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SEISMIC BEHAVIOR OF STEEL STRUCTURES EQUIPPED WITH STEEL SELF-CENTERING DEVICES (SSCD)

F. Morelli[1], A. Piscini[1] and W. Salvatore[1]

[1] Department of Civil and Industrial Engineering, University of Pisa
Largo Lucio Lazzarino 1, 56122, Pisa, Italy
{francesco.morelli, andrea.piscini, walter}@ing.unipi.it

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Abstract. *Recent earthquakes have highlighted not only the need of providing sufficient security level to civil and industrial structures in order to limit the loss of human lives, but also the need of reducing the damaging of structural and non-structural elements so to minimize the economical losses. Within this framework, increasing interest is being given, from national and international standards, to the recentering capability of structures and antiseismic devices. Residual displacements cause, in fact, an important reduction of the security level of the building in case of aftershocks, prevent the recovery of activities inside the building and they are very difficult to be repaired. Within this work, the seismic behavior of a steel structure equipped with a steel self-centering device is studied through several Incremental Dynamic Analyses, IDA. The SSCD characteristics are varied in order to perform parametric analyses and to study the influence of each parameter on the global behavior.*

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1 INTRODUCTION

Industrial facilities often store a large amount of hazardous material and the probability that accidental scenarios such as fire, explosion, toxic or radioactive dispersion may occur in the case of seismic event is very high. The ensuing disaster is sure to harm the people working in the installation and it may endanger the population living in the neighborhood or in the urban area where the industrial installation is located. Even if the content does not represent a direct threat to human lives or to the environment, damage to structural and/or non structural elements can lead to huge indirect economic losses, as testified by the numerous studies on the survey of damage causes [1] [2] [3], by the special attention to the non-structural elements damage [4] [5] and to the speedup of community recovery [6] [7] after the 2012 Emilia (Italy) earthquakes. From this point of view, it is evident that, for industrial buildings, the scope of a retrofit/strengthening intervention should be the increasing of the "seismic resilience" [8] [9] rather than the reduction of "seismic risk", which is more appropriate for civil building [10].

Different strategies can be implemented to focus the inelastic deformation, and so the dissipation of energy, on suitable elements [11] [12] [13] [14] [15] [16].In particular, for the retrofit of existing industrial plants attention is given to the use of passive dissipation systems, such as seismic isolation, e.g. [17] [18] [19] [20]. The initial higher cost associated to a retrofit using seismic isolation or energy dissipation system, comprised the ones consequent to the adaptation of the non-structural elements (e.g. pipelines), will be likely compensate by the avoided losses in case of moderate-to-strong earthquakes. Traditional hysteretic devices, however, do not provide a real "active" re-centering force, resulting in the possibility of residual displacements at the end of the earthquake and in the consequent complication of the substitution operations, such as the need of flame cutting for the removal of dissipative elements [21]. From this point of view, supplying the structure with a re-centering capability, defined as the capacity of minimizing the residual displacement after the end of the seismic action, is an important aim when the increasing of the structural resilience is pursued. Re-centering devices have been the object of ever increasing research studies [22] [23] [24] [25] [26] [27]. This type of dissipative device is characterized by the presence of re-centering elements that mitigate, and may even eliminate, the residual deformations in buildings and/or residual forces in the dissipative devices after earthquakes independently from the displacement demand.

The present work studies the effects on the global seismic behavior of the retrofitting of an existing industrial steel building adopting the steel self centering device (SSCD) developed in [27]. The performances of the structure (in the current state and on the retrofitted ones) are evaluated mainly through two performance parameters: the maximum and the residual displacements. Moreover, a parametric analysis is carried out to highlight the influence of each parameter that defines the device's hysteretic cycle on the global re-centering capability of the structure. The results obtained highlight the effectiveness of the SSCDs in improving the seismic performances of the building and in increasing its resilience by the minimization of the residual displacements.

