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EVALUATION OF RESPONSE OF AN ISOLATED SYSTEM BASED ON DOUBLE CURVED SURFACE SLIDERS

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Abstract. *Nowadays, the use of seismic isolation within the Italian and European context is gaining more and more acknowledgement, thanks to the high level of protection which can be guaranteed to a structure from the earthquake damage. However, the installation of devices within complex structural systems may influence the actual response due to the random variation of the installation and operating conditions with respect to the theoretical structural scheme. It is then of paramount importance a proper assessment of the overall isolating system response, considering the variability of the construction conditions.*

The main objective of the present work is to study the response of a particular installation system for Double Curved Surface Sliders (DCSS) for buildings with large plan development in case of construction defects related to the non-perfect co-planarity of the devices. A case study is presented, in which the effects of randomly simulated construction defects are analyzed. Preliminary results showed that the simulated construction defects have only limited influence on the global hysteretic behavior of the system and that the contemporary loss of contact may occur only for a limited number of devices. On the other hand, the effects of the vertical and horizontal force redistribution may cause important increase of the actions locally induced in the base connecting slab and create an eccentricity of the resultant horizontal force.

1 INTRODUCTION

Nowadays, the use of seismic isolation within the Italian and European context is gaining more and more acknowledgement [1], [2]. The recent coming into force of the European Code for antiseismic devices [3] witnesses such increasing trend and highlights the importance of a major attention to all the aspects related to the response of installed isolators.

Concerning friction devices, a number of studies has been conducted first on curved surface sliders with single sliding surface ([4], [5], [6], [7], [8], among the others), and then on the most recent double / triple sliding surfaces sliders ([9], [10], [11]). Such studies highlighted features and advantages of such technology, from the theoretical, modeling and experimental point of view, at least for what concerns the single device.

However, complex isolation systems and the actual operating conditions of installed devices often differ from the ideal theoretical design conditions. In particular, when several devices are installed to work in parallel, the possibility of random variations in the installation conditions of each single device may arise issues regarding the response of the entire system.

The main objective of the present endeavor is to study a particular isolation scheme for buildings with large plan development (systems consisting of several isolators and a base connection slab upon which the building is constructed, Fig. 1), in order to evaluate the influence of defects related to non-parallel sliding surfaces. Such kind of defects can be generated by phenomena of deferred concrete creep or simply by construction errors: if isolators sliding plates are non perfectly horizontal, for a given slab displacement each device will encounter a differential vertical displacement, possibly leading some device to loose contact and inducing localized stress in the slab. This in turn causes a redistribution of the vertical reactions and consequently of the horizontal forces throughout the whole system.

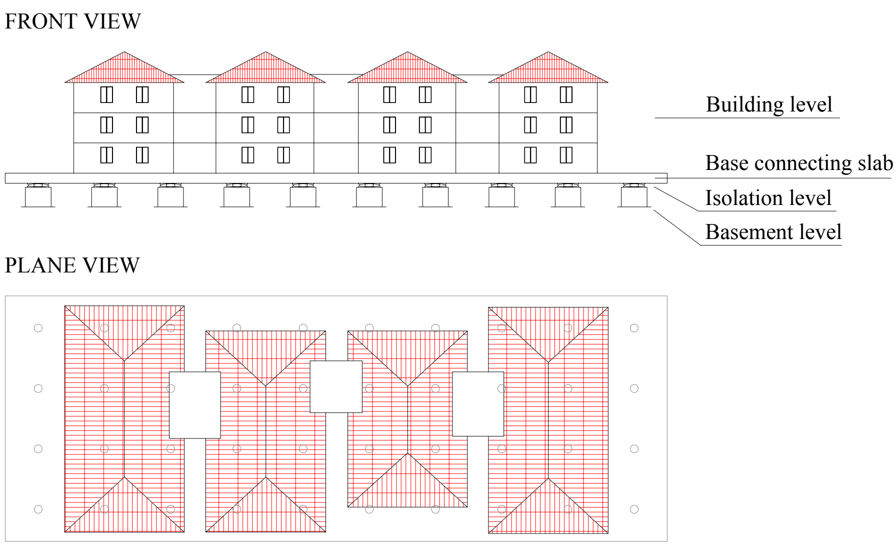

Fig. 1 . Schematic model of the isolated system consisting of isolators-base connection slab-building

The first step of the work has been to define the mechanical model of a single isolator, analyzing the geometry of each component, in order to obtain the value of the vertical displacement induced on the slab, for a given value of horizontal displacement. Subsequently, the interaction among the different devices and the base slab has been modeled, by developing a f.e.m. code able to simulate the varying conditions of the system (contact-no contact condition). Finally, a case study has been presented, in which construction defects have been simulated randomly on the different isolators for a large number of analysis, in order to evaluate the consequences at both global and local level.

Preliminary results showed that the simulated construction defects have only limited influence on the reduction of the global hysteretic behavior of the system, and that the simultaneous detachment during the motion may occur only for a limited number of devices. On the other hand, the effects of the vertical and horizontal force redistribution may cause an important increase of the actions locally induced in the slab (shears and moments) and create a global torsion effect on the system, due to the eccentricity of the horizontal resultant force.

2 THE DCSS MECHANICAL MODEL

The geometric model has been developed based on the general case of a DCSS isolator with articulated slider ([9], [10]). The DCSS isolator consists of two sliding surfaces, in general characterized by different values of curvature radius, separated by an articulated slider which allows differential rotations (Fig. 2), and may feature different dynamic friction coefficient at the interfaces with the two sliding surfaces.

