Seismic protection of structures through an innovative steel-based self-centering hysteretic device: numerical analysis and tests.

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SUMMARY:
The paper presents the geometrical description and the functioning principles of an original Steel Self-Centering Device (SSCD) for the seismic protection of existing and new buildings. In particular, this type of hysteretic device suitably combines two technical features as re-centering capability and recovering of its original dissipative resources, after the seismic event.
Complete mechanical behaviour of the hysteretic device is evaluated as a function of its internal components. In order to optimize protection capabilities of the system, a refined parametric analysis, in which mechanical properties of steel elements devoted to energy dissipation are varied, is also made using a refined numerical model. The actual behaviour of the dissipating device is then investigated through quasi-static cyclic tests executed on a prototype of the device.

Keywords: passive seismic protection, hysteretic device, re-centering, optimized steel grade

1. INTRODUCTION AND METHODOLOGY

The use of passive seismic protection devices is nowadays experiencing a wide application also thanks to the introduction of suitable design rules in modern codes, like for example in the Italian standard (NTC, 2008). The recognized advantages of such devices, when applied to the new and existing structures, addressed research efforts to the development of more and more efficient systems (Christopoulos et al. 2006).
One of the main drawback of usual passive seismic protection devices is that the high levels of deformation reached during the earthquake implies the presence of residual inter-storey drifts at the end of the seismic event. Such residual deformations can result in the complete loss of efficiency of the structure, causing a reconstruction cost possibly higher than the value of the building itself.
In order to mitigate such problems, re-centering devices have been more and more studied (Priestley et al., 1999) (Christopoulos et al., 2002) (Christopoulos et al. 2002a) (Christopoulos et al., 2006) (Christopoulos et al., 2008) (Ma et al., 2011). This typology of dissipative devices is characterized by the presence of a re-centering force that mitigate, and at least eliminate, the residual deformations of the building after the earthquake.
Applications of post tensioned re-centering systems to steel and precast structures have been already successfully realized (Priestley et al., 1999). Coupling pre-tensioned elements with suitable dissipative elements allows obtaining flag shaped structural answer, typical of re-centering dissipative systems. Based on this principle, the general idea for a Self Centering Energy Dissipative (SCED) device, designed as a diagonal brace and so suitable for new and existing buildings, have been proposed by Christopoulos et al., 2008.
In the present paper the development, design and experimental validation of a Steel Self Centering Device (SSCD) is presented. The SSCD was developed within the framework of the PRECASTEEL (*PREfabriCAted STEEL structures for low-rise buildings in seismic areas*, Alderighi et al. 2010) and STEELRETRO projects (*STEEL solutions for seismic RETROfit and upgrade of existing*

constructions, Bonessio et al., 2010) carried out with a financial grant of the Research Programme of the Research Fund for Coal and Steel of European Commission. The device is characterized by the same basic idea of the one proposed by Christopoulos et al., 2008, introducing an hysteretic dissipative system and a steel pretension system for re-centering. Proposed system is so completely steel based and its assembly can be easily made by a steelwork. The dissipative system is constituted by steel fuses easily changeable after use. Aforementioned characteristics make proposed SSCD really suitable for the protection of new buildings, as well as existing ones. Currently, the patent for the developed SSCD has been requested.

The design of the SSCD was conducted by a multidisciplinary experimental and numerical approach applying it to a realistic case-study in order to be closer as possible to current design practice.

The overall dimension of the SSCD were defined fitting it to a reinforced concrete frame properly chosen as case study: in this way, the main geometrical characteristics of the SSCD constitutive elements were fixed. The cross sections of such elements were estimated, on the basis of the strength capacity of the reinforced concrete structure–SSCD system, in order to assure the elastic behavior of the non dissipative elements and to avoid buckling phenomena.

Values of mechanical parameters that optimize the dissipative and re-centering capacity of the SSCD, were evaluated by quasi-static pushover numerical analyses. The maximum deformation demand on the elements in charge to dissipate energy and the number of cycles related to each deformation level were estimated by Incremental Dynamic Analyses (IDA), using 30 natural time-histories accelerograms.

The proper steel quality for these elements was then selected by an experimental campaign in which four different steel grades were subjected to tensile and low cycle fatigue tests.

On the basis of all obtained results, the final design of the SSCD prototype was so carried out defining all its construction details and at last the global cyclic behavior was experimentally verified by a series of quasi-static cyclic tests.