2 CASE STUDY DESCRIPTION

The building analyzed within this work is characterized by a mass placed at significant altitude and different typologies of horizontal forces resisting systems, as it is shown in Figure 1. It has the function of filtering the gasses coming from the steelwork and can be schematized as made up of a supporting structure, the silos containing the filtered material and the roof.

The building has a regular plan, with overall dimensions 37.80 m x 16.94 m and total height 29.64 m. The supporting structure, with a total height of about 10.80 m, has six bays in the longitudinal direction and three in the transversal one. As is typical of industrial buildings, where the functionality issues often prevaricate the rules for an optimized structural design, different horizontal resisting systems (Figure 1) can be individuated such as moment resisting frames (longitudinal direction - ground floor), inverted V bracings (transversal direction - ground floor) and diagonal bracings (both directions - first floors).

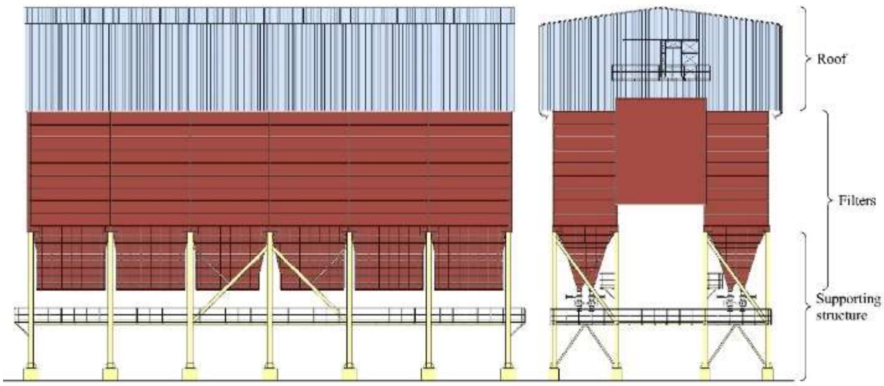


Figure 1: Front (left) and lateral (right) view of the case study

The total mass of the silo (23700 kN), considering the structural elements and the infill material, represents the 86% of the total mass (27650 kN). The roof is connected directly to the filter walls and its contribution is considered only in terms of vertical load and mass.

3 MODELLING AND ANALYSIS

A preliminary comparison between a full-comprehensive linear model and a geometrically-simplified (Figure 2) model was carried out given the need to simplify the structural scheme to obtain a reliable and time-saving nonlinear model. The "complete" linear model highlighted a structural behavior similar to that of a single degree of freedom in both directions, where the great part of the displacement demand is located in the supporting structure. The silos and the roof acted as a rigid body and the resultant stresses were far below the yielding or buckling threshold. It was therefore assumed that the structural behavior could be represented by the simplified model shown in Figure 2. In this model, used to perform nonlinear analyses, each frame was modelled, in OpenSEES [28] using fiber elements and the material was assumed to be elasto-plastic. The global second-order effects were explicitly taken into account. The bracings were modelled introducing an initial local bow imperfection, following the indications of Eurocode 3 [29] in order to consider their post-critic behavior when subjected to compression forces [31].

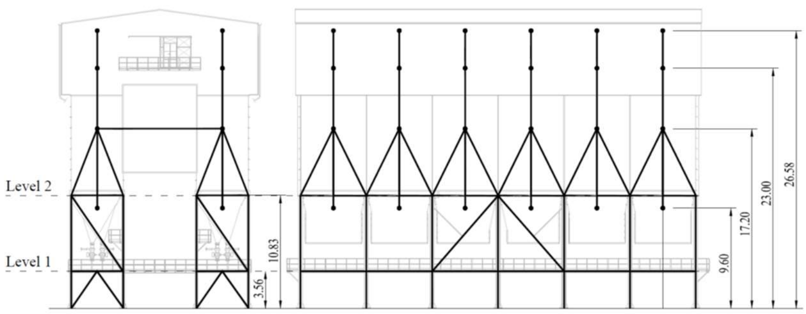


Figure 2: Case study simplified model geometry

The building performances in its current, un-retrofitted, state were evaluated using Incremental Dynamic Analysis, by monitoring two different Engineering Demand Parameters, EDPs:

- maximum displacements evaluated at levels 1 and 2 (Figure 2);
- residual deformations evaluated at levels 1 and 2 (Figure 2);

The IDAs were performed adopting a Uniform Hazard Spectrum - coherent method for the ground motions selection in order to achieve the worst damage scenarios with a robust and reliable procedure. In fact, the 3D analysis of the structure can lead to different results as a function of the procedure adopted for the ground motion recordings selection and of the scaling techniques, as already highlighted by [30] and [32]. The complete procedure, together with all the background and motivations, is described in [30] and [34].

A total of 198 nonlinear time-history were carried out applying simultaneously the three components (2 horizontal and 1 vertical) of the 11 selected ground motions and using 9 scale factors, SFs reported in [35].

4 SEISMIC VULNERABILITY OF THE CURRENT STATE AND SEISMIC RETROFIT

The seismic vulnerability of the case study is studied through incremental dynamic analyses (IDAs). The IDA results are expressed in terms of IDA curves where the Intensity Measure, IM, is quantified through the scale factors, while the EDPs are registered at the two different levels of the supporting structure (Figure 2).

The nonlinear analyses carried out on the current state (see [35] for more accurate information) evidenced several structural problems. The building is characterized by a low stiffness in the longitudinal direction, both at ground and first floor. In the transversal direction, the initial stiffness is sufficient to avoid excessive displacements, but the high slenderness of the bracings implies an insufficiently ductile mechanism. Moreover, the structure is characterized by important residual displacements in both directions at the end of the earthquakes. The presence of such residual displacements lowers considerably the resilience of the building, given the great difficulties in repairing a deformed and unstable structure.

On the base of this results, a seismic retrofit intervention, using the Steel Self-Centering Device described in [27] is proposed. The hysteretic force-displacement curve of such devices is typically characterized by a "flag" shape and, depending on the ratio between the re-centering force and the dissipative one, may present different values of the dissipated energy per cycle, residual displacement and residual re-centering force, as shown in figure 3.

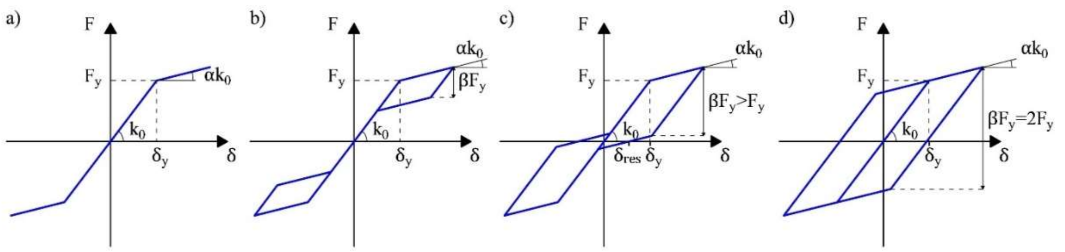


Figure 3: Idealized flag-shaped hysteretic curve: a) $\beta = 0$ (no dissipation), b) $0 < \beta < 1$; c) $1 < \beta < 2$; and d) $\beta = 2$

The shape of the hysteretic curve is determined by 4 parameters, F_y, k_o, α and β, where F_y is the yielding force, k_o the initial stiffness, α the ratio between the hardening and the initial stiffness, while β reflects the energy dissipation and the system's re-centering capacity.

A "reference" configuration of the SSCDs was pre-designed and several parametric analyses were then executed varying one parameter per time in order to study their influence on the structure global behavior. The mechanical characteristics of the SSCDs in the “reference” configuration are resumed in Table 1.