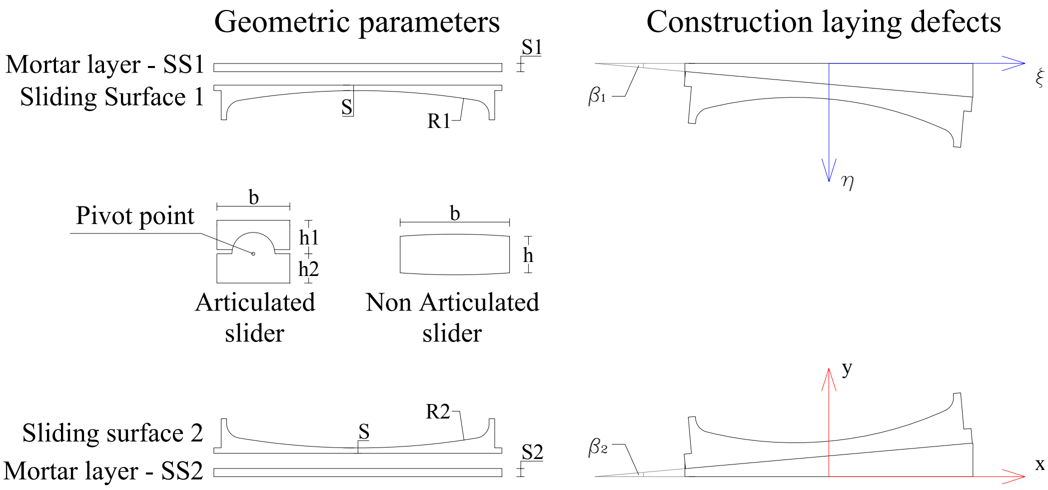

Fig. 2 . section of DCSS with non-articulated slider

The model ([9], [10]) allows to obtain the vertical displacement of the isolator upper surface as a function of the two horizontal displacements between the sliding surfaces and the pivot point of the articulated slider. The equivalent oscillation period of the device is:

$$T = 2\pi\sqrt{\frac{R_{eq}}{g}} = 2\pi\sqrt{\frac{R_1 + R_2 - h_1 - h_2}{g}} \tag{1}$$

When a device is installed, two layers of mortar constitute the interface between the device and the construction system in which it is installed. The construction laying defects can been modeled in terms of non-perfect planarity of such layers of mortar, i.e. as inclinations β_1 and β_2 of the sliding surfaces with respect to the horizontal direction (Fig. 2). The model is plane. In the present work, the model for a DCSS isolator with possible construction defects and with non-articulated slider has been obtained by considering the inclination of the upper and lower plates β_1 and β_2 and imposing no relative rotation between the two units of the slider, thus calculating the vertical displacement only as a function of the total horizontal displacement u between the two sliding surfaces and of the two angles. The inclinations of the sliding surfaces can be described in terms of change of coordinates of the respective center of curvature. Referring to Fig. 3, the angle θ_1 and θ_2 of the two units composing the slide with respect to the vertical axis are thus expressed as:

$$\vartheta_i = \arcsin\left(\frac{u_i - C_{ix}}{R_i - h_i}\right) \qquad i = 1,2 \tag{2}$$

Where C_{1x} and C_{2x} are the x- coordinates of the sliding surfaces centers, and u_1 and u_2 the relative horizontal displacement between the sliding surfaces and the pivot point (Fig. 3).

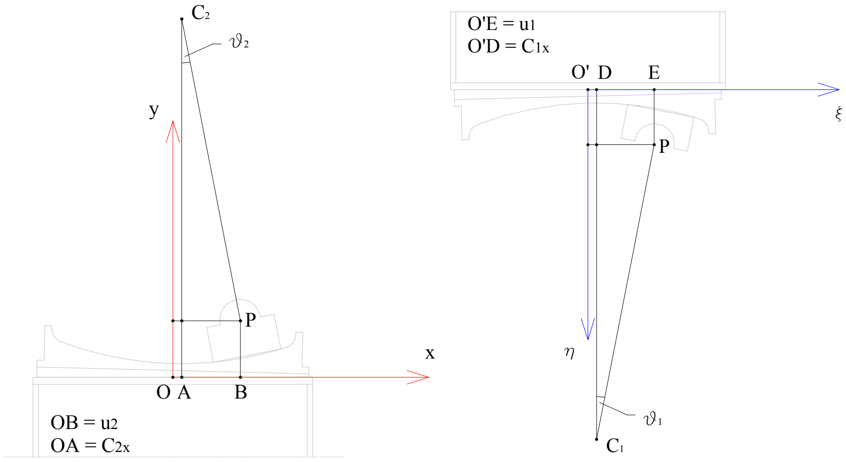

Fig. 3 . definition for the lower surface

By imposing equal to zero the relative rotation of the two axis of the units composing the slider (i.e. $\theta_1 = -\theta_2$), and with the relation among both the relative displacements u_1 and u_2 and the total horizontal displacement u_{TOT} ($u_2 - u_1 = u_{TOT}$), a linear system is obtained, which allows to express the values of u_1 and u_2 as a function of u_{TOT} and of the geometric characteristics of the device:

$$u_1 = \frac{C_{1x}(R_2 - h_2) + C_{2x}(R_1 - h_1)}{R_1 + R_2 - h_1 - h_2} - u_{TOT}\,\frac{R_1 - h_1}{R_1 + R_2 - h_1 - h_2} \tag{3}$$

$$u_2 = u_{TOT} + u_1 \tag{4}$$

Once obtained u_1 and u_2, the height of the extrados of the device can be calculated with the equations of the two sliding surfaces. Fig. 4 shows an example of the profiles of vertical displacement versus horizontal displacement for the device considered in the case study (with characteristics in Table 2), assuming only the upper surface with different inclinations (i.e. $\beta_1 \neq 0$ and $\beta_2 = 0$).

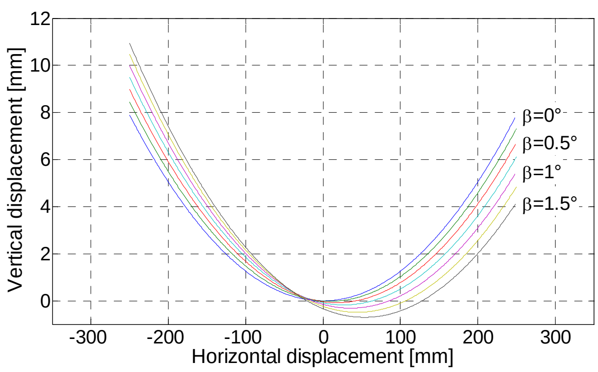

Fig. 4 . example of vertical displacements versus horizontal displacements for inclined upper plate

Regarding the sliding friction coefficient μ, it is well known that for common sliding materials μ is a decreasing function of the acting pressure [12]: a simplified relationship for the variability of the dynamic friction coefficient as a decreasing function of the vertical load is assumed (Fig. 5), based on the several tests carried out at the EUCENTRE TREES Lab (Pavia, Italy) on full scale devices. At this stage of the work, the curve has been assumed linear for sake of simplicity.

