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Numerical parametric study on property modification factors of isolation devices

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ABSTRACT
Modeling strategies of base isolation devices allow extremely realistic simulation of the structural response of seismically isolated systems. Especially whenever Non-Linear Time History Analyses are performed, actual hysteretic constitutive laws can be implemented in the most common commercial software and the proper behavior of all the installed isolators can be consequently defined. Recent research works have shown non-negligible statistical variability of the main mechanical properties of isolation devices; nonetheless, practitioners generally design base-isolated structural systems, by considering mean parameters, as deterministic values, and no variability is accounted for.
In this work a parametric study is performed on a case study structure, in order to assess the variability of the main response parameters. Precisely, rubber bearings and flat slider devices have been implemented, by assuming mechanical properties as random variables, instead of deterministic quantities. Non-Linear Time History Analyses have been performed and special attention has been focused on the mean response of a spectrum-compatible set of natural records, in terms of displacement and force of both superstructure and isolation system. Results lead to some useful considerations for the definition of bound analyses of base isolated structures.

1 INTRODUCTION

Base isolation techniques provide very effective solution for the reduction of the vulnerability of both building and bridge structural systems against earthquake excitations. Thanks to the growing interest in such a protection strategy, a number of research works have been developed in last years on the topic, and several realistic models for the most common isolation devices have been defined, and often calibrated by means of outcomes of research and commercial experimental campaigns (AASHTO 2014, CEN 2018); consequently, the uncertainty of the structural behaviour prediction of base-isolated systems is reduced. Through the elongation of the design period of the structural system, the force demand in the superstructure can be significantly limited at all levels; nonetheless, high displacement values can be found at the isolation level, where the largest amount of deformation is lumped; however, lower values can be achieved, by increasing the hysteretic dissipative properties of the implemented devices. One of the most common solution for seismic isolation of building structures is represented by rubber bearing devices. Such isolators provide limited value of horizontal stiffness, needed for the period elongation, together with a certain dissipative capacity, depending on the rubber compound (equivalent viscous damping ratios for Low Damping Rubber Bearings within 5% and 10%; for High Damping Rubber Bearings within 10% and 15%). The vertical stiffness is significantly higher, in comparison to the horizontal directions, thanks to steel stiffening sheets, which limit the transverse deformation of each rubber layers (Kumar et al. 2014, Quaglini et al. 2015). In some cases, however, it is not possible to install rubber isolators at all the support points locations of a building structure, since geometrical limitations can be found, according to a number of initial assumptions, such as design lateral deformation (generally 100%, which means design displacement equal to the height of the device), rather than ratio between the plan diameter and the height of the device (typically assumed equal to 2.0, in order to avoid vertical instability phenomena). Thus, in order to cover the remaining support points, flat slider are installed, so that the vertical load is transferred to the substructure, and negligible horizontal contributions in the force response are provided (depending on the friction coefficient value) (Dolce et al. 2005, Cardone et al. 2017). Generally in the design phase mechanical properties of devices are assumed to be deterministic quantities, even though a certain variability may be experienced from the experimental point of view for both the shear modulus of the rubber isolator and the friction coefficient of the flat sliders.

In this work the influence of the variability of the mechanical properties of both rubber bearings and flat sliders on the seismic response of a case study structure has been assessed, through of Non-Linear Time History Analyses, according to the prescriptions of the Italian Building code. A spectrum-compatible set of seven records has been adopted, in order to analyze the mean value for all the quantities, and up to 70'000 numerical simulations have been performed (10'000 for each seismic event). Results have shown limited consequences on the mean structural response of the considered case study structure, in terms of displacement, drift, isolation force and building base shear responses.

2 CASE STUDY STRUCTURE

In this work a three storey building has been analyzed, in order to evaluate the influence of the variability of some response parameter of the isolation system on the overall structure: precisely, a reinforced concrete frame structure has been implemented, by means of linear-elastic frame elements and a concrete slab at the interface level between the superstructure and the isolation system, through shell elements (Figure 1).

