**COMPARISON BETWEEN RADIAL AND BIDIRECTIONAL RESPONSES OF A BASE ISOLATED BUILDING EQUIPPED WITH CONCAVE SURFACE SLIDER DEVICES**

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**ABSTRACT**

Concave Surface Slider devices have been more and more investigated in last years, and several issues have been pointed out by several experimental campaigns. Frictional properties at sliding interfaces can be considered as functions of some important response parameters, such as sliding velocity, contact pressure, temperature rise and dissipated energy. Such dependencies can be defined, through the execution of unidirectional tests, according to the most common standard codes for anti-seismic devices; even though a general seismic event is represented by two individual displacement time series along orthogonal directions, resulting into a non-radial path, in most cases bidirectional tests can be substituted by a radial motion along an orthogonal directions with respect to previous unidirectional tests. This assumption may lead to some discrepancies in the response of a structural system, when a non-radial earthquake is applied.

In this work the outcomes of a wide experimental campaign have been analyzed for the characterization of the frictional properties of a Double Concave Surface Slider device, subjected to both unidirectional and bidirectional motions. Such response characterizations have been implemented for Non-Linear Time History Analyses of a case study building structure, in order to evaluate differences between radial rather than general earthquake simulations.

*Keywords: Concave Surface Slider devices, bidirectional motion, Non-Linear Time History Analyses, Friction coefficient.*

**1. INTRODUCTION**

Concave Surface Slider (CSS) isolation devices have become one of the most implemented solutions for mitigation of the seismic vulnerability of both building and bridge structural systems (Fenz and Constantinou 2006). Large displacement demands can easily be achieved, with high energy dissipation capacities and fairly good recentering responses, if properly designed (Mosqueda et al. 2004, Quaglini et al. 2017). A number of important research works have led to a very high level of knowledge about the behavior of such devices, from both the experimental and numerical points of view (Kumar et al. 2005, Mazza and Mazza 2017). In addition, in the common practice, devices for real applications have to be tested according to specific standard code prescriptions for anti-seismic devices, and the effective most important characteristics of the mechanical response of isolators can be assessed and checked (AASHTO 2014, CEN 2018). Among the others, the most relevant aspects to consider in the evaluation of the hysteretic behavior of CSS isolators are the dependency of the friction coefficient on the sliding velocity (“velocity effect”), contact pressure (i.e. applied vertical load – “vertical load effect”) and repetition of cycles and temperature rise (“cyclic effect”) (Lomiento et al. 2013, De Domenico et al. 2018, Quaglini et al. 2014, Dolce et al. 2005). Nonetheless, testing protocols provided by the most common standard codes imply unidirectional tests: for instance, in the European standard code UNI:EN15129:2018 (CEN 2018) just one bidirectional test is listed, which can be substituted by a radial test along an orthogonal direction, if the testing equipment is not able to reproduce a two-components motion. From the numerical point of view recent research works have shown effective agreement of the response of isolated structures between radial and bidirectional seismic events (Furinghetti and Pavese 2017), even though experimental discrepancies have been highlighted in some cases (Furinghetti et al. 2019a).

In the present endeavor a comparison between the radial and bidirectional response of a base-isolated case study structure has been performed, by means of Non-Linear Time-History Analyses. A wide set of natural bidirectional seismic events have been applied, and equivalent radial input signals have been computed for a more consistent comparison. Isolation devices have been properly modeled by means of hysteretic non-linear constitutive laws, according to the frictional characterization curves (1D and 2D) obtained in a previous experimental campaign. Results have led to a better understanding of the influence of both the biaxial interaction of the directions of motion and the effective frictional properties under specific loading conditions.

