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RETROFITTING OF R.C. FRAME BUILDINGS WITH DOUBLE CONCAVE CURVED SURFACE ISOLATOR SLIDERS CHARACTERIZED BY OVER-STROKE DISPLACEMENT CAPACITY

F. C. Ponzo[1], **A. Di Cesare**[1], **N. Lamarucciola**[1]

[1] University of Basilicata
Viale dell'Ateneo Lucano, 10, 85100 Potenza
{felice.ponzo, antonio.dicesare, nicla.lamarucciola}@unibas.it

Abstract

Base isolation system is one of the most widespread passive control system techniques currently used for seismic protection of buildings and bridges. At the ultimate limit state, isolating devices are designed to attain the design displacement at the Maximum Credible Earthquake (MCE), while the superstructure remains in the elastic range for earthquake intensity corresponding to the Design Basis Earthquake (DBE). Among various isolation devices the friction pendulum sliders and elastomeric bearings are the most economical and practical system. Acceptable probabilities of collapse for seismically isolated frame structures could be achieved by a suitable isolator displacement capacity.
This study considers the effects of restraining rings and of the over-stroke displacement capacity of double concave curved surface slider (DCCSS) isolators on the structural seismic response. The seismic behaviour of base isolated six-storey reinforced concrete frame building case study retrofitted for seismic site of L'Aquila has been evaluated considering earthquake intensity levels at Collapse Limit State. Different configurations of the base isolation system, with end-stops placed at maximum isolator displacement capacity or with extra-stroke displacement capacity, have been investigated. In this paper, the results of non-linear static and dynamic analyses at the MCE are compared.

Keywords: Base isolation system, double concave curved surface slider, over-stroke displacement capacity, non-linear dynamic analysis, seismic retrofit.

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1 INTRODUCTION

Different passive control seismic protection technologies have been developed in the last years. The base isolation system is one of the most used techniques for the protection of framed structures to guarantee their post-earthquake functionality, also after high intensity seismic events.

Among the various isolation systems, differing in construction technology, materials, geometry and operating principle, the effectiveness of seismic isolation based on friction pendulum bearings in protecting structural and non-structural elements has been demonstrated by several experimental and numerical studies [1-3].

The sliding isolation systems are composed by a certain number of moving parts (at least two) made of steel and composite materials which slide over each other expressing a specific friction force. One of the most common seismic isolation systems is the Friction Pendulum Slider® (FPS), firstly developed by Zayas [4], which allows both re-centering and good dissipation capabilities, being based on the pendulum mechanic principle.

The Double Concave Curved Surface Slider (DCCSS) consists of two facing concave stainless-steel surfaces separated by a slider which can be either articulated or rigid. The DCCSS can be modelled considering two concave Curved Surface Sliders (CSS) in series characterized by the same coefficient of friction μ and effective radius of curvature R_{eff} [3, 5].

The CSS bearings can be further divided in two main groups: devices with or without a displacement restrainer, such as displacement restraining rings, which prevent the inner slider to slide past a certain point which usually is the perimeter of the housing pad. The displacement restraining rings are made of the same material of the housing plate and can be welded, bolted to it or even form a single block with the pad itself [6] and are widely used in America [7] in order to control displacements and to avoid the isolator disassembly when displacements higher than the design ones occur. Nevertheless, the impact against such restraining end-stroke element may induce significantly high acceleration to the superstructure. In contrast, the European Standards [8] do not allow the presence of these displacement restrainer elements, that can be damaged in case of a seismic event higher than the Maximum Credible Earthquake (MCE) and only approves the use of structural joints separating the superstructure from the surrounding constructions, as ground retaining walls or specific devices such as rubber bumpers attached to the walls, in order to safely accommodate the seismic movement. Usually in Europe, the gap separating the superstructure from the retaining wall is much larger than the displacement capacity of the isolators, and consequently, the inner slider can run on the edge of the sliding surfaces for earthquakes producing displacement larger than the isolators capacity. When displacement end-stroke elements are not employed, and concave plates feature a flat rim [6], the inner slider movement beyond the geometric capacity displacement d_c of the isolator is allowed entering in the so-called over-stroke displacement regime. The slider running in the over-stroke displacement regime can provide the DCCSS device with an increased displacement capacity d_{lim} and sliding force. The force-displacement relationship and the limit displacements for the over-stroke sliding regime have been experimentally characterized in previous studies [9-13].