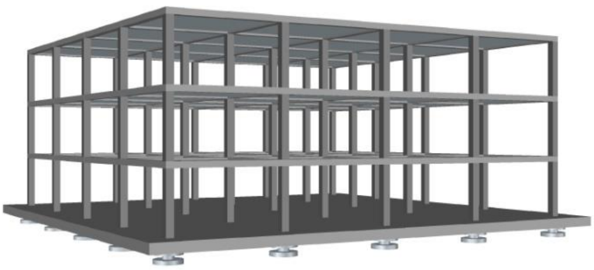

Figure 1. Case study structure

The general floor plan is made up of four spans along both the main directions, with 6m span length; the interstorey height of all floors is equal to 3,0 m. As an interface between the superstructure and the isolation level, a reinforced concrete slab has been considered: the thickness is 500mm and plan dimensions have been obtained by considering the plan development of the superstructure, increased by 1.5m along all sides (27m x 27m). Flexural stiffness coefficients of all frame elements of the building have been reduced by means of scale factors (lower than 1), in order to better fit the equivalent linear-elastic branch of the capacity curve, which has been computed through a pushover analysis carried out by using the software SeismoStruct (SeismoSoft 2016) on the fixed-base configuration. Such a software allows to model force-based frame elements, with distributed plasticity and non-linear constitutive laws for materials (Mander's model for Concrete and Menegotto-Pinto's model for reinforcement steel); by accounting for confinement effects in the concrete core of columns, in order to consider the effective ductility and strength of the sections, the capacity curve shown in Figure 2 has been computed.

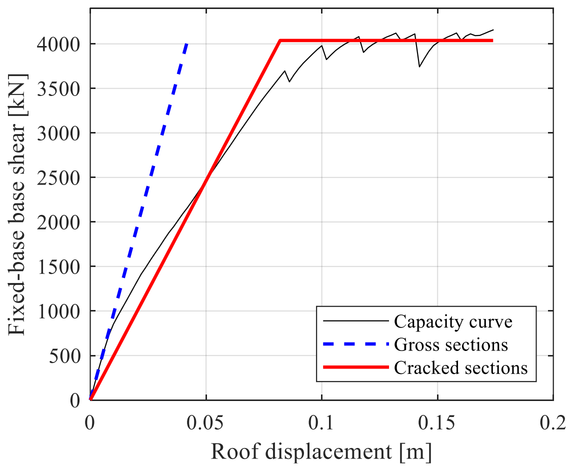

Figure 2. Capacity curves of the fixed-base building

A static condensation procedure to the full 3D FEM model of the structure, in order to compute condensed stiffness and mass matrices for the characterization of a Multi Degree of Freedom system (Chopra 1995, Furinghetti et al. 2019): thanks to such a procedure, a large number of Non-Linear Time History Analyses have been performed, for a comprehensive definition of statistical parameters.

3 MECHANICAL PROPERTIES OF ISOLATORS

Isolation devices are represented by a combination of Low Damping Rubber Bearing Isolators (Figure 3) and Flat Slider devices.

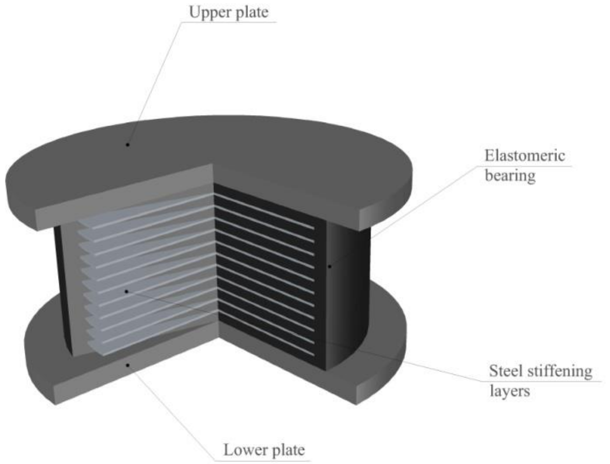

Figure 3. Components of a rubber bearing isolator

According to a design period of 2.75sec and an equivalent viscous damping ratio equal to 7%, twelve cylindrical rubber isolators have been installed, with a nominal value of shear modulus G equal to 1.0 MPa, and 650mm and 325mm of diameter and height respectively (100% of lateral deformation has been assumed). The remaining support points locations (25 – 12 = 13) have been equipped with flat slider devices, which provide a lateral force response through sliding motion between a stainless steel flat sliding surface and a sliding pad: in this work, a friction coefficient equal to 3% has been assumed. In Figure 4 the overall configuration of devices installed into the isolation system is reported.