**2. sEISMIC ISOLATION DEVICES**

In this work the outcomes of a wide experimental campaign have been used for the characterization of the frictional properties of isolation devices (Furinghetti et al. 2019a). Precisely, a Double Concave Surface Slider (DCSS) device has been considered, equipped with an innovative sliding material, which consists of a PTFE sliding pad, filled with carbon fibers. Both the sliding surfaces have the same radius of curvature and the inner slider does not have any articulation (Equivalent radius of curvature approximately equal to 3.0m): consequently, same motions (displacement, velocity) can be considered at both the sliding interfaces. In Figure 1 the tested device is reported.

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Figure 1. Tested prototype: Double Concave Surface Slider

According to results presented in Furinghetti et al. (2019a), the frictional properties of the overall device have been considered as a function of the sliding velocity (velocity effect). Actually, the performed testing campaign provides the response of the device under several combination of sliding velocity and contact pressure, by applying both radial and bidirectional motions, in agreement to the standard code UNI:EN15129:2018. No dependencies on the contact pressure and the cyclic loading have been assumed in this study, and consequently, the friction coefficient has been analyzed at the very beginning of motion (i.e. at zero dissipated energy). Numerical values have been used for non-linear least-square analyses, by assuming the commonly known expression of the velocity effect on the friction coefficient (Constantinou et al. 1990) (Equation 1):

 (1)

Being:

*  and  the friction coefficient at fast and slow velocities respectively;
*  the modulus of the vectorial sliding velocity;
*  a rate parameter which describes the transition between slow and fast friction coefficient values.

In Figure 2 results are analyzed for both radial and bidirectional motions, under two values of contact pressure, as a function of the peak velocity applied to the device.

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Figure 2. Velocity effect for the considered contact pressure

As can be noted from graphical results, the adopted analytical expression for the velocity effect fairly represents the experimental points, under both radial and bidirectional motions. The friction coefficient can be approximately considered as constant for velocity values higher the 50mm/s at both the interfaces (100mm/s for the overall device). In Table 1 summary of results is reported.

Table 1. Summary of non-linear least square best-fit results.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **1D motion** | | | | **2D motion** | | | |
|  |  |  | [m/s] |  |  |  | [m/s] |  |
| **P = 15 MPa** | 13.9% | 7.1% | 0.036 | 99.9% | 15.9% | 10.4% | 0.047 | 100.0% |
| **P = 45 MPa** | 7.4% | 3.8% | 0.019 | 98.7% | 8.0% | 5.9% | 0.019 | 90.6% |

The bidirectional sliding motion leads to higher coefficient of friction: precisely, +14% and +7% percentage variation can be computed for high velocity at 15MPa and 45MPa contact pressure respectively: the difference between radial and bidirectional sliding motions seems to become more and more negligible as the contact pressure increases. Concerning the slow value of friction coefficient, the same average variation can be detected for both the considered pressure values: the bidirectional case leads to an increase of +50% on the friction coefficient at zero velocity. As previously commented, the fairly good agreement of the experimental point and the assumed analytical expression of the velocity effect is numerically described by the significantly high values of R2 parameter.

**3. CASE STUDY STRUTURE**

The response of a 6 storey reinforced concrete frame structure has been investigated, by considering a base isolation system of DCSS devices (Cardone et al. 2017). In Figure 3 a 3D rendering of the building is shown.

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Figure 3. Case study structure

The seismic isolation system consists of 24 isolators, located beneath all columns locations. The total mass is equal to 2080tons, and a first mode period of 0,96sec can be computed, if the fixed-base configuration is assumed. In this work the structural response of the base-isolated case study structure has been assessed by performing Non-Linear Time History Analyses: thus, in order to reduce the runtime of all the analyses, a special static condensation procedure has been applied to the full 3D F.E.M. model of the structure, and an equivalent Multi Degree of Freedom oscillator has been obtained, with same dynamic properties (Furinghetti et al. 2019b, Chopra 1995). Thanks to this assumption, the dynamic system can be considered as a set of equilibrium equations of all the storey masses of the building. The influence of the isolation system is provided by the actual modeling of a hysteretic constitutive law and no contribution is included in the stiffness matrix of the building. For all the analyses, the same stiffness matrix has been considered for both x and y directions of motion of the building, since similar behaviors have been computed.