In the present paper, a description of the conceptual design and functioning principles of the SSCD is reported with the results of the cyclic tests on the SSCD prototype.

2. THE PROPOSED STEEL SELF-CENTERING DEVICE (SSCD)

The SSCD is made up of three element groups, each one with specific functions: the *Skeleton*, the *Dissipative Elements* and the *Pretension Elements* .

The Skeleton has the function of transmitting and distributing the external force between the Dissipative Elements and the Pretension Elements. In the figure 1 the main Skeleton elements (External Carter, Sliding Internal Frame and Endplates), the Dissipative Elements and the Pretension Elements are shown.

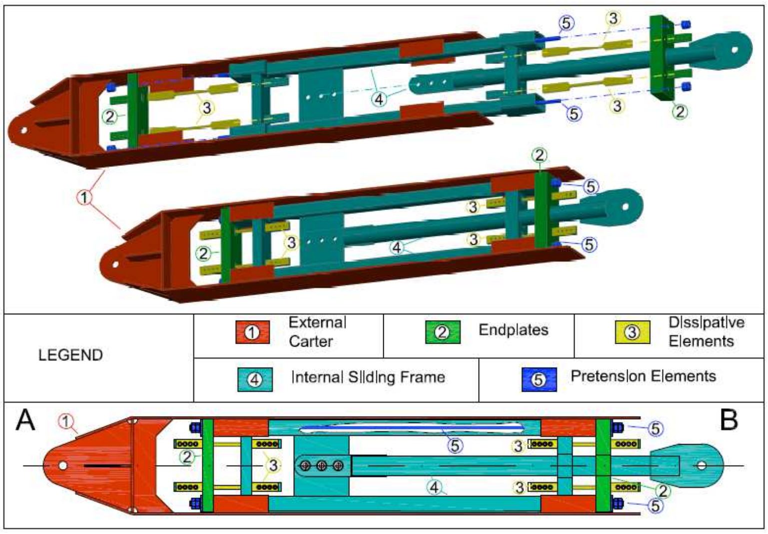


Figure 1. Main elements of the SSCD

The Sliding Internal Frame is positioned inside the External Carter. The Carter is equipped with guiding elements that allow the Sliding Internal Frame to move only in the axial direction and, at the same time, serve as stops of Endplates in the longitudinal direction. Endplates are located in correspondence of the Internal Sliding Frame ends.
The Dissipative Elements, positioned inside the skeleton, is made up of dog bone shaped steel elements linked to the Internal Carter and to the Endplates. They are equipped with a lateral buckling restraining system.
Pretension Elements, made by Prestressing Cables, are located inside the skeleton and linked to both ends at the Endplates.
The elements are positioned and linked each other in order to assure the same global behavior of the SSCD device under both tension and compression external forces.
In the figure 2, the functioning under external compression force is schematically shown. The global behavior can be summarized in three main phases: a) loading phase with the external force P smaller than the pretension force P_{TE}; b) loading phase with P greater than P_{TE}; c) Unloading Phase.
In the first phase a) the overall behavior of the SSCD is linear elastic and the Dissipative Elements are not activated. When the external force value exceeds the pretension force, phase b), the Endplate A and the Internal Frame slide. In such a way there is a relative movement between the Internal Frame and the Endplate B and the corresponding Dissipative Elements are activated, experiencing a tensile deformation in function of the value of the external force. The shift from phase a) to the phase b) is characterized by a sudden stiffness decrease. When the external force decreases, phase c), the force transmitted by the Prestressing Cables tends to bring back the Endplate A to the original position, deforming in compression the Dissipative Elements that, thanks to the lateral restraining systems, do not experience global buckling deformations. This phase is characterized by a sudden variation of stiffness due to the yielding in compression of the Dissipative Elements.
The functioning under external tension force is conceptually the same and shown in the figure 3.

