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SEISMIC RETROFIT OF INDUSTRIAL V BRACED STEEL STRUCTURES THROUGH ASYMMETRIC RE-CENTERING DISSIPATIVE DEVICES

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Abstract

Industrial steel structures designed following old technical standards often do not comply with the current anti-seismic requirements. Besides, their distribution of the masses and of the structural elements can be strongly different from building-like structures. Therefore, they can require retrofit interventions through tailored solutions. This is particularly relevant for structures with V shaped bracings and relevant masses concentrated in the higher floors, as the case of industrial buildings with internal storing silos. This situation indeed implies that the bracings are compressed by the self-weight of the silo's infill, and they can work in strongly asymmetric tension-compression way during the seismic event with several issues from the structural performance perspective. Also, in the case of performing seismic rehabilitation intervention through classical anti-seismic devices, there may be issues related with the accumulation of vertical displacements and dissipating energy in the bracings. To this end, a specific asymmetric re-centering dissipative device has been developed and experimentally tested. The paper presents the dynamic analyses carried out on a simple case-study structure aimed at assessing its seismic behavior in the cases in which Buckling Restrained Braces or Asymmetric Re-Centering Device are used as dissipative bracings.

Keywords: Re-centering, asymmetric behavior, dissipative device, seismic retrofit, V bracings.

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1 INTRODUCTION

Seismic protection of existing buildings can be achieved through several different approaches [1]–[9]. Following the most recent technical standards and latest scientific proposals, the seismic behavior of existing structures can be generally improved modifying their resistance, stiffness, displacement capacity, or a mix of the previous, chosen after a proper assessment of the current performance of the “as-it-is” structure [10].

The choice of the optimal seismic protection strategy is strongly related to the characteristics of the building and not every strategy can be adapted for a specific building. However, the main goal of the seismic protection should be, at least, to minimize the damage to the gravity structure. In the light of this consideration, in the recent years several systems were specifically developed with the aim of increasing the seismic performance of new and existing buildings. Among the numerous systems, a particular success was obtained by Buckling Restrained Braces (BRBs), characterized by the capacity of exploiting the high anelastic deformability and energy dissipation capacity of steel also in compression thanks to presence of a lateral stability system that avoid the global instability of the brace. Several studies recently investigated the performance of buildings equipped with these systems, to the point that their use has recently also been formalized in the new draft of Eurocodes [11]–[14]. However, if on one hand the high dissipation capacity of this system helps in reducing the maximum displacement and acceleration of the retrofitted building, on the other hand it can lead to relevant residual displacement, especially in those cases in which the gravity resisting system has a very low lateral stiffness. For the purpose of limiting the residual displacements exhibited by the buildings after the seismic event, a special class of dissipative devices, the re-centering devices, have been developed in the last two decades [15]–[17]. These devices are characterized by the presence of a recentering force and sacrifice some energy dissipation capacity to obtain an active global recentering behavior.

All these devices, however, are characterized by a common aspect: the behavior’s symmetry in tension and in compression. Indeed, the basic idea of BRBs is to avoid uncontrolled response in compression with the consequent reduction of resistance and dissipation capacity due to buckling phenomena. Re-Centering Devices (RCDs) are, as far as the Authors known, also characterized by a symmetric behavior, also considering that the dissipation capacity is assigned to small BRBs, friction based or viscous elements. One of the few, if not the only, Asymmetric Re-Centering Devices (ARCDs) developed in recent years is described in [18] together with the idea at the base of the development and the practical cases in which this type of system can be useful. Indeed, these systems can be used to optimize the seismic behavior of structure in which the bracings are used to resist both to relevant vertical loads and to the horizontal seismic action, see Figure 1.