**4. SELECTION OF SEISMIC INPUT SIGNALS**

In order to provide a wide statistical population of data for the comparison of radial and bidirectional responses, a large set of 71 natural bidirectional seismic events has been adopted, by using the database of the software REXEL (Iervolino et al. 2009). Furthermore, components of all the considered earthquakes have been scaled, by applying an ad hoc scaling procedure, which minimizes the error between the single-event and the target spectra; scale factors have been bounded between 0.5 and 2.0, in order not to obtain unrealistic ground motion signals, in terms of amplitude and frequency content. Spectrum compatibility has been checked, according to prescriptions of the Italian Building Code 2018; for the definition of the reference spectrum, L’Aquila hazard has been considered, within the collapse limit state (5% of probability of exceedance), in addition to nominal life of the structure equal to 50 years, soil class C, a plan ground surface (topographic category T1) and an ordinary typology of strategic importance (functional type II). Upper and lower bounds for spectrum-compatibility have been defined as 130% and 90% of the target spectrum respectively, within a period range between 0,15s and 3,0sec. In Figure 4 results of the spectrum compatibility check are provided.

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Figure 4. Spectrum-compatible selection of 71 natural scaled records

It has to be noted that spectrum compatibility has been assessed, by considering displacement spectra, associated to each bidirectional seismic event. In order to compute the bidirectional displacement spectrum, a set of Single Degree of Freedom oscillators have been analyzed, subjected to both x and y components, and the spectral coordinate has been computed as the maximum value of the modulus of the displacement vector.

The present endeavor aims to compare the response of a base-isolated structure under both radial and bidirectional seismic events. In order to make a reasonable and consistent analysis, radial and bidirectional earthquakes have to be comparable. Thus, for each bidirectional seismic event, the optimum horizontal radial direction has been computed, which returns the best comparison, in terms of displacement response spectrum at 5% damping, between the radial and the bidirectional cases (Furinghetti and Pavese 2017).

**5. DYNAMIC SYSTEM FOR N.L.T.H.A.**

Thanks to the applied static condensation procedure, the dynamic system for Non-Linear Time-History analyses can be defined as follows, for both x and y directions.

 (2)

 (3)

Being:

*  and derivatives the translational degrees of freedom along the i-th direction and at the j-th floor;
*  and  the mass and stiffness matrices of the superstructure;
*  and  the components of the considered seismic event;

The components of the seismic event can be either the individual signals of the bidirectional case, or the optimal radial projection of the equivalent unidirectional motion.

The dynamic systems along x and y directions are coupled, since the response of all the implemented isolators accounts for the biaxial interaction of the directions of motion, as shown in the next equation.

 (4)

With:

* Modulus of the vectorial velocity: 
* Average contact pressure: P
* Rate parameter:  = 0.0075 m/s

Concerning frictional properties , both the experimentally investigated contact pressure values have been assumed; in addition, two cases have been defined: in the former the 1D frictional properties have been implemented for both the radial and the bidirectional motions; in the latter, the actual frictional properties (1D and 2D) have been considered individually for radial and bidirectional motions. In this way it is possible to evaluate influences of both the bi-axial interaction of the directions of motion and differences of frictional behaviors.

**6. RESULTS**

In this section results are shown for the main peak response quantities: distributions have been computed for the ratio between the values related to the bidirectional and the radial cases respectively (2D over 1D), by considering same (radial only) and individual (radial and bidirectional) frictional properties. In Figure 5 results for the isolation displacement demand are reported.