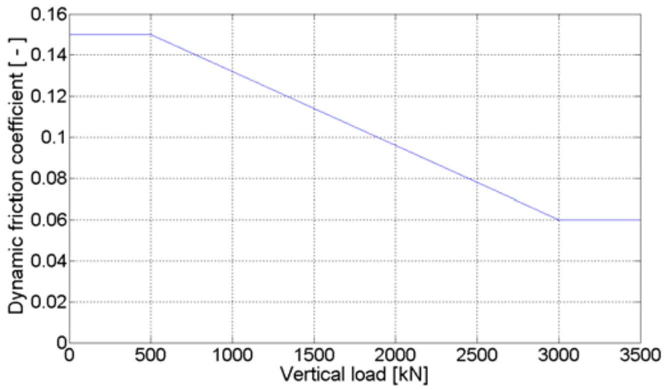

Fig. 5 . dynamic friction coefficient – vertical load variation curve

3 VARIABLE BOUNDARY CONDITIONS CODE

Subsequently, the interaction among the different devices and the base slab has been modeled, by developing a f.e.m. code able to simulate the varying contact-no contact conditions of isolators (Variable Boundary Conditions code, VBC).

The code flowchart is illustrated in Fig. 6: at each loading step, the program is able to identify devices still in contact and devices which have lost contact, updating the total system stiffness matrix at each new configuration.

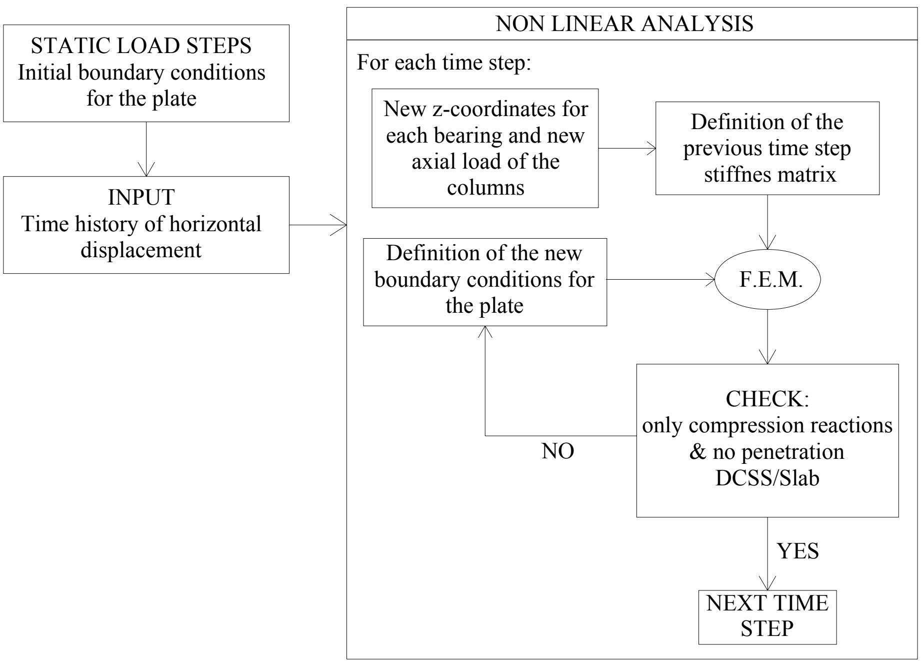

Fig. 6 . Flowchart of the VBC code

The first step of the program is the analysis of the system configuration corresponding to a zero horizontal displacement. The ideal situation of infinitely rigid slab is first studied, with an algorithm able to identify the plane determined by the three devices containing the vertical resultant application point, and with z-coordinate equal or greater than the other isolators (i.e. the three isolators bearing the infinitely rigid plate). Starting from the ideally rigid slab condition, the real deformation of the plate is then obtained by implementing the finite element problem: modeling the plate with its actual stiffness, the vertical load is applied by steps, checking that reactions are purely compressive that there is no penetration between the plate and the isolators. Once defined the zero-displacement deformed shape, the horizontal displacement is stepwise applied to the slab, considering the effects of the dynamic interaction of the building.

The weight of the plate is considered as evenly distributed over the entire surface, while the loads (static and dynamic) transmitted by the building are modeled in terms of concentrated vertical forces imposed on the isolated slab, according to the influence area of each building column. At this stage, the dynamic response of the system has been simulated in a simplified way, by imposing a sinusoidal displacement time history directly to the isolated plate, as during the dynamic testing of the system. The period of the input waveform is taken equal to the oscillation period of the isolation system, calculated as a function of the equivalent radius of the devices.

The dynamic interaction between the building and the isolation system has been simulated by considering the isolated building as an equivalent SDOF of given mass and period. The total base shear V_b is estimated by integrating the equation of motion of a SDOF oscillator. Assuming an equivalent height h_{eq} of the oscillator, the corresponding overturning moment M_{ovt} is computed, which in turn is used to obtain the axial load variation P_i of the building columns acting on the slab, for the x and y motion direction, respectively:

$$M_{ovt}(t) = V_b(t) h_{eq} \tag{5}$$

$$P_{i-X\_motion} = \frac{M_{ovt}(t)}{\sum x_j^2} x_i \tag{6}$$

$$P_{i-Y\_motion} = \frac{M_{cvt}(t)}{\sum y_j^2} y_i \tag{7}$$

Where x_i and y_i coordinates of isolators are measured with respect to the center of mass of the building columns. For each value of horizontal displacement and axial load variation, the new z_i coordinates of the isolators are calculated based on the DCSS model and imposed to the plate only for the isolators still in contact at the previous time step (compression reactions). Then boundary conditions are newly updated, considering at each iteration only the isolators still in contact.

According to the axial load acting on each isolator and to the actual position, the corresponding reaction force is step by step computed for each device.

4 CASE STUDY

The analyzed case study consists of a reinforced concrete frame structure, built on a slab of thickness 0.5 m, placed on a grid of 10 x 4 DCSS isolators with non-articulated slider. The plan view and a section of the system is shown in Fig. 7. The weight of the plate is 12.5 kN/m^2, while the building static vertical loads on the base slab are listed in Table 1, according to the position of the building columns. The geometric and mechanic characteristics of the DCSS are shown in Table 2 (geometric quantities refer to Fig. 2).