This paper focuses on a case study of a RC building designed in the 1980s and retrofitted by means of DCCSS isolators [14] designed following the Italian seismic code [15]. The building represents an existing six-storey reinforced concrete frame structure located in the city of L'Aquila (Italy) on soil class C. Nonlinear time histories (NTHA) and non-linear static analyses have been carried out considering earthquake intensity levels at Collapse Limit State (with a return period of 1000 years) and different end-stop conditions (with and without over-stroke displacement and moat wall). Analyses results have been compared in terms of top displacement and base shear of the retrofitted case study building.

2 CASE STUDY

The case study considered in this paper is a typical residential RC-frame buildings designed in the 1980s considering a low seismic design approach according to the outdated İtalian seismic code [16]. The building is located in L'Aquila (Italy) and has been retrofitted using a seismic isolation system [15]. The frame is characterized by a regular plan of about 240 m^2, with 3.4 m inter-storey heights for the 1^{st} level and 3.05 m for all the other floors (Figure 1). All stories have the same 25 cm-thick slab. The structure includes a staircase with knee beams. Masonry infills, that are regularly distributed in plan and elevation, are characterized by various opening percentages. Infills dead loads have been considered in the design process. More details about RC structural members and infill panels can be found in [14]. In the isolated configuration, the total mass *M* considers a supplementary RC base slab added at the base below the ground floor columns.

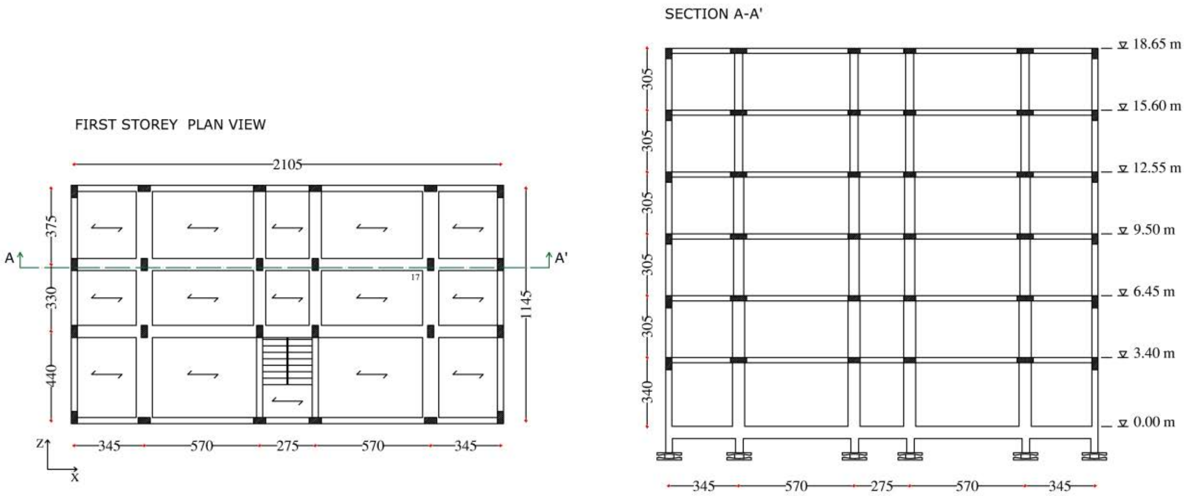

Figure 1. Case study building: plan view and longitudinal sections.

The isolation systems consisted of 24 DCCSS isolators placed below the columns have been designed considering the superstructure elastic limit, structural behaviour factor *q* equal to unit [15]. The design procedure of the isolation system started from the evaluation of the spectral acceleration S_e^* of the existing building associated with the occurrence of the first plastic hinge ($S_e^*=V_e / M$) by means of a push-over analysis of the superstructure subjected to a forces distribution proportional to the floor masses V_e. Assuming the Design Basis Earthquake (DBE), the S_e* value allowed to identify the minimum fundamental period $T_{iso,min}$ of the base isolation system, as shown in Figure 2 (red dashed lines).