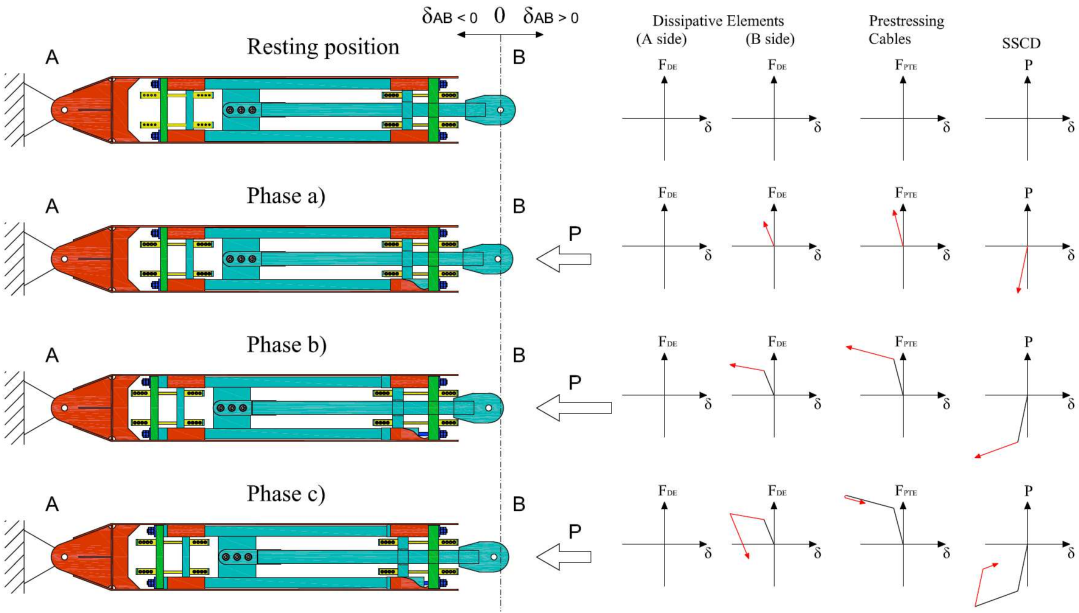


Figure 2 Main phases of the SSCD behavior under external compression force

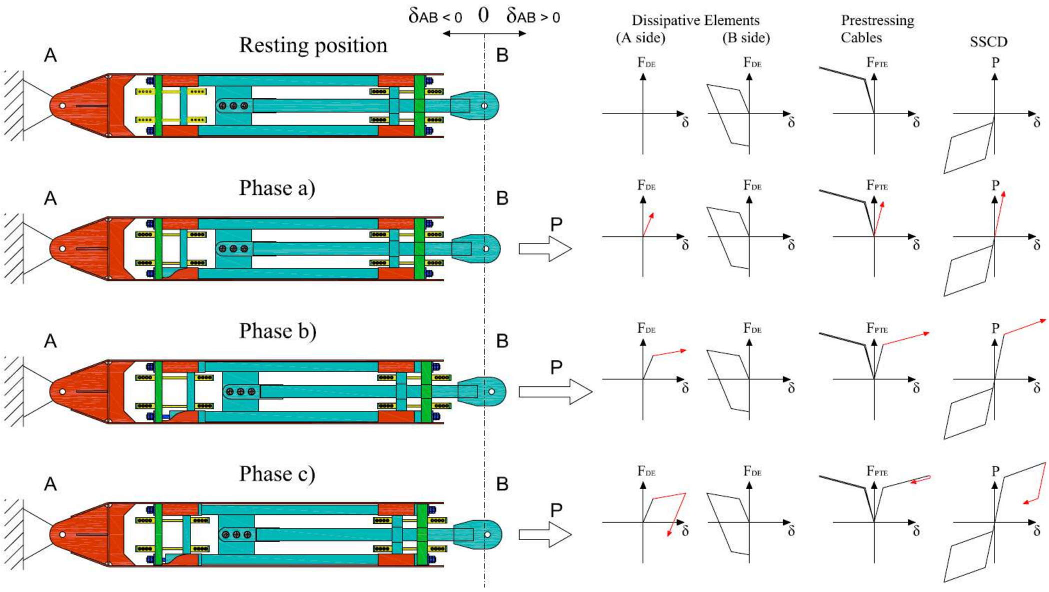


Figure 3. Main phases of the SSCD behavior under external tensile force after compression cycle.

3. CASE-STUDY

As case study a concrete building located in Assisi, Italy, was chosen. The building was designed according to an old design code, the Royal Decree n.2229. November 16, 1939 (R.D. 39), and used as benchmark during the STEELRETRO project (*STEEL solutions for RETROfit and upgrade of existing structures*, Bonessio et al., 2010). The plan view of the building and the front view of principal and secondary frames are shown in the figures 4, 5 and 6, respectively.