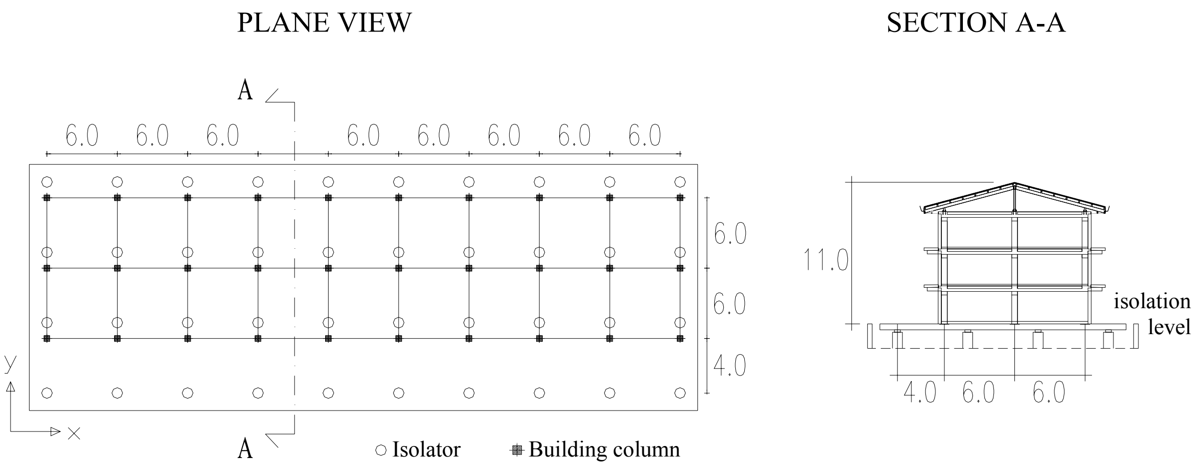

Fig. 7 . Schematic view of the studied isolating system

Table 1. static vertical load transmitted by the building columns on the base slab [kN]

Corner column	Edge column	Internal column
280.4	560.8	1121.6

Table 2. Geometric Characteristics of the isolator

$R_1 = R_2$	$s_1 = s_2$	B	h	S	$\mu_1 = \mu_2$
2024 mm	15 mm	335.44 mm	66.31 mm	20 mm	Variable with vertical force

The input for the analysis is a sinusoidal displacement waveform imposed to the plate (as during the dynamic testing of the system), with amplitude of 260 mm and period of 4 s, i.e. equal to the system design displacement and isolation period, respectively. For the dynamic interaction, the building has been modeled as a SDOF with period equal to 0.48 s, 5% damping, and h_{eq} of about 7 m (2/3 of the height).

The construction laying defects have been simulated by considering for each device the parameters β_1 and β_2 , randomly selected within an established range of variation, for a total of 135 and 125 configurations in the x and y direction of motion analysis, respectively. In order to maintain the maximum generality and to minimize the imposed a priori information, parameter distributions are assumed uniform and in general independent. Wide variation ranges are intentionally considered (±1.5°, much beyond the allowed installation tolerances) in order to evaluate the consequences in extreme conditions (an inclination of 1.5° corresponds to a total offset of 2 cm over a length of 80 cm).

Results are presented in comparison to the reference configuration, which is the ideal situation with isolators having perfectly horizontal sliding plates. At a global level, results are shown in terms of analysis of devices which loose contact, of global hysteretic response of the system and of eccentricity of the horizontal resultant force, while at a local level the variation of vertical loads and the moments induced in the slab are analyzed. The isolators labels and groups are illustrated in Fig. 8, according to their position with respect to the building projection. For the considered case study, it has been seen that isolators belonging to the same line (group 1 to 4, Fig. 8) feature similar response.

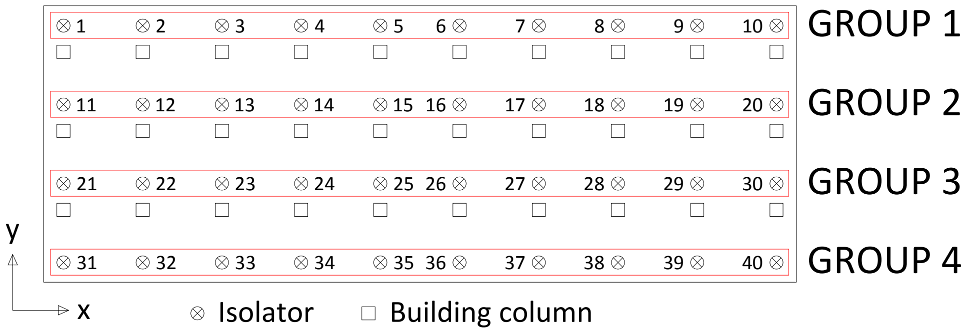

Fig. 8 . Nomenclature of the devices

4.1 Numerical results: global response

Fig. 9 and Fig. 10 show the number of devices which simultaneously lost contact at each value of horizontal displacement: averagely less than 5 DCSS out of 40 have lost the contact at the maximum displacement.

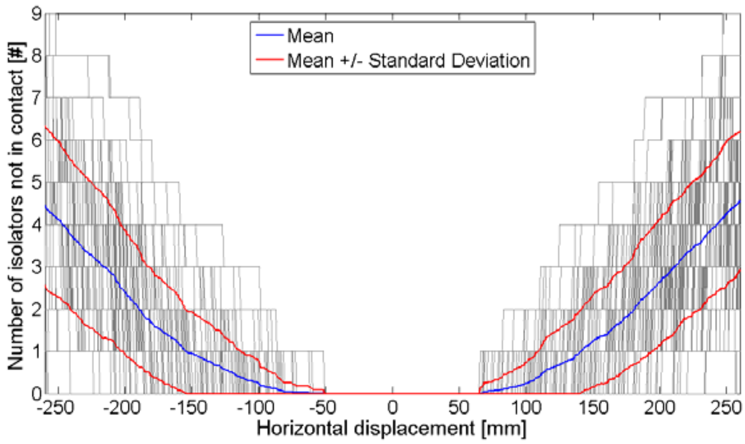

Fig. 9 . Number of isolators simultaneously not in contact (motion in the x direction)