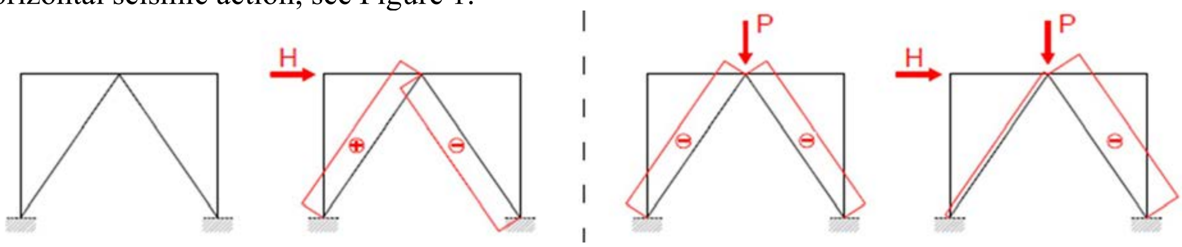


Figure 1: Forces induced in the inverted V bracings by horizontal forces in the cases of (left) negligible and (right) relevant vertical loads.

The present paper analyzes more in depth the behavior of buildings equipped with the ARCDs through the use of Incremental Dynamic Analyses in order to better understand the influence of the dynamic behavior on the global performance when the seismic intensity increases.

2 THE ASYMMETRIC RE-CENTERING DEVICE

The ARCDs studied within the present research is described in details in [18]. The device is designed to work as a brace, with an axial behavior characterized by an asymmetric flag shaped curve. In particular, the curve is not centered to the point where axial load is zero, but it is possible to center the behavior on the required compression or tension force. Figure 2 shows both the theoretical and experimental hysteretic curves, the latter obtained during an experimental campaign described in details in [18].

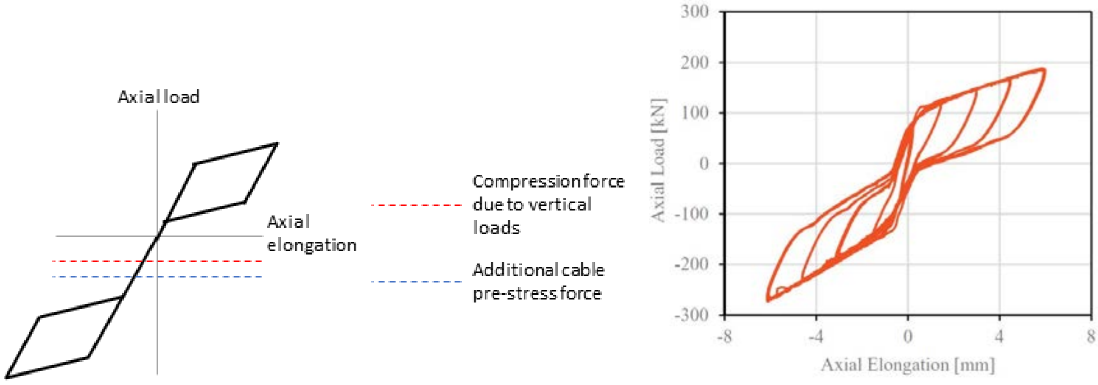


Figure 2: Schematic representation of the asymmetric re-centering device hysteretic behavior (left) and experimental validation (right, [18]).

To obtain such a asymmetric behavior, an additional pre-tensioned tendon is required compared to the "classical" solutions, as the ones described in [16], [17], [19], see Figure 3.

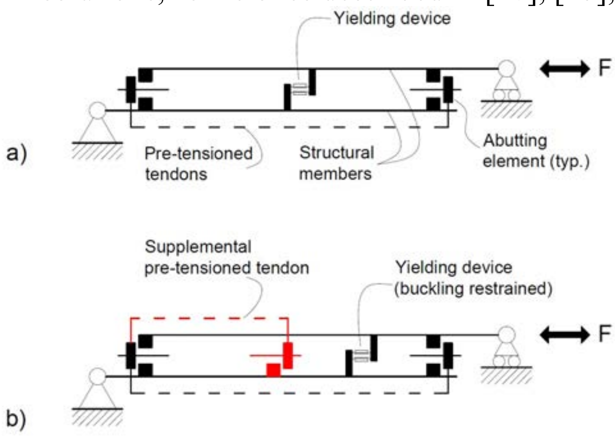


Figure 3: schematic representation of the re-centering device a) developed by [19] with symmetric tension-compression behavior and b) the version studied in the present research with an higher resistance and post elastic stiffness in compression thanks to a supplemental pre-tensioned tendon.