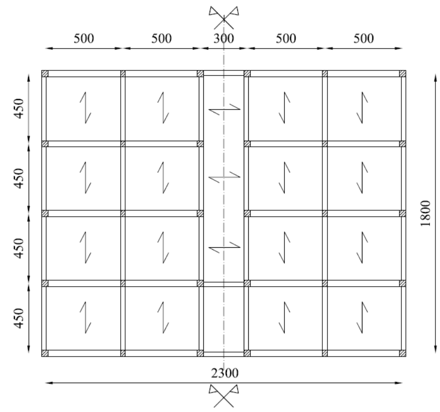


Figure 4. Case study: plan view of the first floor.

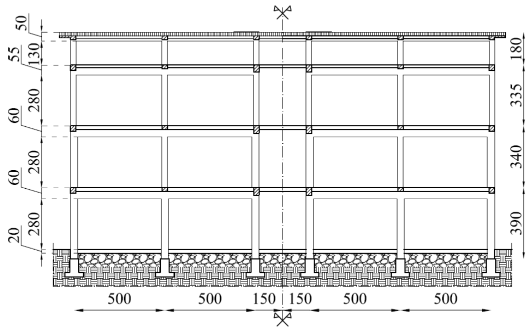


Figure 5. Case study: front view of the main frames in correspondence of the top of the roofing.

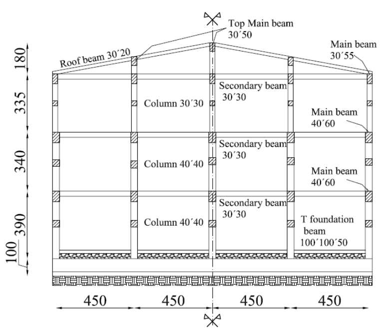


Figure 6. Case study: front view of the secondary external frames of the building.

Common materials used in the 1950-s, as concrete with characteristic compressive strength equal to f_{ck}=20 N/mm^2 and a characteristic yield strength for reinforcement equal to f_{sk}=230 N/mm^2, were considered. The detailing of the reinforcement was the one used in design practice of the considered period: poor anchorage length of steel reinforcing bars in correspondence of the external beams-to-column joint, use of plane (not ribbed) steel reinforcing bars, inclined steel reinforcement used to absorb shear force, largely spaced stirrups (15 cm for columns, 25 cm for beams).
The SSCD preliminary design was carried out with the idea of retrofitting the isolated frame of the structure located at the third floor, in the direction of the secondary frames, as shown in the figures 9b and 9c.

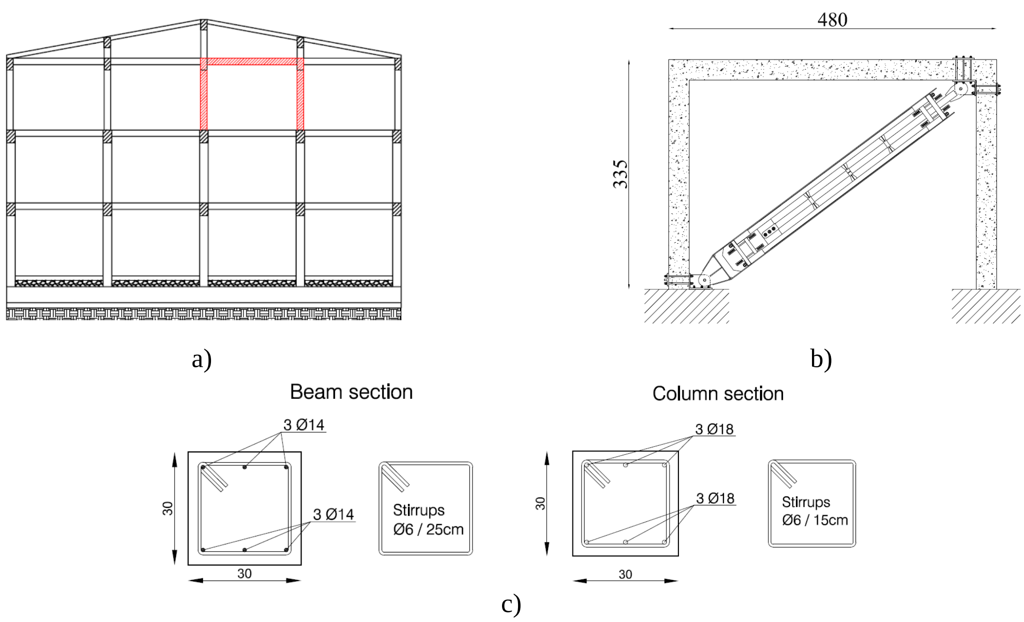


Figure 7. a) location of the isolated frame within the building b) main dimensions of the frame c) beam and column cross sections.

