases the slab rotation assumes low values, which tend to increase considering the defects, because of the redistribution of the vertical loads due to the detachments of some devices, with the consequent influence on the dynamic friction coefficient and on the horizontal response of the isolators.

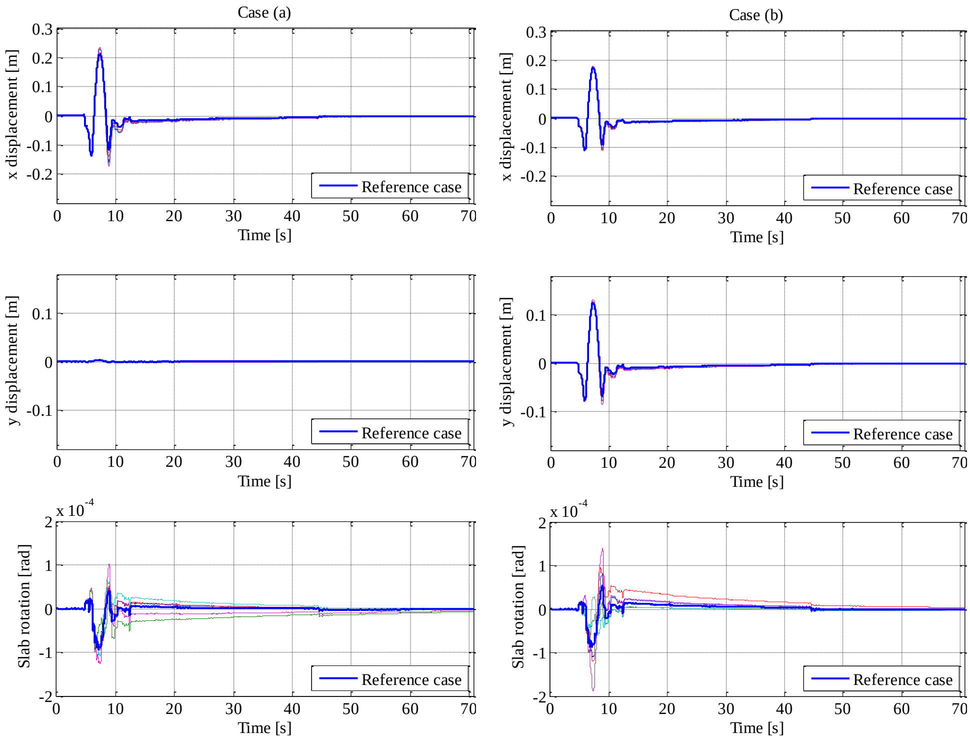

Figure 12. Displacements of the slab versus time, case a (x-motion, left) and case b (35°-motion, right)

Fig. 13 shows the response of the building, in terms of relative displacement between the lumped total mass and the isolated slab. For both the cases the maximum experienced displacement is about 1 cm. moreover, in the unidirectional motion the transversal displacement in the y direction is negligible.

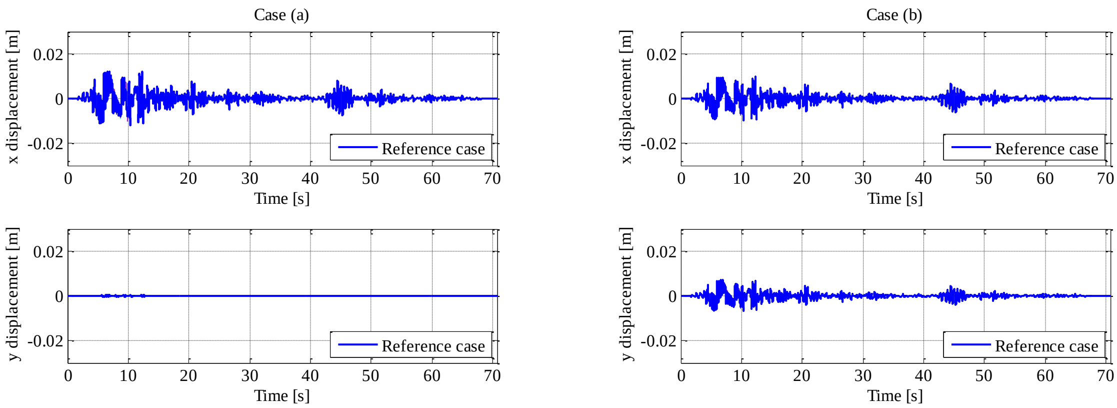

Figure 13. Relative displacements of the building (M_s) with respect to the base slab versus time, case a (x-motion, left) and case b (35°-motion, right)

Fig. 14 shows the number of devices which simultaneously lost contact at each time step. The reference case for both the cases, has shown, as expected, zero detached devices in the whole duration of the event. The number of detached devices for case a is considerably higher compared to case b: this is the reason why the whole response of the system is more affected by the presence of defects.
Fig. 15 shows the global hysteretic response. Results are in good agreement with the previous study (Pavese et al., 2011). Considering the laying defects, the hysteretic loop of the whole system becomes smaller, compared to the reference case, with lower values of base shear, which imply a higher seismic demand in terms of lateral displacements. In the bi – directional motion the difference between the reference case and the other analysis is less important: particularly, it can be noted that, for a given value of displacement, the base shear does not decrease as much as in the unidirectional case (a), resulting in seismic demand comparable to the reference case.