Level - Direction	Number of SSCDs	k_{0R} [kN/mm]	F_{yR} [kN]	α_R	β_R
Ground floor – longitudinal	8	72	529	0.26	1.00
First floor – longitudinal	8	88	848	0.26	1.00
Ground floor – transversal	28	112	332	0.16	1.00
First floor – transversal	14	77	556	0.20	1.00

Table 1: Mechanical characteristics of the SSCDs in the reference configuration

Starting from the reference configuration, the behavior of the building in its retrofitted state was studied varying the values of the re-centering factor β from 0.85 to 2.00, the initial stiffness k_0, from 0.5 to 2.0 times k_{0R}, the post-elastic stiffness k_h, from 0.5 to 2.0 times k_{Hr} and the yielding force F_y, from 0.5 to 2.0 times F_{yR}.

The influence of the SSCDs position on the overall behavior of the structure was not studied within this research. It was then fixed limiting, as much as possible, the interferences with the functionality of the building. The position of the SSCDs were the same of [35].

5 IDA RESULTS FOR THE RETROFITTED STATE

With reference to the levels definition of Figure 2, the main results in terms of IDA curves are shown in the following.

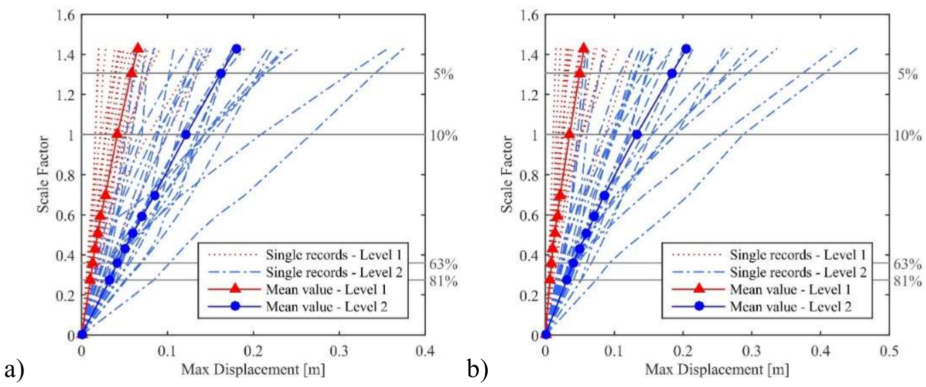


Figure 4: Maximum displacements in the a) longitudinal and b) transversal directions

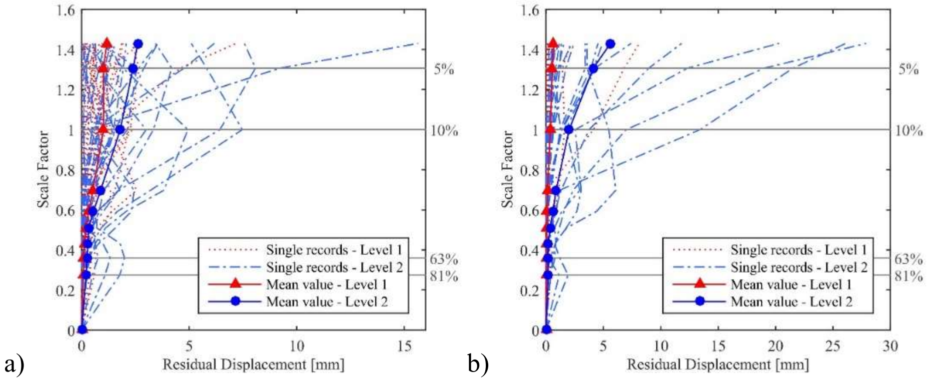


Figure 5: Residual displacements in the a) longitudinal and b) transversal directions