4. DESIGN OF SSCD

The main dimensions of the SSCD were defined fitting geometrical parameters of the reinforced concrete frame and maximizing the displacement capacity d_U of the SSCD directly connected with dissipated energy.
Considering that the behavior of the Prestressing Cables cannot be pushed over the elastic limit, the displacement capacity d_U is set equal to their maximum elongation d_{PTE}, defined as follows:

$$d_{PTE} = d_U = \frac{f_{yPTE} \cdot (1-\rho_{PTE})}{E_{PTE}} \cdot L_{PTE} \qquad (3.1)$$

being f_{yPTE}, ρ_{PTE}, E_{PTE} and L_{PTE} respectively the yield stress, the initial prestress ratio, the elastic modulus and the length of the Prestressing Cables.
Higher is value of L_{PTE}, compatibly with the dimensions of the frame in which the SSCD is installed, higher is the elongation capacity of the Prestressing Cables and so of the SSCD. The maximum length, compatible with the reinforced concrete frame and with all the elements necessary to connect the SSCD to the frame, was then assumed equal to about 3600 mm.
The range of the main mechanical parameter, such as the yield stress f_{yDE} of the Dissipative Elements and the initial prestress ratio ρ_{PTE} of the Prestressing Cables, that optimize the SSCD global behavior,

were evaluated by parametric studies carried out executing nonlinear static pushover analyses. The maximum deformation demand on the Dissipative Elements and the number of cycles related to each deformation level were evaluated by the execution of incremental dynamic analyses (IDA).
To these purposes, a SSCD model was developed by using the finite element program OpenSEES; a schematic representation of the model is shown in the figure 8.

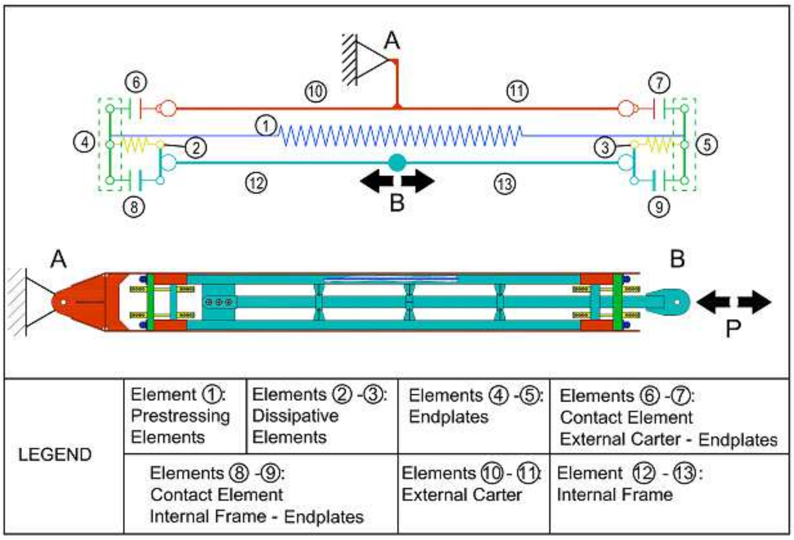
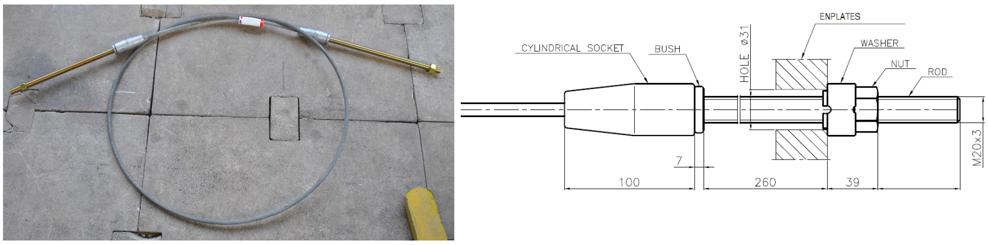