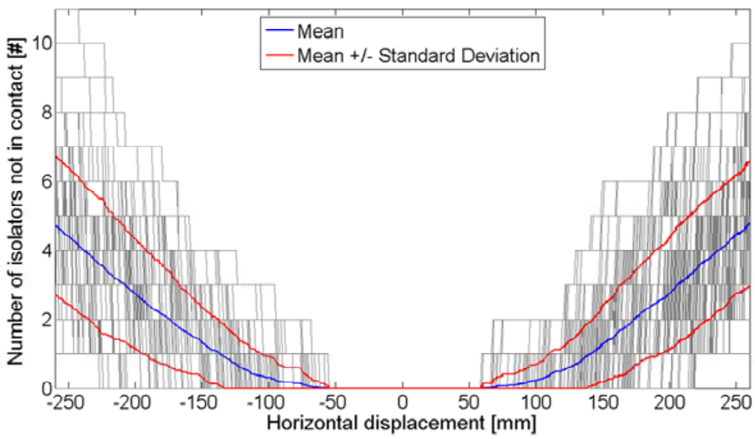

Fig. 10 . Number of isolators simultaneously loosing contact (motion in the y direction)

Fig. 11 and Fig. 12 show, for the motion in the x and y direction, the rate of contact loss for each device during the analyses, i.e. the rate of the cases in which an isolator looses contact at least once during motion: it is evident the similar response of isolators belonging to the same alignment. This is due to the position of the building with respect to the base slab. The most external line (group 4) has in fact the highest probability of detachment, while group 2, which is the closest line to the building center of mass, is the most stable. Table 3 shows the values of frequency of contact loss per group of isolators at the maximum displacement.

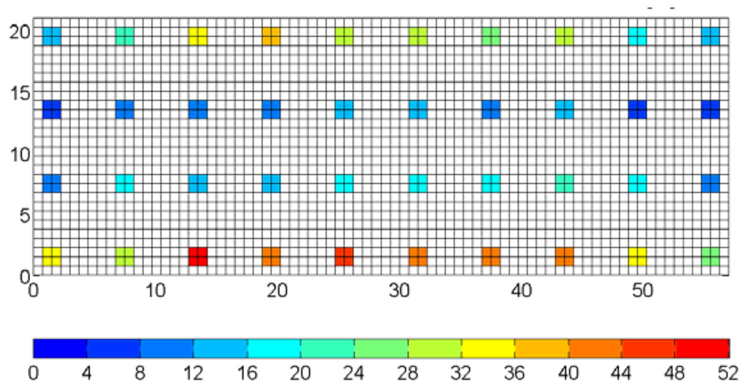

Fig. 11 . Rate of cases in which an isolator looses contact at least once during the motion (x direction)

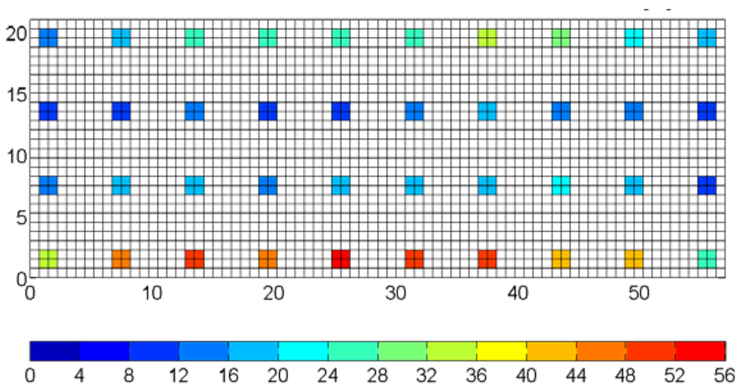

Fig. 12 . Rate of cases in which an isolator looses contact at least once during the motion (y direction)

Table 3. Frequency of no-contact across all the analyses, at the maximum displacement

	Motion x	Motion y
Group 1	14.48 %	13.56 %
Group 2	5.75 %	6.44 %
Group 3	9.18 %	9.28 %
Group 4	20.41 %	23.12 %

The total base shear as a function of the horizontal displacement is shown for both directions of motion in Fig. 13: the effects of the construction errors result in a limited reduction of the hysteresis loop. This is due to the redistribution of vertical loads among the isolators still in contact, which increase their reactions but not proportionally, due to the varying friction coefficient. Moreover, isolators not in contact do not contribute to the dissipative behavior.

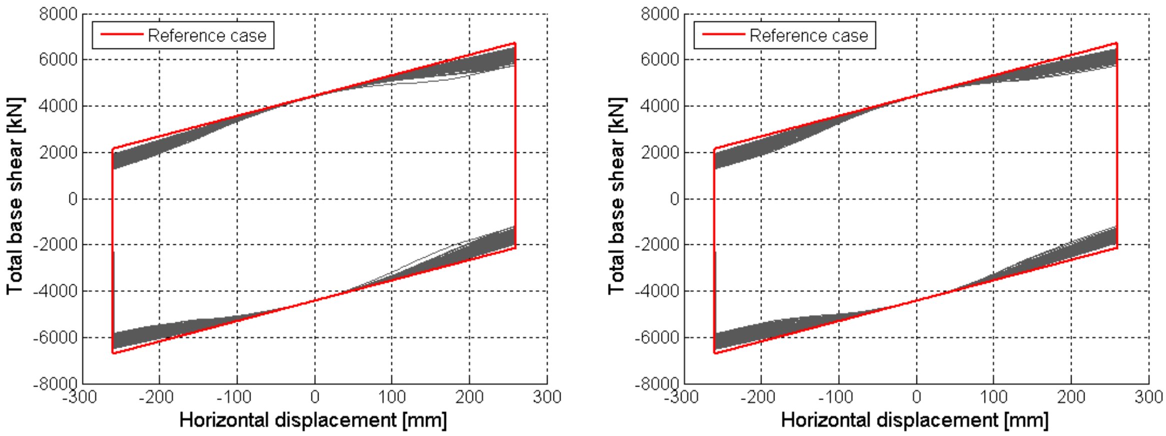

Fig. 13 . Global hysteresis cycles for the x (left) and y (right) direction of motion

Finally, the horizontal eccentricity of the DCSS resultant reaction with respect to the system center of mass has been evaluated. Fig. 14 illustrates the values of the eccentricity as a function of horizontal displacement. Values of eccentricity are normalized with respect to the correspondent plan dimensions of the base slab (L_x and L_y):

$$E_i = \frac{e_i}{L_i}[\%] \qquad (i = x, y) \tag{8}$$

For both directions of motion, at the maximum displacement, the normalized maximum eccentricity is about the 7%.