Analyzing Figure 4 it can be seen that, in both directions, thanks to the symmetric behavior of the SSCD, the displacement demand is equally distributed between the first and second floor. The IDA curves of Figure 5 testify the optimum re-centering capability of the retrofitting solutions: the residual displacements are lower than 3 mm in the X direction and 5 mm in the Y direction. In figure 6 the displacement time-histories and the cyclic force-displacement curve for the ground motion IN445A, SF=1.430, in both directions highlight, together with the global force-displacement curves, the differences in terms of maximum and residual displacements in the case of un-retrofitted and retrofitted structure. The un-retrofitted structure tends to accumulate displacement as the seismic action goes on, while the application of SSCD helps in avoiding this accumulation, giving the whole structure a flag-shaped hysteretic behavior.

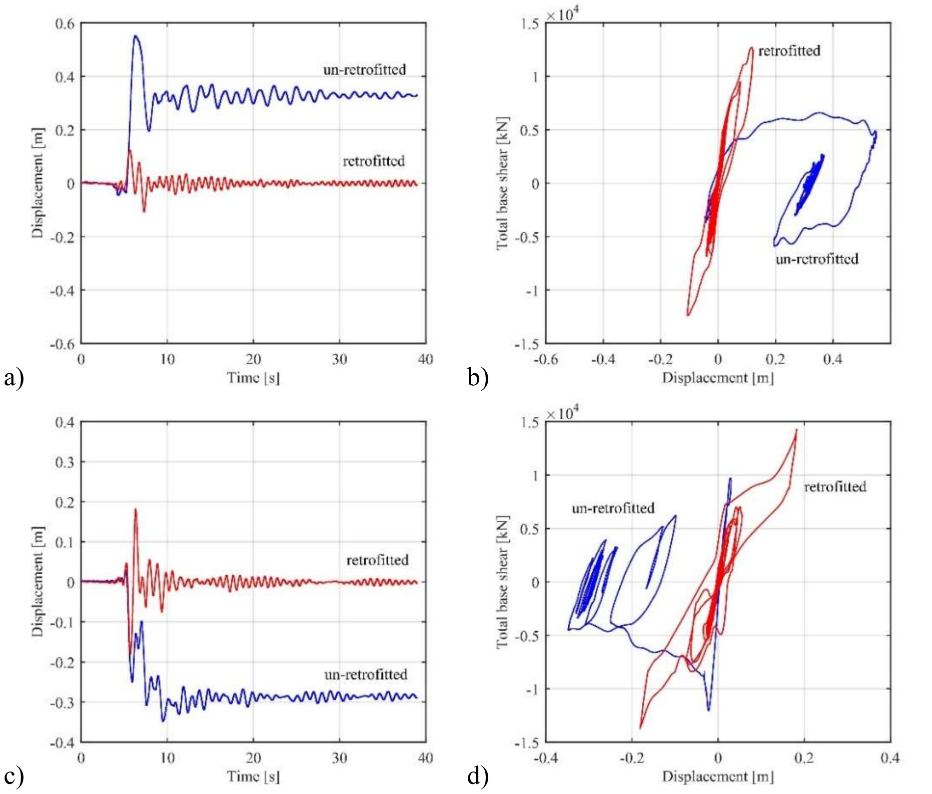


Figure 6: Ground motion IN445A, SF=1.430: level 2 mean displacement time history in a) X and c) Y directions; level 2 mean displacement vs total base shear in b) X and d) Y direction.

6 INFLUENCE OF THE PARAMETERS ON THE RE-CENTERING CAPABILITY

The re-centering factor, β, governs the shape of the hysteretic loops and influences the re-centering capability of the SSCDs: values of β close to zero maximize this capability, while values close to 2 makes the hysteretic cyclic behavior similar to a traditional hysteretic dissipative devices nullifying the active re-centering forces.

The IDA results reported in Figure 7 show that a β factor close to 2 reduces considerably the re-centering capacity of the SSCDs, while there are no particular differences in the other cases.