The connection of the supplemental pre-tensioned tendon to the structural members of the ARCD is set up in a way that grants its activation only when compression forces are applied, whereas in case of tensile forces the tendon do not exercises any supplemental resistance to the deformations. In this way, the re-centering system is characterized by a higher opening force in compression (meaning the force that determines the sudden stiffness variation in the hysteretic curve during the loading phase) and post-opening stiffness.

The study described in [18] demonstrated, for structures similar to the one showed in Figure 1 with inverted V bracings, a relevant constant vertical load and a quasi-static cyclic horizontal force acting on the beam:

i. the tendency of accumulating vertical and horizontal displacements in case classical structural profiles as bracings.
ii. Substituting the bracings with modern Buckling Restrained Braces does not solve the issue of the displacement's accumulation. Moreover, the BRBs dissipate energy only in compression and not in tension.
iii. Using RCDs with symmetrical behavior partially solves the issue of the displacement's accumulation but the energy dissipation is still obtained only when the bracings are in compression.
iv. Asymmetric Re-Centering Devices solve both the issues of displacement's accumulation and of dissipating the seismic energy in tension in the bracings.

These results demonstrate the ARCDs' capability of optimizing the structural behavior of these structures. However, their validity is limited by the type of analysis carried out that does not consider the dynamic behavior of the system.

To this end, within this paper, the study of the structural behavior is deepened enhancing the numerical model and performing Incremental Dynamic Analyses (IDA). The analyses have been performed for the case study structure analyzed in [5] considering the adoption of both BRBs and ARCDs to properly compare the performance of the two systems.

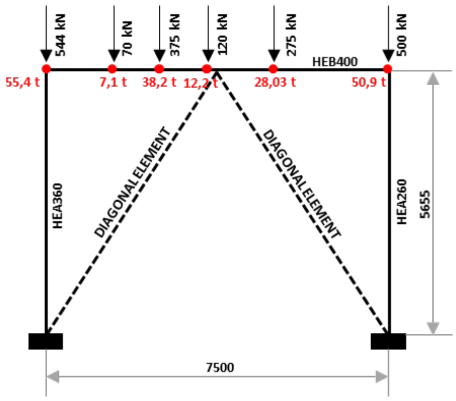
3 THE CASE STUDY STRUCTURE AND NUMERICAL MODEL

Figure 4a represents the geometry of the case study structure, which is a V-bracings frame extracted from an industrial building and supporting a steel silo [18]. The figure shows also the vertical loads applied to the beam as well as the corresponding masses used for the dynamic analyses. Originally, the bracings were not designed to resist seismic loads, and as a possible seismic retrofit, both the use of classical BRBs (Figure 4c) and ARCDs (Figure 4b) are here investigated focusing in comparing their dynamic behaviour. The numerical models are realized using the Opensees [20] software. All the non-dissipative elements are modelled as *nonlinearBeamColumn* elements, with the geometrical characteristics defined according to the cross-section of the steel profiles and the adoption of *steel02* material (uniaxial steel material with hardening after yielding, the steel grade is S275, with a yielding stress of 275 N/mm^2). All the end sections of these elements are fixed, and *PDelta* effects are taken into account for the two columns.

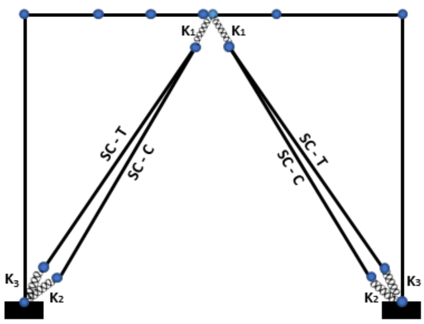
The diagonal elements, either BRBs and ARCDs, are designed with the yield strength in tension F_{yt} and in compression F_{yc} equal to the buckling resistance of the bracings assumed for the un-retrofitted state analyzed in [18]. which is equal to 1600 kN. BRBs (Figure 4c) are modelled as *nonlinearBeamColumn* elements, adopting a *steel02* material and geometrical cross-section characteristics in order to have the initial yielding forces in tension, F_{yt}, and in compression, F_{yc}, equal to 1600 kN. The two elements are hinged to the other components of the frame by using a *zeroLengthElement* (***k1*** in Figure 4c and Figure 5) with high stiffness in the axial, shear and torsional directions, and a negligible one in bending. In the case of ARCDs (Figure 4b), the starting compression axial force due to the vertical loads is about 400 kN, therefore a yielding force in tension F_{yt} of 1200 kN and in compression F_{yc} of 2000 kN are used. To obtain this desired behaviour, two different *SelfCentering* materials are defined to model the behaviour of the elements under axial force: *SelfCentering* material 1 (**SC-T** in Figure 4b and Figure 5) is defined for the behaviour under tensile force, with a yielding force (*Forward Activation Stress/Force* parameters) equal to 1200 kN; the *SelfCentering* material 2