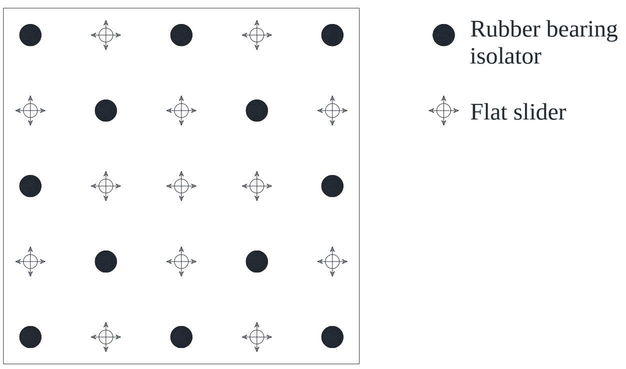

Figure 4. Isolation devices layout

Since rubber bearings can be modelled by considering a linear constitutive law, together with a constant damping ratio, the variability of of the devices response has been studied, in terms of variation of the shear modulus of the rubber compound. The effective variability has been computed, by analysing the outcomes of the wide test database of the laboratory of EUCENTRE Foundation in Pavia (Italy) (Peloso et al. 2012). Precisely, dynamic tests at 100% of lateral deformation have been studied: the experimental shear modulus has been computed by evaluating the secant stiffness value at maximum displacement, and then by reversing the expression.

$$K_{IS} = \frac{F_{\max} - F_{\min}}{D_{\max} - D_{\min}} = \frac{G \cdot A_{IS}}{H_{IS}} \tag{1}$$

In Figure 5 the resulting statistical variability is shown, by considering 213 tests. Results are provided, in terms of distribution of the ratio between the experimental and the nominal value of shear modulus for all the considered tests.

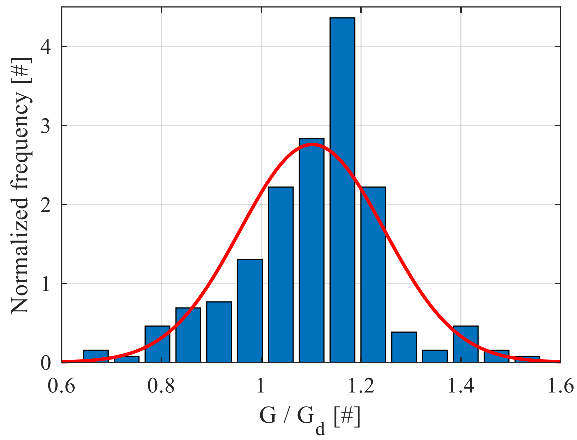

Figure 5. Experimental variability of shear modulus for rubber bearings

As can be noted, the computed histogram can be approximated by means of a Gaussian's distribution. The mean value is actually higher than 1.0 (precisely 1.105): thus, the statistical analysis of the tests database seems to suggest a mean discrepancy between the nominal and the experimental value of the shear modulus, the latter is averagely higher (variation +10%). In addition, a standard deviation of 14.5% can be computed. Since the non unitary mean value can be addressed only to the discrepancy between the experimental and the theoretical behaviour of such devices, in the analysis a unitary mean value has been assumed, in order to consider the variability of the parameter, with respect to the same design value. Thus, in all the analyses, the shear modulus has been randomly extracted by a numerical simulator, according to a normal distribution, with 1.0 and 14.5% of mean and standard deviation values respectively.

Furthermore, the friction coefficient of flat sliders has also been considered as a random variable, by considering a normal probability density function, with unitary mean and 30% of standard deviation (Barone et al. 2017).