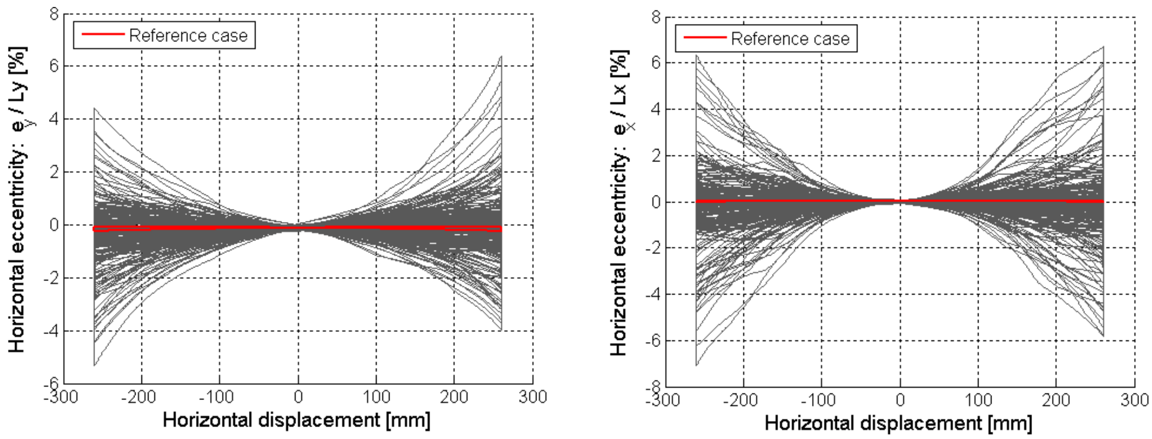

Fig. 14 . Horizontal eccentricity for the x (left) and y (right) direction of motion

4.2 Numerical results: local response

Fig. 15 and Fig. 16 show the distribution of the amount of the vertical load variation for each device at the maximum displacement, for the x and y motion respectively:

$$Var_j = \frac{R_j - R_0}{R_0}[\%] \tag{9}$$

Where R_0 represents the reaction of the reference case, and R_j is the reaction of the j-th analysis. The histograms representing the rate of variation of the vertical reactions with respect to the reference case confirm what already observed: the outer rows of isolators, in particular group 4, are characterized by more dispersed axial load variations, thus by the highest frequency of contact loss due to the considerable distance from application point of the vertical load resultant, whereas internal groups (e.g. group 2) are less susceptible to important axial load variation and thus to detachment. It is possible to see that compressive load can increase more than twice with respect to the reference situation.

Fig. 17 to Fig. 20 present at a local level, the range of variation of the bending moments induced in the base slab at the isolator locations: results are shown for both the main bending moments and for the two directions of motion. It can be seen that the mean value and the reference value approximately coincide, but the actual values are greatly dispersed, especially for the internal groups of isolators (from isolator #11 to isolator #30). This is due to the fact that, when an isolator looses contact, the plan dimensions of the corresponding slab field doubles, with immediate effects on the induced bending action. Such effect is increased for central devices since they are also subject to greater vertical loads, but are not aligned to the central columns of the building.

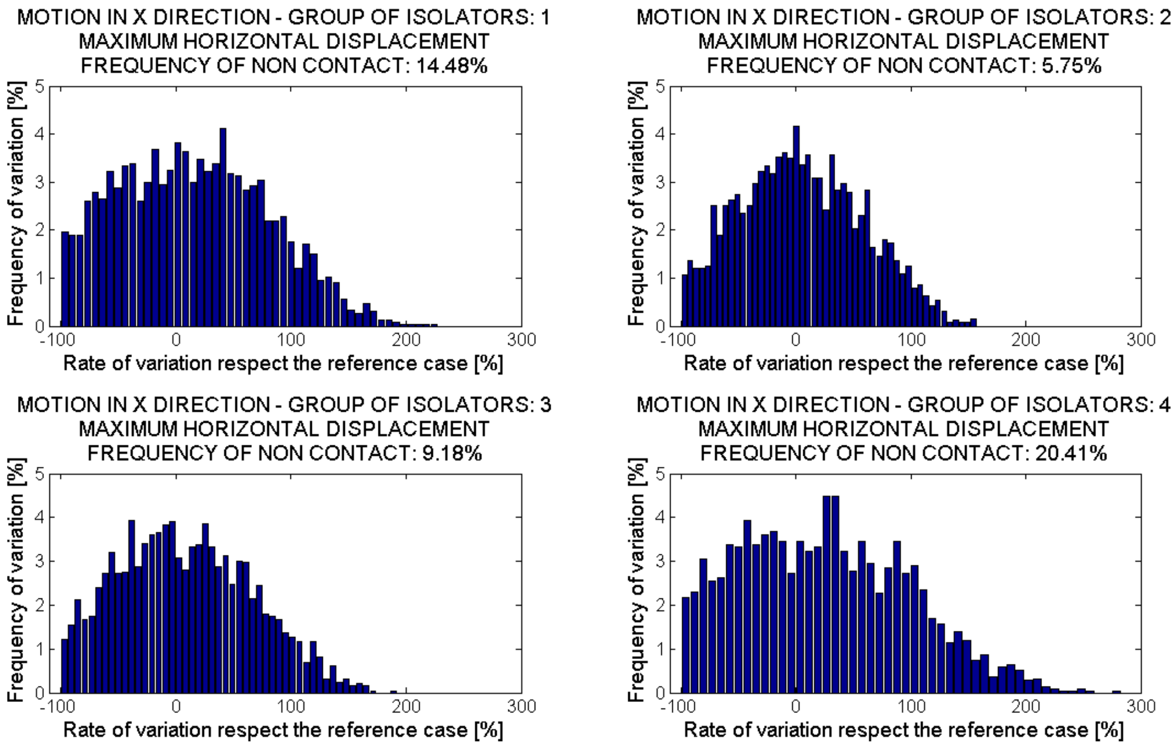

Fig. 15 . Rate of variation of the vertical reactions (motion in the x direction)