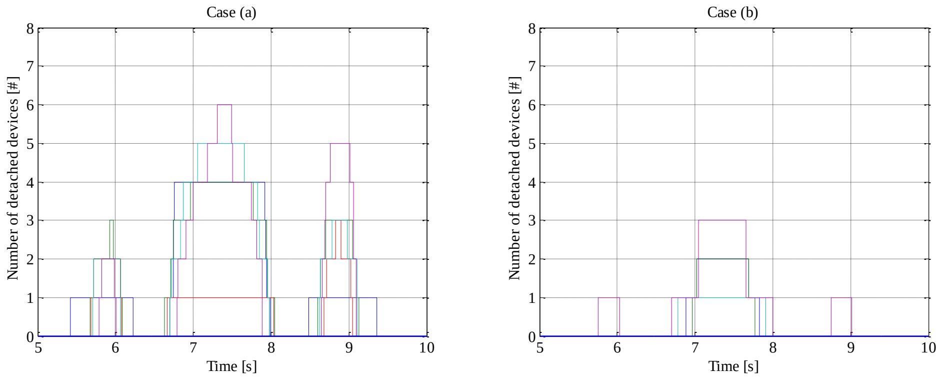

Figure 14. Number of detached devices vs. time, case a (x-motion, left) and case b (35°-motion, right)

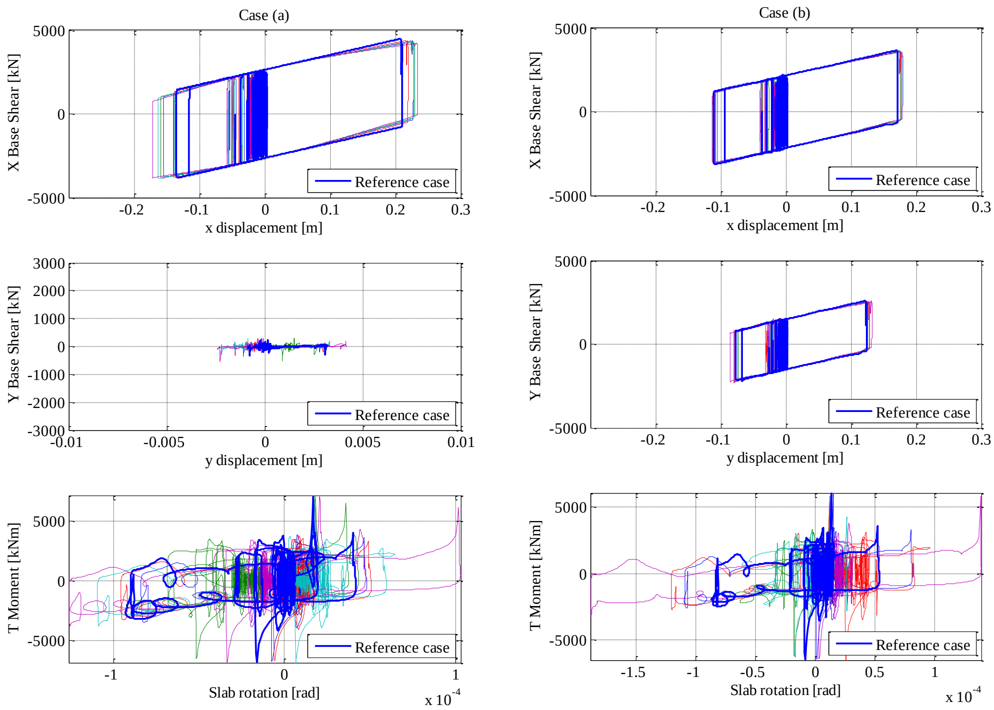

Figure 15. Base forces of the whole system, case a (x-motion, left) and case b (35°-motion, right)

5. CONCLUSIONS

The present work is the development of a previous study in which the response of a structural system isolated with DCSS devices has been analyzed. In the current endeavour, a new tridimensional model of the DCSS device has been defined, accounting for the complex bi-directional response of the isolators subjected to non-radial motion, and modelling possible construction laying defects of the devices. In particular, the behaviour of the system subjected to a generic direction of motion has been studied, with the scope of evaluating the consequences of the construction laying defects on the whole system. The attention has been focused on the torsional rotation of the isolated slab, which can cause an increasing displacement demand at the local level, on the global base shear in both the principal directions, aiming to see the consequences of the construction laying defects on the global hysteretic behaviour of the system, and on the number of devices contemporary detached for each time step, which can cause an excessive redistribution of the vertical load graving on the devices, with the consequent variation of the lateral local and global response.
The results underline that such defects lead to an increased displacement demand on the structure, with reduced values of the base shear at high displacements; this aspect is more evident in the unidirectional motion, because of the larger number of detached devices, implying a more important redistribution of the vertical forces on the isolators in contact, which in turn reduce the total horizontal

force due to the variation of the dynamic friction coefficient with the vertical load.
The next development of the present work is to apply the motion with the actual earthquake components in the two directions, and carry out a statistically significant number of analysis, in order to generalize results for randomly selected sample of isolators defects. Moreover, the study will be extended to different structural schemes, aiming to generalize the results for a larger class of building typologies: hence, different spatial distributions of the building will be considered, together with different mass locations, in order to quantify the consequent changing in the slab rotation.

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