With reference to the initial stiffness of the SSCDs, k_o, it is intuitive to see how the residual displacements decrease as k_o increases for practically all the values of the seismic intensities (see Figure 8). The residual displacements in the Y direction (Figure 8b) highlight also how a low value of k_o can limit the re-centering capability of the system for high values of the seismic intensity.

Unlike the initial elastic stiffness, the post-elastic stiffness, k_h, only influences the values of the residual displacements for higher seismic intensities, causing them to increase as k_h decreases, see Figure 9.

Regarding the yielding force, Fy, the IDA curves in Figure 10 show that an increasing of this parameter tends to reduce the residual displacements.

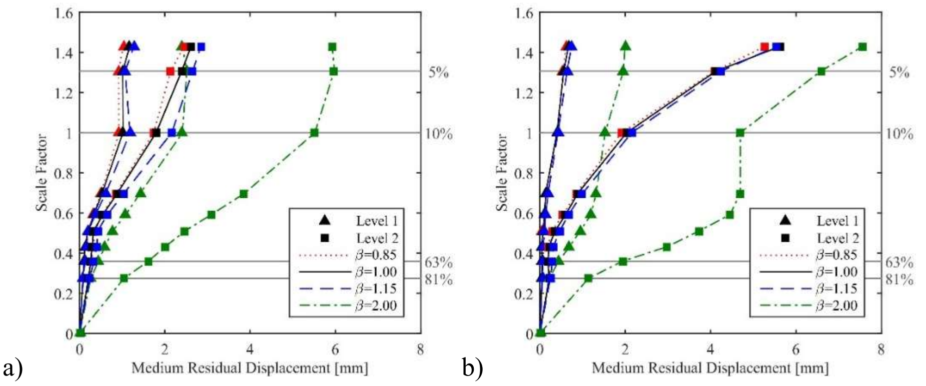


Figure 7: Influence of β on the residual displacements (mean values) in the a) longitudinal and b) transversal directions

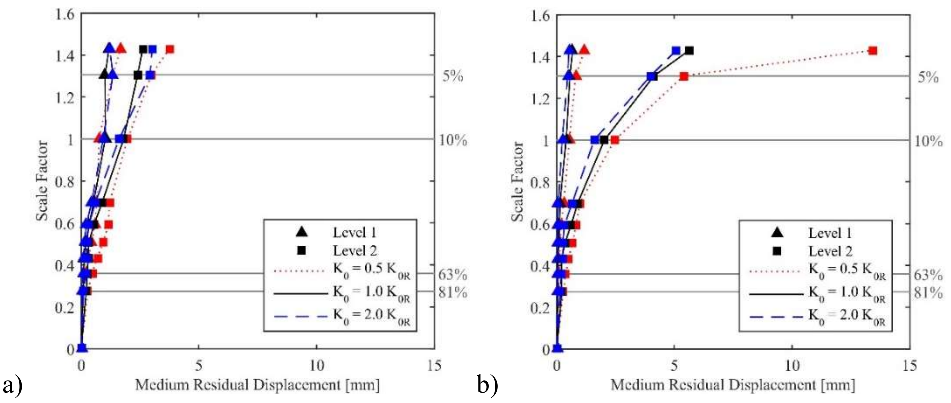
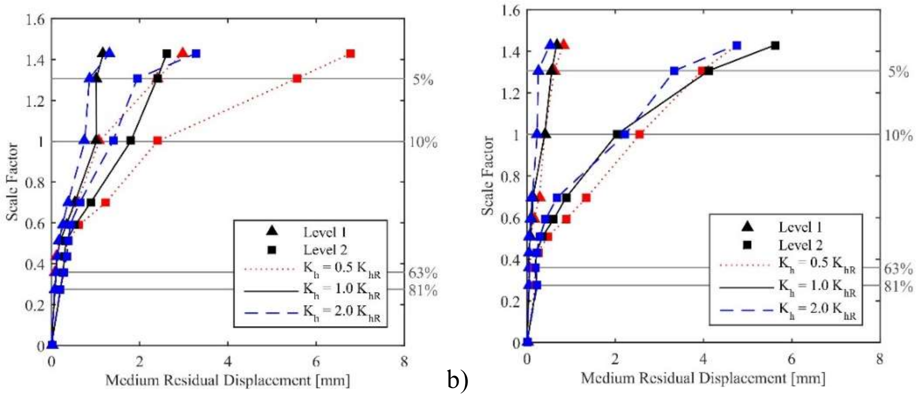
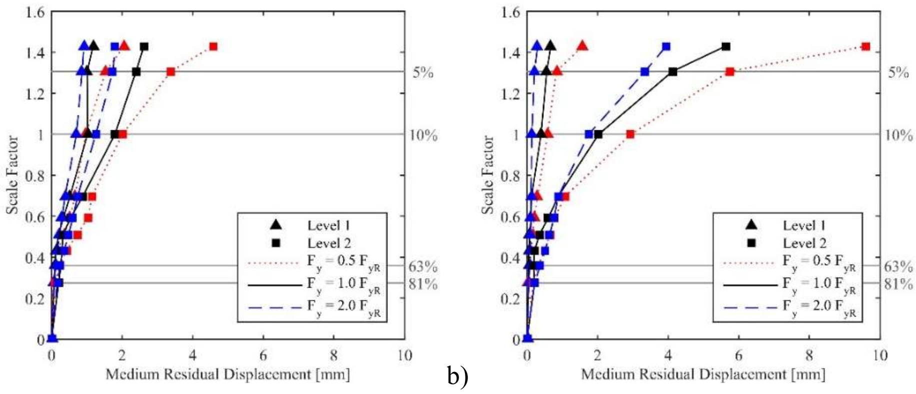