4 DEFINITION OF THE DYNAMIC SYSTEM

The case study structure presented in this work has been modelled as an equivalent multi degree of freedom (MDOF) oscillator (Furinghetti et al. 2019), with statically condensed stiffness matrix. Thanks to the adopted static condensation procedure, the computed stiffness matrix is able to reproduce the actual dynamic behaviour of the system, with approximately same results of a Non-Linear Time History Analyses carried out on the full 3D FEM model. Hence, the dynamic system can be expressed as follows:

$$\overline{\overline{M}} \cdot \begin{pmatrix} \ddot{u}_0 \\ \ddot{u}_1 \\ \ddot{u}_2 \\ \ddot{u}_3 \end{pmatrix} + \overline{\overline{K}} \cdot \begin{pmatrix} u_0 \\ u_1 \\ u_2 \\ u_3 \end{pmatrix} + \langle F_{is} \rangle \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} = -\overline{\overline{M}} \cdot \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} \cdot \ddot{x}_g \quad (2)$$

Being:

- $\overline{\overline{M}}$ the condensed mass matrix of the system;
- $\overline{\overline{K}}$ the condensed stiffness matrix of the system;
- u_i the translational degrees of freedom at the centre of mass location of the i-th floor;
- $\ddot{x}_g$ the considered ground acceleration time series;
- $\langle F_{is} \rangle$ the isolation force response.

The isolation force response has been considered as a separated contribution, so that the stiffness matrix is just related to the building response. The total force response of the isolation layer can be instantaneously computed as the summation of the rubber bearings and flat slider lateral forces:

$$\langle F_{is} \rangle = \langle F_{RB} \rangle + \langle F_{FS} \rangle \quad (3)$$

$$\langle F_{RB} \rangle = n_{RB} \cdot k_G \cdot K_{RB} \cdot u_0 + 2 \cdot \xi \cdot \omega_{is} \cdot M_{tot} \cdot \dot{u}_0 \quad (4)$$

$$\langle F_{FS} \rangle = \frac{n_{FS}}{n_{RB} + n_{FS}} \cdot W_{tot} \cdot k_\mu \cdot \mu \cdot f_{FN} \quad (5)$$

Being:

- M_{tot} and W_{tot} the structural mass and weight of the system respectively;
- n_{RB} and n_{FS} the number of rubber bearing isolators (12) and Flat slider devices (13) respectively;
- K_{RB} the stiffness coefficient of the single rubber bearing device;
- ξ the equivalent viscous damping of the system (7%);
- ω_{is} the angular frequency related to the design period (2.75sec);
- u_0 , $\dot{u}_0$ displacement and velocity at the centre of mass location of the concrete slab (isolation level);
- μ the design friction coefficient of flat slider devices (3%);
- f_{NF} a normalized frictional hysteretic parameter;
- k_G and k_μ a variability scale factor of rubber shear modulus and flat slider friction coefficient respectively.

The hysteretic parameter f_{NF} allows to model the frictional hysteretic response of the isolation system, by assuming an elasto-plastic rule (Figure 6).

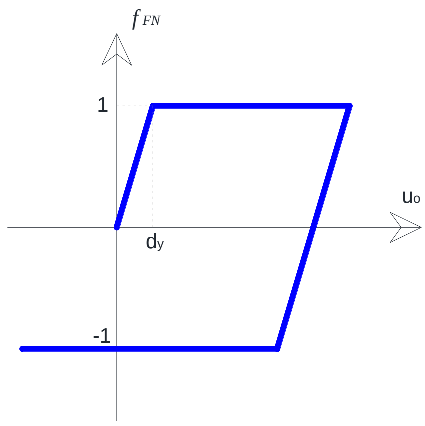

Figure 6. Normalized friction force

The actual variability of both shear modulus for rubber bearings and friction coefficient for flat slider, variability scale factors has been adopted: such scale factors for each analysis are returned by numerical simulators, which follow the probability density functions discussed in section 2. In order to obtain a consistent and statistically robust set of data for all the main response parameters of the system, a large number of analyses have been performed. Precisely, 10'000 simulations have been performed for each record, by considering for each set of seven seismic event different scale factors for both shear modulus and friction coefficient, so that the most general cases are covered. Finally, a total number of Non-Linear Time History Analyses equal to 70'000 has been obtained.