Figure 8. Simplified mechanical model of the SSCD

Each SSCD component was modeled by mono-dimensional element, suitably linked to the others and constrained allowing displacements only in the axial direction of the SSCD. To each of these elements a suitable constitutive model was assigned.
From each analysis, the re-centering capacity, global displacement ductility and equivalent viscous damping factor were evaluated as a function of f_{yDE} and ρ_{PTE}.
The analyses results showed that:

- high value of the initial prestressing ratio ρ_{PTE} assures good re-centering capacity but reduces the global displacement ductility and the equivalent viscous damping factor;
- value of the yielding stress f_{yDE} of the Dissipative Elements lower than approximately 500 MPa, assures good re-centering capacity and displacement ductility;
- higher is the yielding stress f_{yDE} of the Dissipative Elements, greater should be the initial prestressing ratio.

Beside the monotonic behaviour of the SSCD, the cyclic demand on the Dissipative Element was studied through a numerical model of the considered reinforced concrete frame equipped with the SSCD. Incremental Dynamic Analyses (IDA) were so performed, assessing the mean value of the deformation level and the number of cycles typically imposed on the Dissipative Elements by earthquakes.
Different steel grades, typical not only of the structural engineering but also of the automotive one, were then subjected to tensile and low cycle fatigue tests. In this way an appropriate steel grade for the Dissipative Elements, characterized by a yield stress equal to about 220 N/mm^2 and adequate resistance to low cycle fatigue, calibrated on the results of the IDA, were selected.
For the Prestressing Cables, open spiral strands were used, equipped, at both ends, with adjustable cylindrical sockets with threaded rod, spherical nut and spherical washer (Redaelli Tecna S.p.a. technology), as schematically shown in the figure 9. Pretension force was applied by a controlled fastening torque.



a) b)

Figure 9. a) Prestressing Cables and b) cylindrical socket detail

5. EXPERIMENTAL TESTS ON THE SSCD PROTOTYPE

Two different tests were performed on the SSCD prototype: preliminary tests were executed on the SSCD without the Dissipative Elements in order to evaluate the actual value of the re-centering force applied by the Prestressing Cables; afterwards final tests were executed on the SSCD equipped with the Dissipative Elements, in order to characterize the global behavior of the device.
Different choices of initial pretension force and of cross-sections of Dissipative Elements (see table 4) were considered in order to assess their influence on the global behaviour of the device.
The experimental tests on the SSCD prototype were performed by the "Laboratorio Ufficiale per le Esperienze dei Materiali da Costruzione" of the Department of Civil Engineering of the University of Pisa. The general view of the test setup is shown in the figure 10.

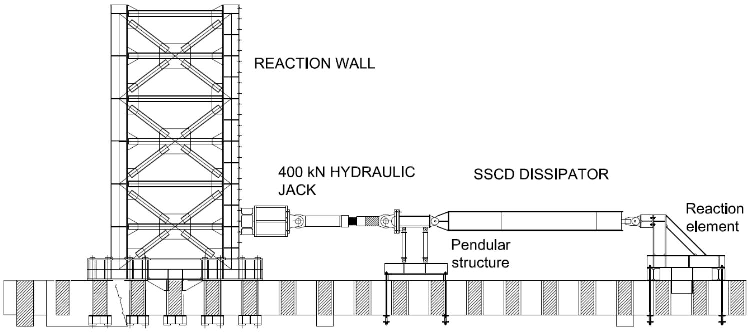


Figure 10. Test setup front view.

The external force was applied by means of a 400 kN hydraulic jack equipped with a loading cell and a displacement sensor. The jack, placed horizontally, was linked to the reaction wall and to a pendular steel structure allowing horizontal displacements. The SSCD prototype was linked, by pinned joints, at one end to the same pendular steel structure (see figure 11a) and at the other end to a steel reaction element that avoided any horizontal or vertical displacement of the device (see figure 11b).

(a) (b)

Figure 11. a) Pendular steel structure. b) Steel reaction element.

Preliminary tests were executed completing one cycle of loading-unloading both in tension and in compression, controlling amplitude of displacement imposed to the jack till a maximum/minimum value equal to ± 5mm. Test results are shown in the figure 12, varying the value of the fastening torque for the pretension force.
In the figure 12, the force applied by the jack is represented as function of the relative displacement between the External Carter and the Internal Sliding Frame.