Figure 8: Influence of k_o on the residual displacements (mean values) in the a) longitudinal and b) transversal directions



a) b)

Figure 9: Influence of k_h on the residual displacements (mean values) in the a) longitudinal and b) transversal directions



a) b)

Figure 10: Influence of F_y on the residual displacements (mean values) in the a) longitudinal and b) transversal directions

7 CONCLUSIONS

The present work studied the seismic behavior of an industrial steel structure retrofitted with self-centering devices. The preliminary nonlinear static and incremental dynamic analyses proved main structural problems of the un-retrofitted structure in both directions. In particular, the structure shows the tendency to accumulate residual displacements at both levels in the X direction, while only at the first level in the Y direction.

The effectiveness of the seismic retrofit through the self-centering devices was first studied in this study by analyzing a "reference" configuration of the SSCD mechanical parameters. They were then varied performing a parametric analysis to investigate their influence on the global behavior. The analysis of the "reference" configuration evidenced that the retrofitting through the SSCDs reduces the maximum displacements of the supporting structure, limiting so the damages to structural and non-structural elements. Furthermore, the retrofitting supplies to the whole structure a global flag-shaped hysteretic behavior, granting an optimum re-centering capability and reducing so the damage of structural elements, difficult to be repaired after the end of the earthquake.

A parametric analysis was then carried out varying the values of the re-centering factor, β, the initial stiffness, k_0, the post-elastic stiffness parameter α, and the yielding force F_y, to study their influences on the global re-centering capability of the structure. The main conclusions are the following:

- an increasing of β does not influence so much the residual displacements if his value is close to 1, however, a β factor equal to 2 reduces considerably the re-centering capacity of the SSCDs;
- the residual displacements decrease as the initial stiffness of SSCDs, k_o, increases for practically all the values of the seismic intensities;
- the post-elastic stiffness, k_h, influences the values of the residual displacements only for higher seismic intensities, increasing them as k_h decreases;
- an increasing of the yielding force, F_y, tends to reduce the residual displacements.

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