5 SEISMIC INPUT

For the Non-Linear Time History Analyses, a spectrum-compatible set of seven ground acceleration time series has been selected, according to the prescription of the Italian Building Code (D.M. 17/01/2018), in order to study the variability of the mean value for each considered response parameter, as a consequence of the effective random distribution of both shear modulus of rubber bearings and friction coefficient of flat sliders.

Natural records have been adopted, and scaled, in order to obtain better agreement of the single event response spectrum with respect to the target one, provided by the code. The seismic hazard of the construction site has been defined, according to the following assumptions:

- Construction site: L'Aquila
- Soil class: C;
- Topographic category: T1;
- Limit state: Collapse Limit State (return period: 975 years).

REXEL software (Iervolino et al. 2009) has been used for the initial selection of records. Then, scale factors bounded between 0.5 and 2 have been considered, in order not to obtain unrealistic ground motion time series, in terms of frequency and amplitude contents. As ruled by the code, upper and lower bounds for spectrum-compatibility have been defined, according to 90% and 130% of the target spectrum; the mean response spectrum among the selected events has been bounded in the defined limits in a period range between 0.15sec and 120% of the isolation period (equal to 3.3 sec). In Figure 7 results of the spectrum-compatibility study are reported.

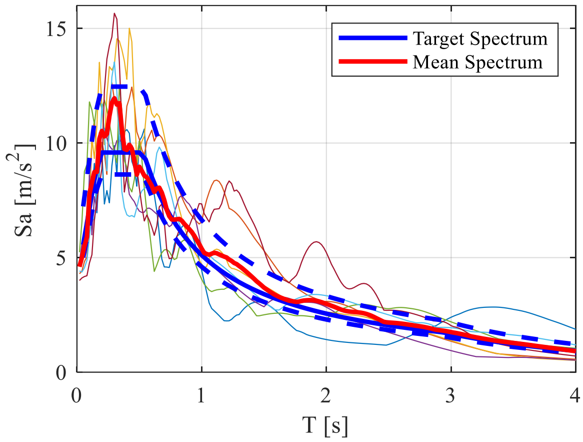

Figure 7. Selection of spectrum-compatible events

With a selection of at least 7 records, the Italian Building Code allows to consider the mean response as reference quantities in order to check the structural behaviour of the designed system.

6 RESULTS

In what follows results have been analyzed, in terms of statistical variability of all the considered mean response parameters, among the selected seismic events. Firstly, the mean response of the reference case, i.e. no variability for the mechanical properties of the adopted isolation devices, are shown: in Figure 8 and Figure 9 results are reported in terms of displacement and force responses for single-events and mean values.

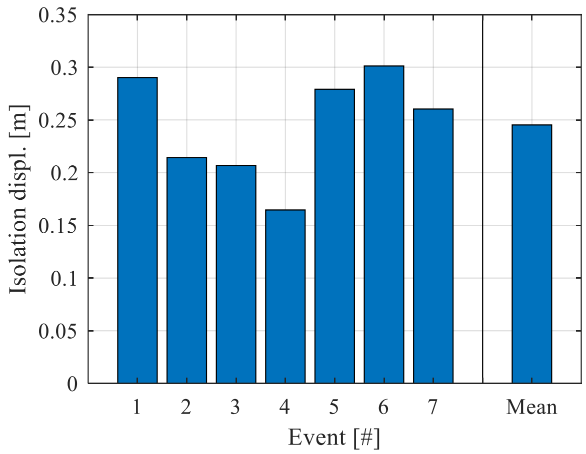

Figure 8. Displacement response

As can be noted, the mean displacement is lower than the design value of rubber bearing isolators (325mm, equal to the height of the device, since 100% lateral deformation has been assumed): the simultaneous effect of flat sliders with 3% of friction coefficient provide additional hysteretic damping which decrease the displacement demand at all levels.