Both concave plates of the DCCSS, featuring a rigid inner slider, are characterized by the same radii of curvature *R* and the same friction coefficients μ = 2.5%, and the assumed hypothesis is that sliding occurs simultaneously on both surfaces. Starting from the design displacement d_{Ed}, evaluated considering accidentally torsional effects also, the maximum displacement d_{max} has been assumed by catalogue and the geometric capacity displacement d_c has been supposed to be 10% higher than d_{max}.

The total seismic weight *W* of the isolated structure is about 15560 kN and the maximum vertical loads N_{Sd} on the isolators is about 650 kN. The isolation system is designed considering the spectrum of the Maximum Credible Earthquake (MCE) shown in Figure 2 [17] with a return period of 1000 years.

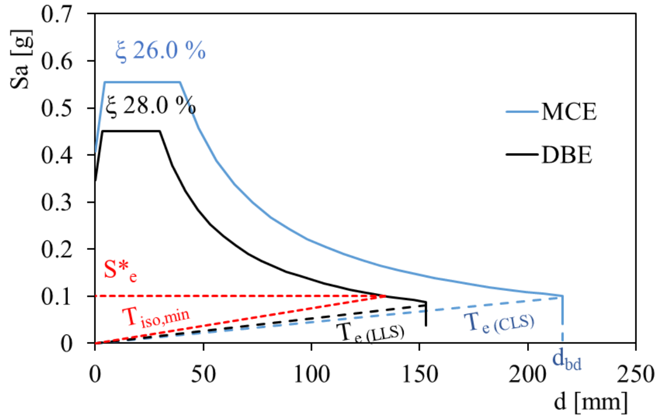

Figure 2. Isolation systems design procedure on ADRS Spectra for DBE and MCE.

The main design parameters and the geometric characteristics of the designed isolation system are reported in Table 1, in terms of equivalent radius R_{eff}, equivalent stiffness K_{eff}, effective period T_{eff}, effective damping ξ_{eff}, the design displacement d_{Ed} of the isolation system at the MCE, the slider diameter Φ, the maximum displacement d_{max} and the geometric capacity displacement d_c.

The overstroke ultimate displacement d_{lim} corresponds to the slider overturning around its center of rotation beyond the geometrical capacity or to the maximum contact pressure between the rigid slider and housing plate, equal to the slider surface reduced by the area of the slider external to the sliding [18].

R_{eff} [mm]	K_{eff} [kN/mm]	T_{eff} [sec]	ξ_{eff} [%]	d_{Ed} [mm]	Φ [mm]	d_{max} [mm]	d_c [mm]	d_{lim} [mm]
3700	0.296	2.97	26	216	200	±300	±330	±420

Table 1: Main characteristics and design parameters of the DCCSS isolation system.

3 NUMERICAL MODELLING

The numerical model of the existing frame has been implemented in OpenSEES [19], based on a lumped plasticity approach for the elements of the superstructure. Elastic beam elements have been used for the base floor grid above the isolation system. The plastic hinges (*modIMKmodel*) have been modelled considering the cyclic degrading behaviour model proposed by Ibarra [20]. In this study, 5% Rayleigh damping is used to model the viscous damping of the super-structure. Second order effects have not been considered. The masonry infills in-plane behaviour has been modelled considering an equivalent compression-only strut, with a backbone curve defined on the basis of a modified version of the [21] model, while the effect of openings has been taken into account through suitable strength/stiffness reduction factors. More details about superstructure modelling can be found in previous studies [14].