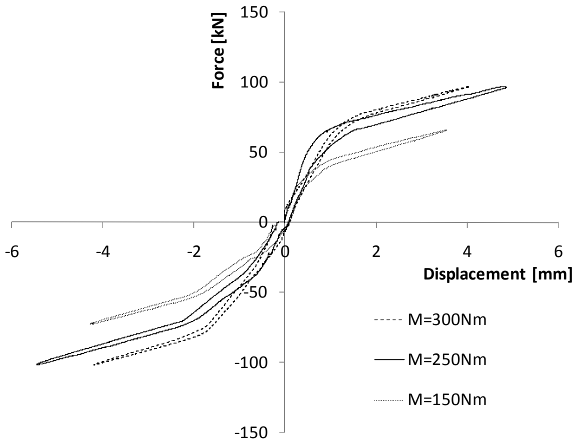


Figure 12. Force-displacement curve of the SSCD without the Dissipative Elements.

For each fastening torque value, the behavior of the SSCD was modeled by a bilinear curve. The pretension force was evaluated as the value corresponding to the global stiffness change. The first branch of the bilinear model corresponds to the behavior of the SSCD till the Endplates are forced to be in contact with the Internal Frame by the action of the Prestressing Cables. When the external force exceeds the prestressing one, the Endplates loose the contact with the Internal Frame and the stiffness decreases. The results obtained, for both tension and compression phase, are listed in the table 5.1.

Table 5.1. Pretension force for different values of the Fastening torque

Prestressing strand diameter [mm]	Fastening torque [Nm]	Pretension force [kN]	
		Tension	Compression
12	150	41	49
12	250	66	67
12	300	72	77

Final tests were carried out following the *short testing procedure* described by the ECCS group. In the first phase of the test, reduced displacement increments (equal to 0.1mm) were used in order to carry out at least 4 complete cycles before the yielding of the Dissipative Elements. Afterwards, the displacement increments were assumed equal to 1 mm and, for each increasing displacement level, 3 complete cycles were performed. The speed of the hydraulic actuator end was set equal to 3mm/min. Three cyclic tests varying geometrical and mechanical characteristics of the Prestressing Cables and Dissipative Elements as summarized in the Table 6 were executed.
In the figure 13 the cyclic behavior of the SSCD prototype, equipped with the Dissipative Elements and for different values of initial pretension force, is shown. It can be easily noticed that, at the end of every loading-unloading cycle, the residual displacement was practically equal to zero (however smaller than 0.5 mm) and so the SSCD exhibited an optimal re-centering capacity. Moreover, for every maximum displacement level, the SSCD exhibited stable hysteretic loops, assuring a constant level of dissipated energy. At last the introduction of the Dissipative Elements obviously increased the hysteretic loops area, but the slope of the curve was practically the same as the one showed by the SSCD without the Dissipative Elements.