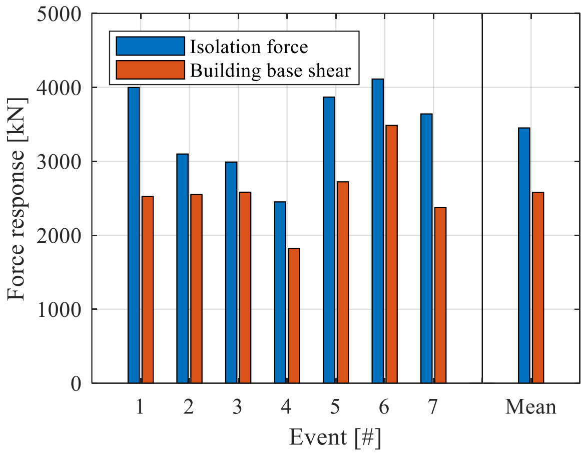

Figure 9. Isolation and building force responses

Concerning the force demand at the base of the building, the mean value (together with all the single event values) is significantly lower than the equivalent yielding force, computed through the pushover analysis of the fixed-base configuration: thus, the designed isolation system is capable to ensure a linear elastic response for the building.

Then, variability of some important response parameters have been studied, by dividing the mean value among the selected set of ground motion signals by the reference mean value previously shown. In Figure 10 displacement variability is reported, for all levels of the structural system.

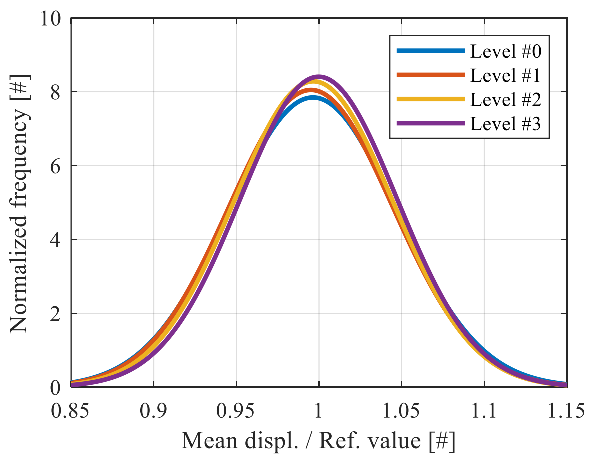

Figure 10. Mean displacement variability

In comparison to the assumed variability for shear modulus of rubber bearings and for friction coefficient of flat sliders, the standard deviation for mean displacement response is significantly lower; histograms of such quantities for all levels of the structures can be fairly approximated by a normal distribution, exactly as the assumed probability density functions for mechanical properties. Mean values at all the storeys are significantly close to one, as expected, and variability looks to slightly decrease, as upper floors of the building are considered.

In Figure 11 same variability analysis is performed for the mean interstorey drift at all floors of the building.

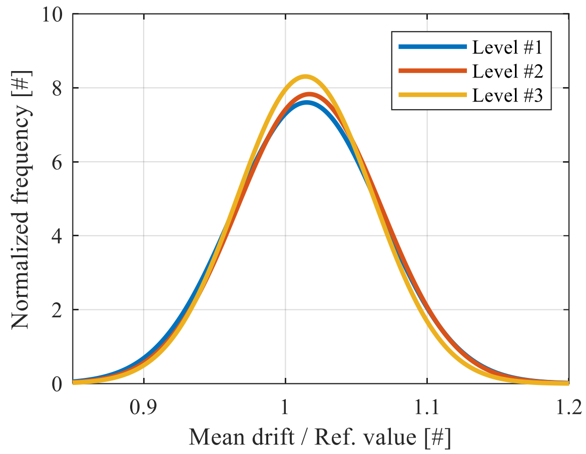

Figure 11. Mean interstorey drift variability

Also for all drift responses the overall variability can be fully described by a Gaussian's distribution. Mean values are slightly higher than one, even though an exceedance lower than 3% can be noticed. In addition, as well as the displacement response, variability, in terms of standard deviation, looks to decrease, as upper floors are considered.

Finally, force response variability for both isolation system and building base is show in Figure 12.