The DCCSS cyclic response of the isolation system has been implemented with a *SingleFP-Bearing* element of a zero-length sliding hinge. The basic model has been modified in order to simulate the overstroke regime, by adding three zero-length elements in parallel, from the top node of the *SingleFPBearing* to a new fixed node. Two zero-length elements have been implemented as elastic-perfectly plastic gap elements (*elasticPPGap*), defined by a gap displacement d_c, an elastic stiffness k_2, increased friction coefficient and a yielding force F_y. The last zero length element has been modelled considering a multi-linear elastic material (*elasticMultiLinear*), defined by a nonlinear elastic stress-strain behaviour without energy dissipation. The Rigid Gap has been implemented with a zero-length hinge, from the top node of FPBearing to another new fixed node, consisting of an elastic-perfectly plastic gap element (*elasticPPGap*) with infinite stiffness ($k=\infty$), defined by a d_C gap displacement for isolation devices with rings or d_{lim} for isolators with rigid moat walls. More details about numerical modelling of DCCSS in overstroke regime and/or with displacement restrainers can be found in [11, 12].

4 ANALYSES RESULTS

Nonlinear static and dynamic analyses have been carried out considering different conditions of the isolation system. The seismic response of the isolated structure and isolation system were investigated by comparing the results of nonlinear static analysis (Pushover) in the longitudinal direction with those of nonlinear dynamic analyses.

Figure 3 shows the comparison between the pushover curve of not-isolated, base-isolated building, without and with overstroke and without and with rigid end-stops. Pushover curves of base-isolated building model (ISO) show the basic behaviour of the isolation system, with a first quasi-rigid branch (pre-sliding stage), followed by a second branch accounting for isolators restoring stiffness. As shown in Figure 3, for the configuration with isolation system and displacement restraining rings (ISO+Stop), the isolation system stops when the base displacement reaches d_c and a nonlinear behaviour curve similar to that of the not-isolated superstructure is shown again. The system with isolation system, and over-stroke until a moat wall (ISO+Over-stroke+Stop) perfectly overlaps the previous response for the first two branches, then, when the geometric capacity displacement d_c is reached, the isolation system starts the over-stroke sliding regime with a third branch having increased stiffness friction force, and finally, when the end-over-stroke is reached (end of sliding), the superstructure nonlinear behaviour curve is shown again. It can be pointed out that the shape of the first part of the pushover curve of isolated structures can be approximated by an elastoplastic hardening behavior.

Nonlinear time-history analyses (NTHA) of the isolated building with rigid end-stop (ISO+Stop) and with overstroke and rigid end-stop (ISO+Over-stroke+Stop) at intensity level corresponding to the MCE have been performed considering 20 unidirectional horizontal ground motions [22].

Figure 4 shows the comparison between the results of non-linear static and dynamic analyses, reported in the acceleration displacement response spectrum (ADRS) in terms of top displacement and corresponding ratio between base shear and total seismic weight. As can be observed, the dynamic results are in good agreement with the pushover curves. In the configuration with rigid end-stop due to restraining rings (ISO+Stop), the superstructure impacts against the end-stop for two seismic inputs, reaching values of base shear significantly high due to the dynamic effects. In the configuration with over-stroke capacity (ISO+Over-stroke) the geometrical capacity displacement d_c has been exceeded for the same two seismic inputs, due to the variability of the selected spectra-compatible ground motions and no impact against the moat wall has been verified. Moreover, as can be observed in Figure 3 the mean value of base displacement obtained by non-linear time histories analyses is in line with the design displacement d_{Ed}.