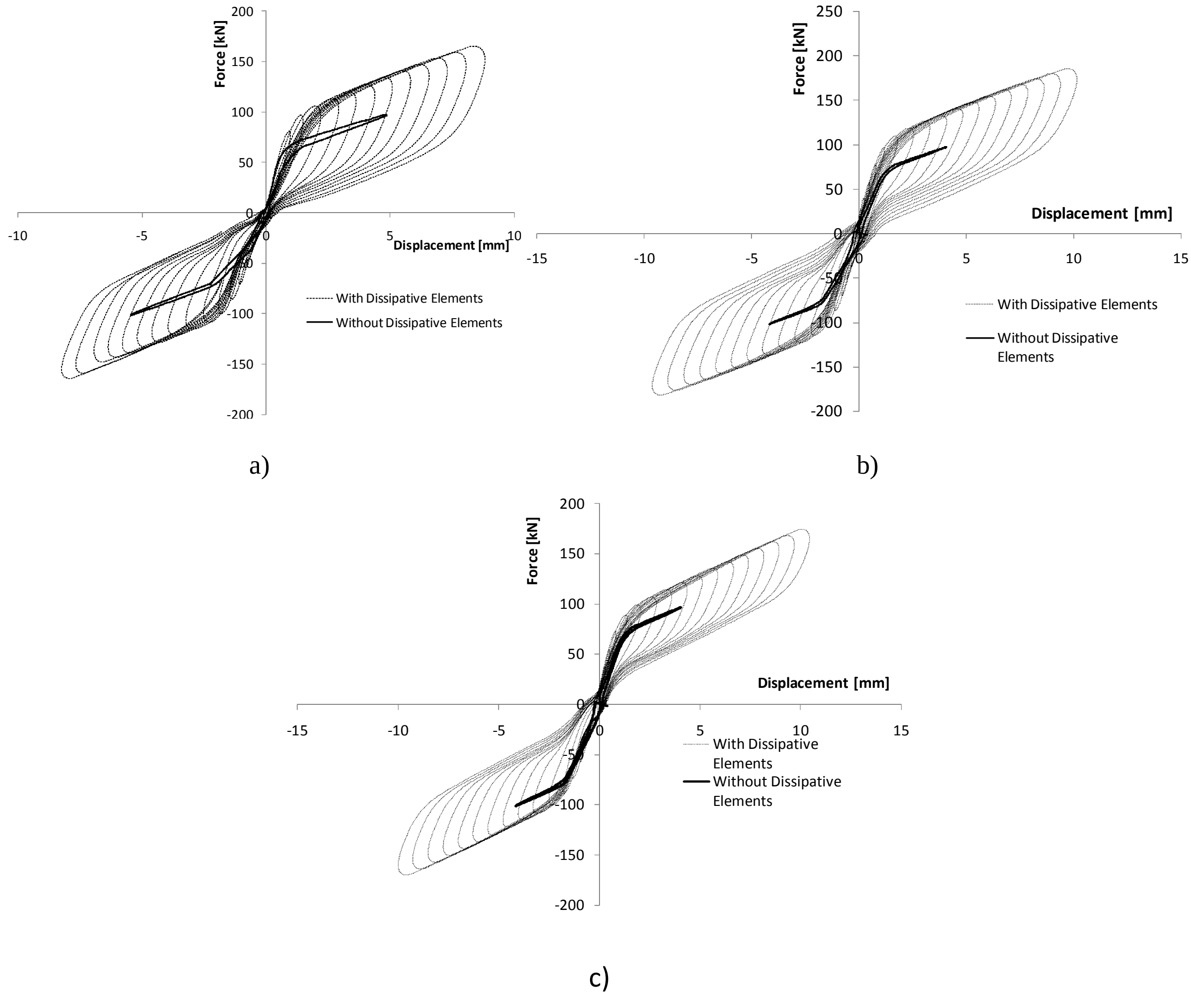


Figure 13. Force-displacement curve of the SSCD with Dissipative Elements, a) test 1, b) test 2 and c) test 3.

Table 5.2. Geometrical and mechanical characteristics of the Prestressing Cables and Dissipative Elements used for the tests.

Dissipative Elements	Number of elements	8
	Cross section of each element	40 mm^2 (tests 1 and 2) 32 mm^2 (test 3)
	Yield stress (mean value)	240 N/mm^2
	Length of the reduced section	170 mm
Prestressing Cables	Number of strands	2
	Outside diameter	12 mm
	Yield stress (design value)	1670 N/mm^2
	Total length	3500 mm
	Fastening torque	250 Nm (test 1) 300 Nm (tests 2 and 3)

6. CONCLUSIONS

The present paper describes the conceptual and definitive design of a Steel Self-Centering Device (SSCD) for the seismic protection of existing and new buildings. The proposed SSCD is provided with replaceable steel Dissipative Elements subjected to high levels of plastic deformation and with Prestressing Cables that minimize the residual deformation of the system after the seismic event. The small size and replaceability of the Dissipative Elements enables the use of an optimized steel quality.
Experimental tests executed on the prototype of the SSCD confirmed the results obtained by the preliminary results, highlighting the good dissipative and re-centering capacity of the SSCD.
The calibration of the global hysteretic behavior of the SSCD (such as the initial and post elastic stiffness, the yield force, re-centering ability and displacement capacity) modifying the mechanical and geometrical characteristics of the internal components, allows the SSCD to be fitted for the protection of structures with different mechanical and dynamic properties.
The shape of the SSCD, similar to a brace, the possibility of using Dissipative Elements realized with different steel grades and the possibility of reducing the damage after a seismic event, ensuring the reparability of the structures, make the SSCD developed very interesting.

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