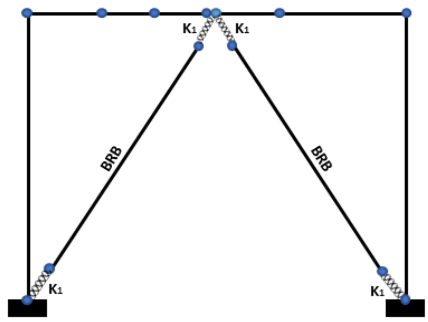
(**SC-C** in Figure 4b and Figure 5) is defined for the behaviour under compression force, with a yielding force equal to 2000 kN. The initial and post-elastic stiffness is equal in both cases. These two materials are associated to the axial behaviour of two *nonlinearBeamColumn* elements acting in parallel, and the activation the two is controlled by two *zeroLengthElement* (***k2*** and ***k3*** in Figure 4b and Figure 5) with high stiffness only in compression (and non-relevant in tension) or only in tension (and non-relevant in compression), connecting the base end section of the elements to the base of the column. About the other degree of freedoms, the diagonal elements are hinged, with non-relevant stiffness in bending and high stiffness in shear. Indeed, the upper end section of the elements is connected to the mid-section node of the beam using a *zeroLengthElement* (***k1*** in Figure 4b) with high stiffness in the axial, shear and torsional directions, and a negligible one in bending.

IDA are performed using a set of 14 natural accelerograms as seismic input, which is selected for a site located in a European high-seismicity zone from the NGA-West2 database [21] that matches the target conditional spectra [22]–[24] at a 2475 years return period, or equivalently an exceedance probability of 2% in 50 years, and that has been extended to a wider range of probabilities of exceedance [25]. The selection procedure was based on the approximate method of conditional spectra [23] using the geometric mean of spectral accelerations (AvgSA) as the intensity measure [26]. The selected records are represented in Figure 6 together with the AvgSA parameter for each one and the scale factors for each considered probability of exceedance (60%, 30%, 10%, 5% and 2% in 50 years). The records have been applied in the horizontal direction.



(a)





(b) (c)

Figure 4: a) Geometry of the case study structure; b) diagonal elements in the ARCD model; c) diagonal elements in the BRB model.