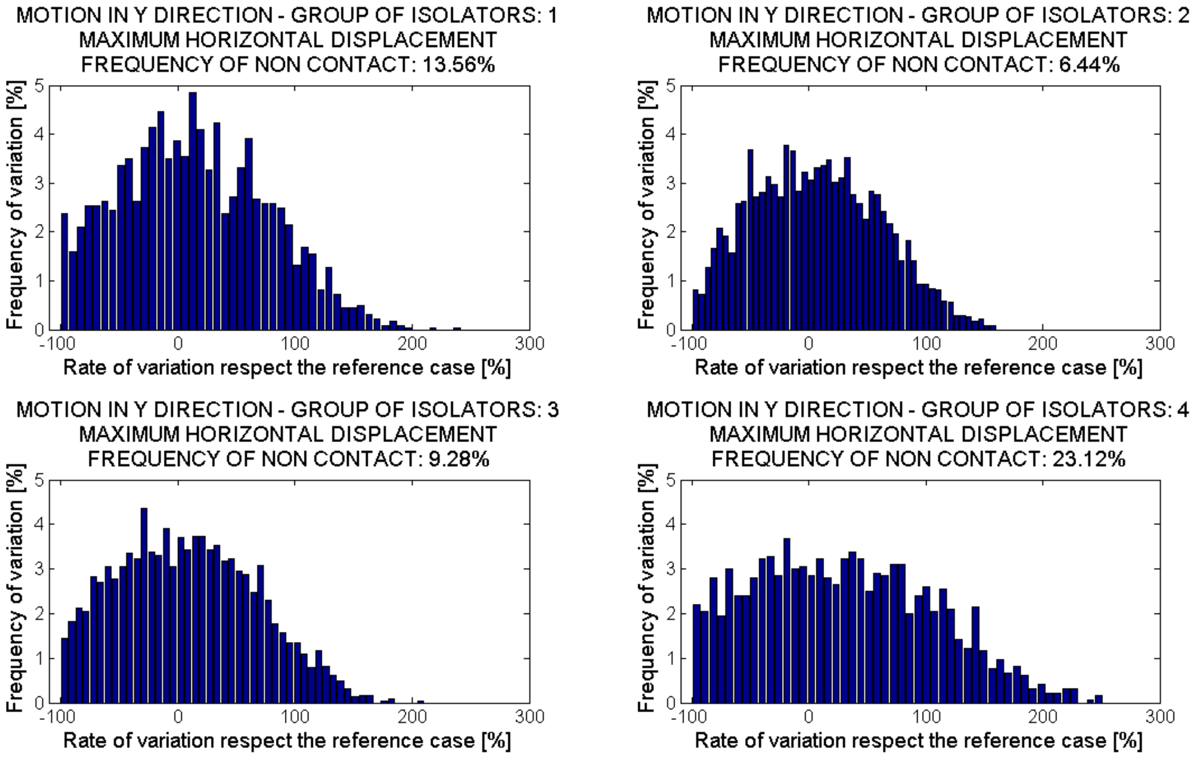

Fig. 16 . Rate of variation of the vertical reactions (motion in the y direction), at the maximum displacement

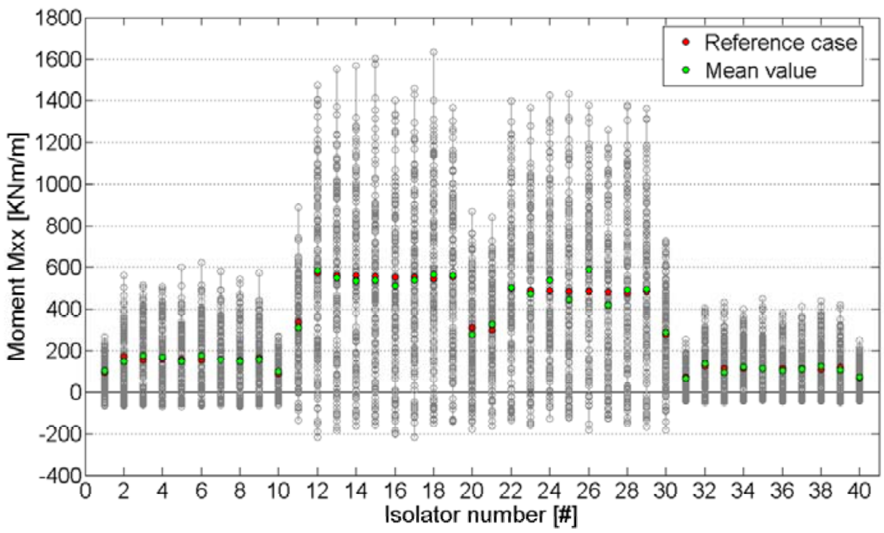

Fig. 17 . Moment M_{xx} for each isolator (motion in the x direction)

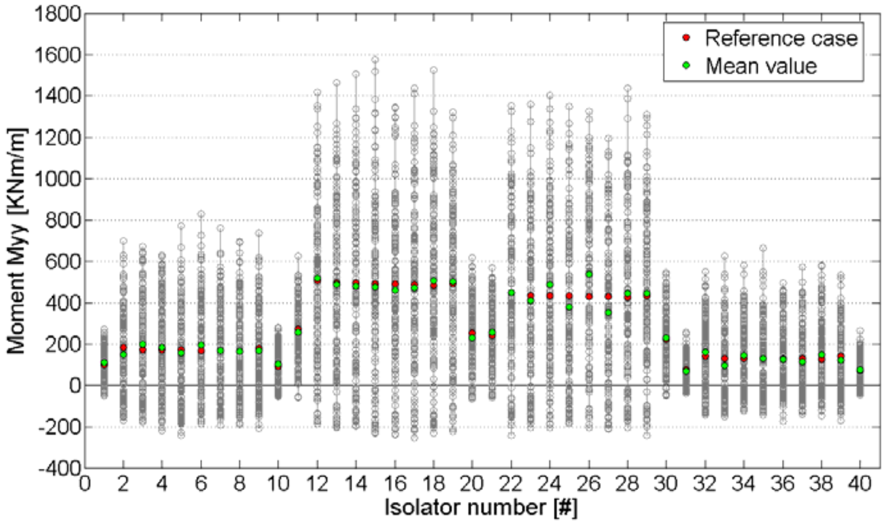

Fig. 18 . Moment M_{yy} for each isolator (motion in the x direction)