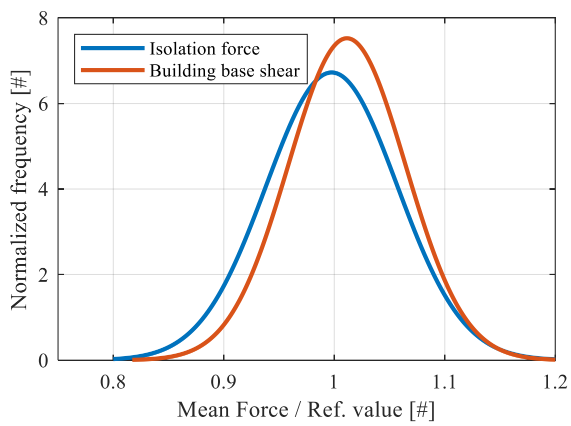

Figure 12. Mean force response variability

Normal probability density functions can be adopted for both the considered force responses. Mean values are close to one, and very low standard deviation can be computed, in comparison to the assumed values for mechanical properties of devices.

In order to better analyse variability results of all the considered mean parameters of the case study structure, Table 1 provide a list of the main characteristics of the previously shown distributions.

Table 1. Summary of results.

	Mean	**Std**
G	1.000	0.145
μ	1.000	0.300
D_0	0.996	0.051
D_1	0.995	0.050
D_2	0.997	0.048
D_3	1.000	0.047
Dr_1	1.015	0.052
Dr_2	1.017	0.051
Dr_3	1.014	0.048
F_{is}	0.998	0.059
V_b	1.011	0.053

As can be noticed, all the computed mean values of the obtained probability density functions are significantly close to 1.0, so that it can be assessed that variability of mechanical properties does not lead to changes in the average response, in comparison to the reference case, which corresponds to deterministic values of devices parameters. Concerning the induced variability in the structural behaviour, all standard deviation values are approximately equal to 5%, close to 33% of the assumed variability of the shear modulus, which provides the most significant contribution in the overall response. Thus, results seems to suggest that if a combination of rubber bearing isolators and flat slider devices are used for the mitigation of seismic vulnerability of building structures, the effective variability of mechanical properties of the implemented devices produces very limited effects on the mean response quantities. Nonetheless, much more research has to be carried out on the topic.

7 CONCLUSIONS AND FUTURE DEVELOPMENTS

In the present work the variability of the seismic response of a case study structure has been numerically investigated, through Non-Linear Time History Analyses, by considering proper distributions for the shear modulus of rubber bearings and for the friction coefficient of flat sliders. The considered structural system consists of a three storey reinforced concrete frame structure, base isolated by means of 12 Low Damping Rubber Bearings (LDRB – equivalent viscous damping ratio: 7%), and 13 flat sliders (friction coefficient: 3%). A Multi Degree of Freedom oscillator has been characterized in order to fully reproduce same dynamic properties of the 3D F.E.M. of the building, by adopting mass and stiffness matrices obtained from a static condensation procedure. No additional viscous damping has been modelled for the building, since the non-linear hysteretic behaviour of the isolation system already provide sufficient dissipative characteristics to the overall structure. Non-Linear Time History Analyses (NLTHA) have been performed according to the Italian Building Code 2018, by applying a spectrum-compatible set of natural seismic events. Both the shear modulus for Rubber Bearings and the friction coefficient for Flat Sliders have been considered as random variables, by providing a multiplication factor, according to the initially assumed distributions: such parameters, in all simulations, have been randomly extracted by numerical simulators, and 10’000 analyses have been performed for all records (total number of NLTHA: 70’000). Results have been analyzed in terms of reference case single-event and mean responses (i.e. with nominal deterministic mechanical properties of devices), and finally distributions of the mean response parameters have been studied.

Results have shown that normal probability density functions can be adopted for all the considered response quantities, which implies that the considered variability of rubber bearings and flat sliders lead to symmetric behaviours. Mean values are close to 1.0 in all cases, and consequently the average response coincides to the reference case value, even though mechanical properties are assumed as random variables. Concerning variability values, very low standard deviations have been computed for all parameters: precisely, for approximately all quantities 5% standard deviation has been found, which represents 33% of the assumed variability of shear modulus of rubber bearings.

Even though results seems to suggest that the variability of rubber bearing based isolation systems does not significantly affect the overall response of the structure, much more case study structures have to be investigated, with different combinations of isolators and flat sliders; in addition, different shear modulus have to be assumed, aiming at generalizing the drawn conclusions.

ACKNOWLEDGEMENT

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