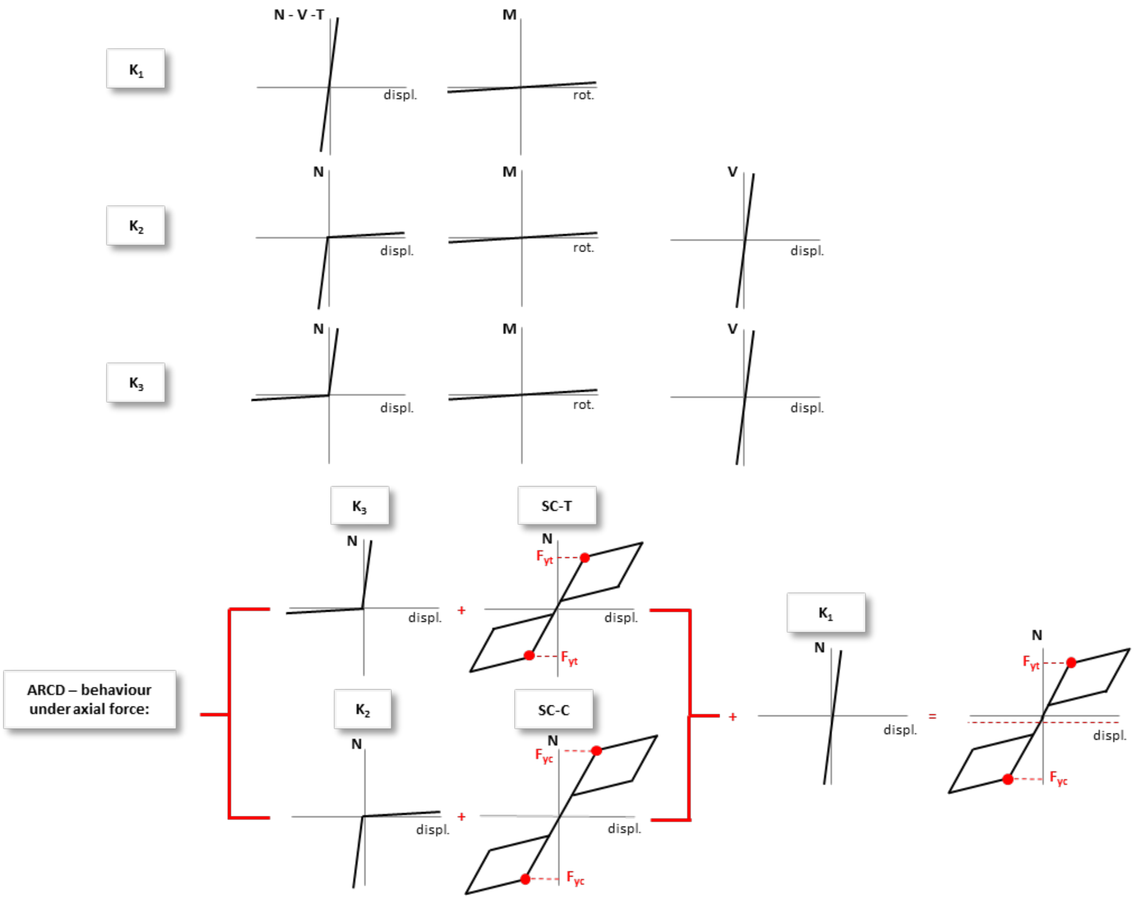
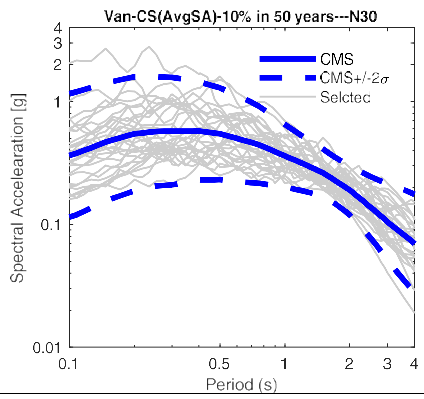


Figure 5: Expected behaviour of the most significative components as defined in the numerical models (N is axial load, V is shear force, T is torsion and M is bending).



Probability of exceedance in 50 years	AvgSA [g]	Accelerograms – scale factors													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
60%	0,087	0,723	0,995	0,404	1,706	0,644	1,392	0,882	0,750	0,970	0,157	0,702	0,449	0,952	1,681
30%	0,138	1,146	1,578	0,641	2,706	1,022	2,208	1,399	1,190	1,538	0,249	1,114	0,712	1,510	2,667
10%	0,241	2,002	2,756	1,119	4,725	1,784	3,856	2,443	2,079	2,686	0,434	1,945	1,244	2,637	4,657
5%	0,334	2,774	3,820	1,550	6,549	2,473	5,344	3,385	2,881	3,722	0,602	2,696	1,724	3,655	6,454
2%	0,499	4,144	5,707	2,316	9,784	3,694	7,984	5,057	4,304	5,561	0,899	4,028	2,576	5,461	9,642

Figure 6: Selected records corresponding to a probability of exceedance of 10% in 50 years, and corresponding scale factors.