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Figure 5. Results: Isolation displacement ratio

When the lowest contact pressure is considered, which corresponds to the highest frictional properties, the variability is very high. Histograms of the isolation displacement ratio for both pressures suggest a non-symmetric log-normal distribution, which has been considered for the computation of the correspondent probability density function (p.d.f.). If same material properties are assumed the mode value of the distribution is higher than 1, since in the bidirectional case the bi-axial interaction leads to the stepwise projection of the frictional force along the trajectory of the device: consequently, the frictional force is no longer parallel to the recentering ones, and higher displacement demands are more likely to be experienced, rather than the unidirectional case. If the proper characterization curve is considered for the bidirectional case, higher friction coefficient values are computed and, consequently, lower displacement demands are found: this aspect, together with the bi-axial interaction influence, leads to mode values closer to 1. On the other hand, variability between 1D and 2D frictional properties comparison look very similar for both the applied average contact pressure values.

In Figure 6 similar results are presented for the isolation force response.

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Figure 6. Results: Isolation force ratio

The variability of the isolation system is significantly lower than the obtained values of the displacement demand (approximately ±5%). In addition, opposite results are found in terms of mode values, assuming normal distributions: as expected, the actual bidirectional characterization curve leads to higher force values, whereas if same properties are considered, unitary mode values can be computed.

In tFigure 7 he building base shear is considered and the correspondent variability is analyzed.

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Figure 7. Results: Building base shear ratio

Also concerning the building base shear the overall variability is significantly reduced with respect to the displacement demand, even though doubled values (approximately ±10%) can be noticed in comparison to the isolation force. Mode values of the correspondent Gaussian’s distributions are higher than 1 if the proper frictional curve is considered for bidirectional motions, whereas values close to 1 can be found, as direct influence of the bi-axial interaction only.

Finally, interstorey drift ratios have been analyzed for all levels of the building, in order to consider a response parameter directly correlated to the internal forces of all the structural elements of each storey. In Figure 8 and in Figure 9 results for interstorey drift ratios are presented, for average contact pressure 15MPa and 45 MPa respectively.

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Figure 8. Results: Inter-storey drift ratio (P = 15MPa)

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Figure 9. Results: Inter-storey drift ratio (P = 45MPa)

For all levels of the superstructure same conclusions can be drawn in comparison to the base shear behavior. The effective frictional response of the bidirectional motion, in addition to the bi-axial interaction of the directions of motion, leads to higher mode values of all the normal distributions, whereas approximately unitary values can be found if the same radial frictional characterization curve is implemented (i.e. bi-axial interaction influence only).

In order to better understand the distribution characteristics for all the investigated response quantities, in Table 2 values for mode and standard deviation are listed.

Table 2. Summary of statistical results.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **P = 15 MPa** | | | | **P = 45 MPa** | | | |
|  | **1D friction** | | **2D friction** | | **1D friction** | | **2D friction** | |
|  | **Mode** | **Std** | **Mode** | **Std** | **Mode** | **Std** | **Mode** | **Std** |
| **Isolation displ.** | 111.9% | 47.2% | 100.8% | 42.1% | 114.2% | 25.8% | 110.0% | 24.6% |
| **Isolation force** | 101.5% | 4.0% | 112.7% | 5.0% | 101.3% | 6.0% | 106.1% | 6.4% |
| **Building base shear** | 101.2% | 7.6% | 111.3% | 8.9% | 99.5% | 11.1% | 105.9% | 11.3% |
| **L1 drift** | 101.2% | 7.1% | 110.9% | 8.1% | 99.0% | 10.0% | 105.2% | 10.7% |
| **L2 drift** | 101.9% | 8.8% | 111.6% | 9.3% | 99.2% | 11.4% | 105.0% | 11.9% |
| **L3 drift** | 101.7% | 10.8% | 110.9% | 12.0% | 98.1% | 10.4% | 103.7% | 11.3% |
| **L4 drift** | 103.7% | 14.2% | 112.3% | 15.8% | 99.6% | 12.5% | 105.4% | 13.2% |
| **L5 drift** | 105.8% | 16.4% | 114.6% | 17.3% | 101.8% | 14.8% | 108.7% | 15.8% |
| **L6 drift** | 105.1% | 16.6% | 113.5% | 17.0% | 100.6% | 15.1% | 108.3% | 15.8% |