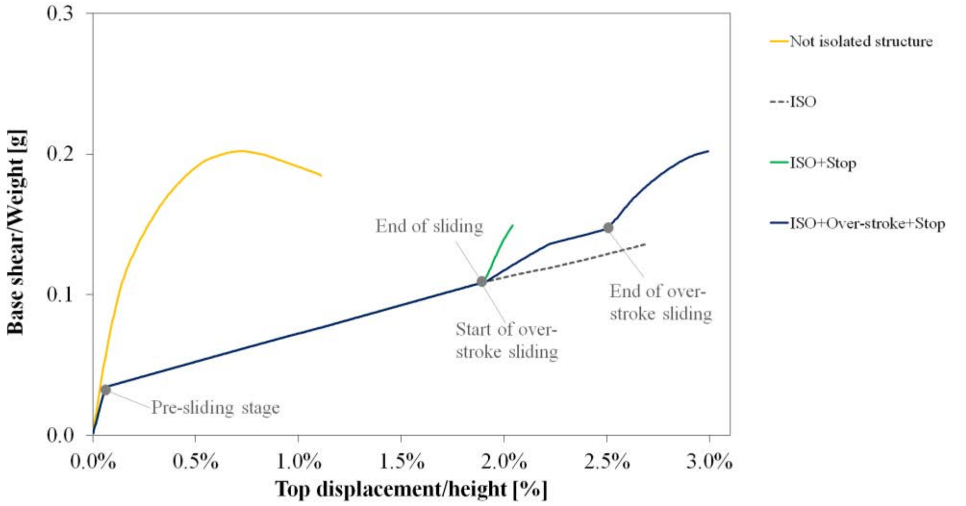

Figure 3. Pushover curves of not-isolated building and of building isolated with and without over-stroke and with and without end-stop for horizontal longitudinal direction.

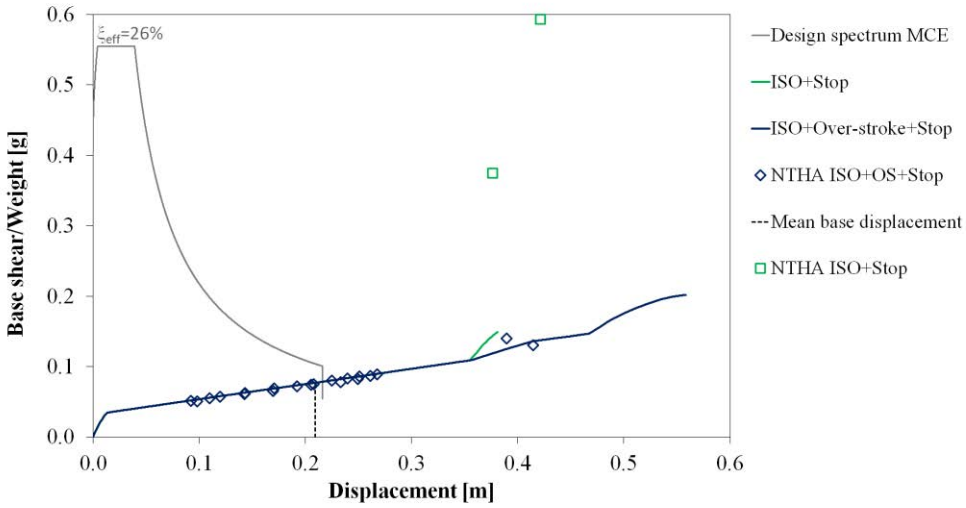

Figure 4. Comparison between non-linear static and non-linear dynamic results in terms of maximum top displacement and acceleration at the base level for horizontal longitudinal direction.

5 CONCLUSIONS

In this paper a case study of a seismic retrofitting of RC frame structure with DCCSS isolation system was investigated based on non-linear static and dynamic numerical analyses.

The oversizing of DCCSS due to industrial discretization where considered in the design and the over-stroke displacement capacity were accounted for the numerical simulations. A case study of base isolation system with overstroke, characterized by a ratio d_{lim} / d_c= 1.27 between the over-stroke displacement d_{lim} and actual geometric displacement capacity d_c, and by a ratio d_c / d_{Ed} =1.5 between d_c and the design displacement d_{Ed}, was considered. The non-linear time histories analysis at MCE pointed out that the force-displacement response of the structure is in good agreement with results of push-over analysis and that the mean value of maximum base displacement evaluated by nonlinear dynamic analysis in line with the design displacement evaluated by equivalent static analysis.

Results from nonlinear dynamic analyses highlighted that over-stroke displacement of the isolation devices may significantly increase the safety factor for seismic inputs higher than the design ones, without drawing on the plastic resources of the superstructure and changing the construction costs.

Further analyses are currently underway considering different case studies and different seismic sites of new and retrofitted RC frame.

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