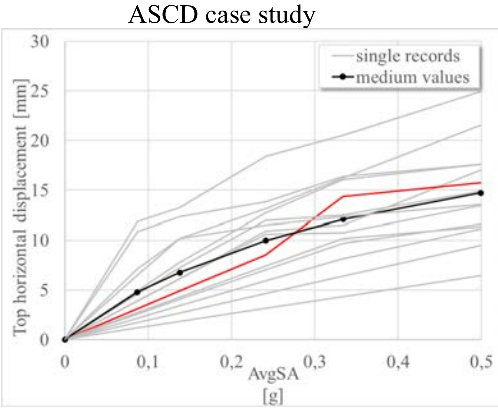
4 INCREMENTAL DYNAMIC ANALYSES - OUTPUT

Figure 7 to Figure 9 show the IDA curves obtained from the two models. Comparing the global performance in terms of maximum horizontal displacements of the beam, Figure 7a, it can be seen that, even if the mean values are comparable, the BRBs are more effective in limiting these displacements thanks to the higher dissipation capacity. Figure 7b shows the IDA curves for the total base shear force, and Figure 7c plots the base shear force with the maximum top horizontal displacement. Looking at the medium values curves, it can be noticed that for the same AvgSA, the base shear is higher in the ARCD case study.

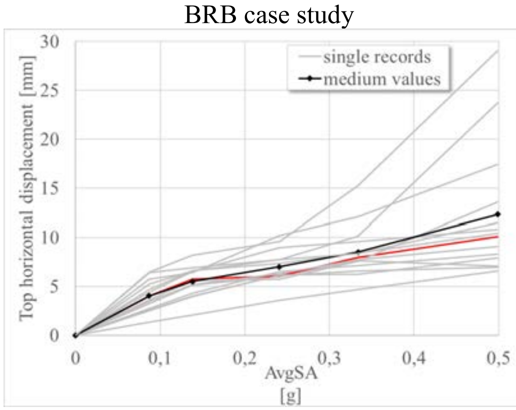
Finally, looking at the IDA curves for the residual horizontal and vertical displacements (respectively Figure 8 and Figure 9), they definitely testify the optimal re-centering capacities of the ARCDs in the both directions. The residual horizontal displacement is on the order of tenths of a millimeter and remains almost constant with the increase of AvgSA, while in the case of BRBs is on average around the millimeter and increases with the increasing of the earthquake intensities. It should also be noticed that a certain level of re-centering capacity in the horizontal direction is provided by the columns, which are fixed to the ground. Looking at the residual vertical displacement, the re-centering capacity of the ARCDs is optimal, with mean values close to zero, while in the case of BRBs, the medium trend increases with the increasing of the AvgSA.

Looking at the dissipative elements' behaviour, Figure 10 shows axial force vs. elongation curves plotted for both ADC and BRB case studies, together with total base share vs. top horizontal displacement curve, for one of the selected records and 2% probability of exceedance in 50 years (this accelerogram has been selected since it is representative of the average behavior among all – red curves in Figure 7 to Figure 9). In particular, it can be observed that BRBs dissipate the most in compression, while ARCD have a balanced participation in tension and in compression. From these curves, it can also be noticed the trend in the BRBs case-study of accumulating residual displacements in the horizontal direction.