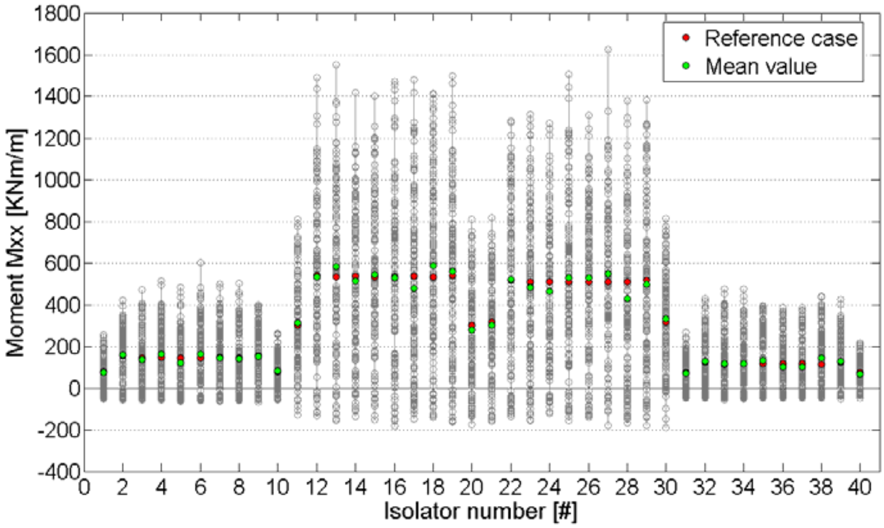

Fig. 19 . Moment M_{xx} for each isolator (motion in the y direction)

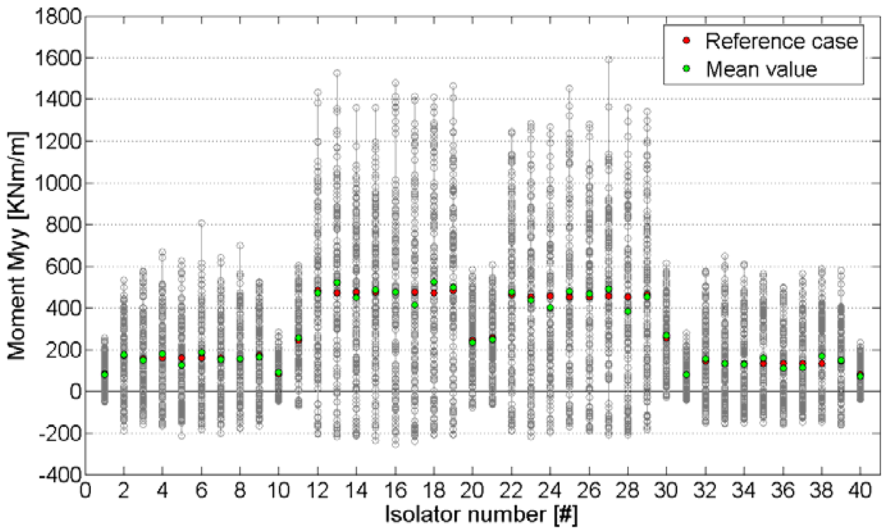

Fig. 20 . Moment M_{yy} for each isolator (motion in the y direction)

5 CONCUDING REMARKS AND FUTURE DEVELOPMENTS

In the present paper a particular isolation scheme for buildings with large plan development has been studied, consisting of a connecting base slab isolated by several DCSS devices upon which the structure is built. In particular, it is analyzed the problem of the possibility of construction laying defects of the isolators, in order to evaluate the influence on the system response of non-parallel sliding surfaces and to estimate the effects on the installed system with respect to the idealized configuration with perfectly horizontal sliding surfaces.

In order to study the problem, a plan geometric model of a single device has been first developed, considering the real geometry of each component, and modeling the defects in terms of inclination of the two sliding surfaces of the device. A f.e.m. code has been implemented, able to simulate the interaction between the devices and the base slab upon which the building is constructed, including the variability of the boundary conditions of the plate in case of isolators loosing the contact during the motion.

A case study has been finally analyzed, for which 260 analyses have been run, with different configurations simulating random defects in the isolators. The inclinations of the sliding surfaces of each device constituted the varying parameters of the analyses and were randomly selected within uniform distribution range. Such a range has been assumed intentionally large (±1.5°, much higher than admitted tolerances), in order to evaluate the consequences in extreme conditions.

The results of the numerical analyses showed that installation defects can influence the response of the isolated building more importantly at a local rather than at a global level. Results have been compared to the "ideal" reference case, corresponding to isolators with perfectly horizontal sliding surfaces.

From the global point of view it can be observed that:

• the dissipative behavior is only moderately affected, with a general reduction, due to the detachment of some device and to the redistribution of the vertical load among devices still in contact, considering the dependence of the friction coefficient on the vertical load.

• at the maximum displacement, the horizontal eccentricity of the system reaches values close to the 7%. The actual effects of such eccentricity have still to be evaluated, with a proper tridimensional model of the devices.

• the rate of devices loosing contact during the motion is a function of the relative position of the building with respect to the isolating base slab. As expected, the rows of isolators close to the centre of mass of the building have the lowest probability of loosing contact, while external rows are the most susceptible to detachment.

• For the considered case study, featuring some degree of asymmetry of the building location with respect to the plate, no more than 5 devices out of 40 loose contact simultaneously during the motion.

From the local point of view the analysis have shown that:

• the construction defects may result in localized concentration of vertical loads on occasion importantly higher than the reference situation.

• the loss of contact of some device may result in important increase of bending actions locally induced in the base slab.

From a merely structural point of view, the location of columns close to the devices would allow a more direct transmission of the vertical loads, thus reducing the risk of detachment of the isolators and the localization of high stress values in the slab.

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