Results show that the displacement demand at the isolation level can be overestimated, if isolation devices are characterized by applying a unidirectional testing protocol, even though the force response is properly modeled by accounting for bi-axial interaction of the direction of motion. The influence of the proper frictional curve for the velocity effect in the bidirectional motion is represented by a slight reduction of the variability for both contact pressures, becoming negligible if high pressures are applied (corresponding to the asymptotic branch of the vertical load effect). If the highest contact pressure is analyzed, which implies lower friction coefficient values and less differences between radial and bidirectional properties, variability if approximately halved.

Concerning isolation force and building base shear, approximately same mode values can be noticed, and doubled variability has been obtained for the superstructure response in all cases.

Results of interstorey drift ratios show increasing values for both mode and standard deviation as higher floors are considered, and approximately doubled values of variability can be found at the last level, in comparison to results at the ground floor.

**7. CONCLUDING REMARKS**

In this work the comparison of radial and bidirectional motions have been investigated, by considering a base isolated frame structure equipped with Double Concave Surface Slider (DCSS) devices. In order to consider realistic frictional properties, the outcomes of a wide experimental campaign have been analyzed, in order to obtain frictional characterization curves for the velocity effects, under radial and bidirectional sliding motions. The structural response of the case study structure has been investigated by performing Non-Linear Time History Analyses. To this aim, a wide set of 71 natural bidirectional seismic events has been defined, by assessing the spectrum-compatibility with respect to the prescriptions of the Italian Building Code: each seismic event has been scaled, in order to make the single-event spectrum more comparable to the target one, defined according to the seismic hazard of the construction site, and scale factors have been bounded between 0,5 and 2,0. Furthermore, for all the bidirectional earthquakes an optimum direction angle has been computed, for the computation of an equivalent radial event, able to return approximately the same response spectrum of the case with both the simultaneous components. Non-Linear Time History Analyses have been performed, by using a statically condensed Multi Degree of Freedom model of the superstructure, together with an actual hysteretic constitutive law for the isolation system force response, modeled as an equivalent single device. Results have been analyzed by focusing the attention on some important response parameters, such as displacement demand and force response of the isolation system and base shear and interstorey drifts for the superstructure; precisely, for each event the dynamic system has been solved, by applying the bidirectional and the radial ground acceleration signals, and the ratio between the 2D and the 1D peak response quantity has been computed; furthermore, such analyses have been performed by accounting for same frictional properties (related to the radial characterization curve) and by distinguishing between bidirectional and radial frictional responses. Thanks to the presented results the following influences can be studied:

* Bi-axial interaction of directions of motion (1D friction, i.e. same frictional properties);
* Bi-axial interaction and different frictional response (1D and 2D frictional responses).

Results have shown that the isolation displacement demand is generally higher in the 2D case, with respect to the radial one, by accounting for same frictional properties, because of the stepwise projection of the frictional force along the trajectory of the devices; as soon as the proper characterization curve is considered for the bidirectional event, differences between 1D and 2D responses averagely become negligible, with small consequences in the variability. Concerning the isolation force and the building base shear responses, much lower variability values have been noticed, and the opposite behavior has been found: if the real 2D frictional properties for the bidirectional events are implemented, higher force values are likely to be obtained. Finally, the analysis of the interstorey drift response for all levels of the building have highlighted that mean and standard deviation slightly increase as upper storey are considered, and same behavior of the force response can be found (the proper 2D characterization curve for the bidirectional event leads to averagely higher values).

The drawn conclusions of the present work would need further research, from both the experimental and the numerical points of view, in order to consider different mechanical properties for isolation devices and a number of case study structures.

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