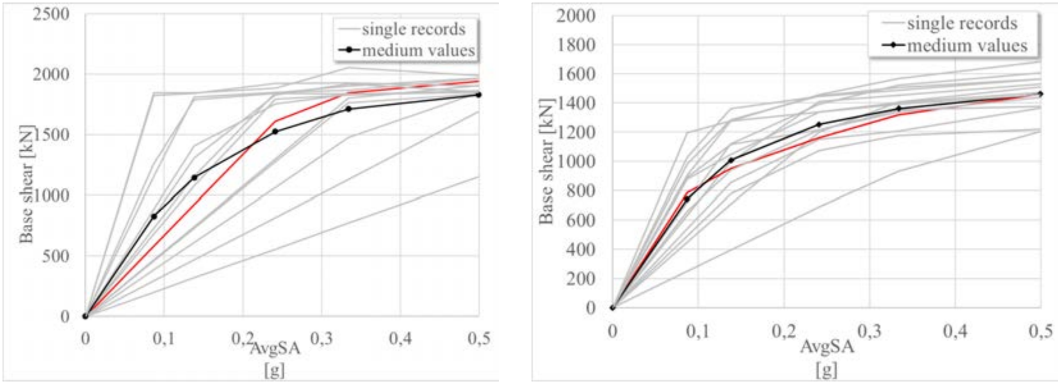
ASCD case study



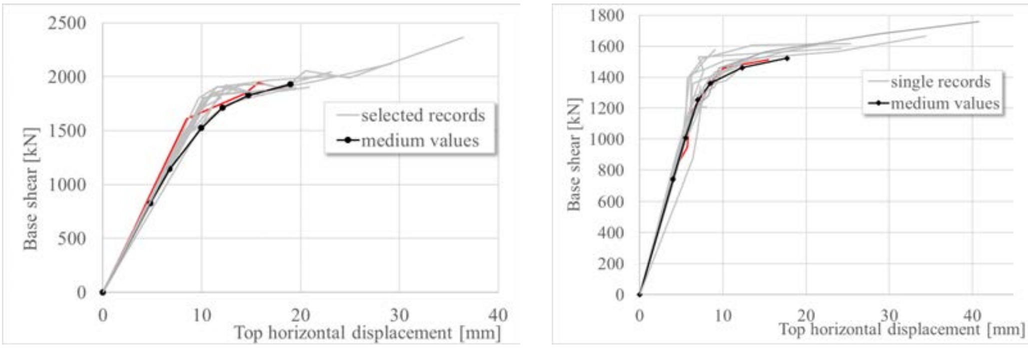
BRB case study



a)



b)



c)

Figure 7: IDA curves for the ASCD (left side) and BRB (right side) case studies: a) top horizontal displacement vs. AvgSA; b) base shear vs vs. AvgSA; and c) base shear vs top horizontal displacement. The curves for the accelerogram 6 are highlighted in red.

ASCD case study

BRB case study

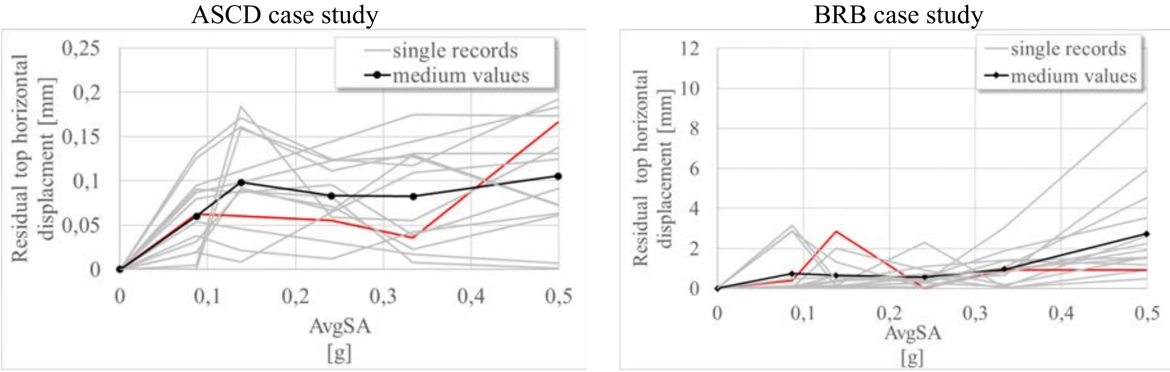


Figure 8: IDA curves for the residual top horizontal displacement for the ASCD (left side) and the BRB (right side) case studies. The curves for the accelerogram 6 are highlighted in red.

ASCD case study

BRB case study

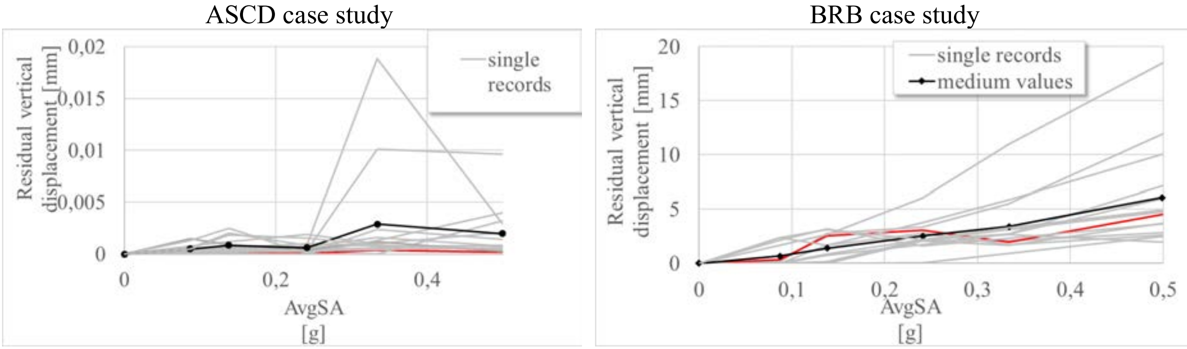


Figure 9: IDA curves for the residual vertical displacement for the ASCD (left side) and the BRB (right side) case studies. The curves for the accelerogram 6 are highlighted in red.

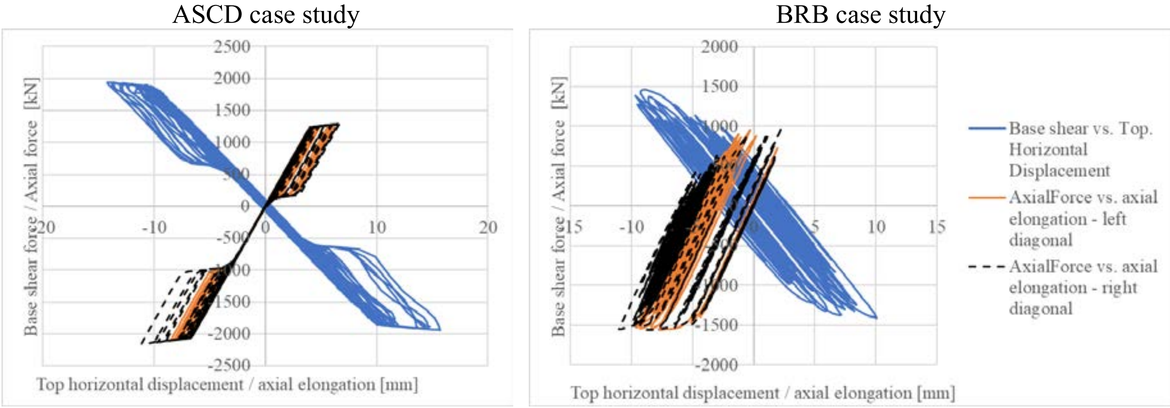


Figure 10: Force-displacement curves for the accelerogram 6, 2% probability of exceedance in 50 years for the ASCD (left side) and the BRB (right side) case studies.

5 CONCLUSIONS

The paper shows the application of a novel Asymmetric Re-Centering Device to a simple case-study structure characterized by V bracings and relevant vertical loads acting on the beam. The benefits of its application are highlighted also thanks to the comparison of a retrofit intervention through classical buckling restrained braces. The Incremental Dynamic Analyses carried out show that the presence of an initial compression force on the bracings, indeed, causes the bracings characterized by a symmetric hysteretic behavior, such as the BRBs, to dissipate energy only in compression and the trend to accumulated residual displacement both in the horizontal and vertical directions.

On the contrary, the ARCDs assure a very high re-centering capacity in both directions together with a relevant dissipation of the seismic energy that allows to contain the maximum horizontal displacements of the system.

The results showed within this paper, even if clearly highlight the benefits and potentialities of using ARCDs for the retrofit of the structural typology analyzed, are still preliminary and further studies are needed to:

- evaluate the influence of the seismic vertical component in the global behavior of the structure;
- evaluate the possibility of a more evident asymmetric behavior (e.g. reducing, or even nullify, the re-centering force in tension of the ARCDs);
- evaluate the possibility of optimizing the dissipation capacity of ARCDs increasing the values of the β factor, also depending on the design requests, of the structural characteristics of the existing structure and on the values of the seismic action;
- understand the influence of the geometrical and loading configurations of the structure in the global behavior when the ARCDs are used;
- develop a design strategy for the ARCDs on the base of the performance targets (e.g. protection of the non-dissipative elements, limitation of the horizontal/vertical displacements, etc.).

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