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Seismic Response of Multistory Buildings with Double Telescoping Self-Centering Energy-Dissipative Brace (DT-SCED)

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Abstract

Telescopic Self-Centering braces are one of the very successful examples of Self-Centering braces which perform well in seismic loading. In this study, a new example of Telescopic Self-Centering brace is introduced, which has superior features over other telescopic braces. These include: high axial load capacity, use of shorter cables in brace construction, simplicity of construction, use of separate cables for compressive and traction modes, less fatigue in cyclic loads and, allowing for more dynamic loading cycles. In this paper, a sample was designed with an axial force capacity of 300kN. Modeling of behavior (DT-SCED) was accurately expressed using numerical relationships. nonlinear incremental stiffness analysis method was also used to calculate the hysteresis brace behavior. The cyclic load test was applied to this brace and the result showed complete Self-Centering behavior. Then, a sample building with the double telescoping Self-Centering Energy-Dissipative Brace (DT-SCED) was subjected Single direction pushover analyses and the results are compared with the sample buildings with the Self-Centering Energy-Dissipative Bracing (SCED) and the Telescoping Self-Centering Energy-Dissipative Bracing (T-SCED). The results of the analysis and comparing with other samples confirm the seismic superiority of performance of the DT-SCED brace over other samples.

Keywords: Telescoping Self-Centering Energy-Dissipative Brace, pushover Analysis, Cyclic Load Test, Nonlinear Incremental Stiffness Analysis.

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1. Introduction

In the last two decades, one of the issues discussed by structural researchers has been the control of structural behavior against earthquakes. The major focus on designing structures is the performance of the structure during an earthquake and its operational status after the earthquake. The design of high-value structures such as hospitals and schools. Should be such that they can be used after an earthquake, and this makes performance-based design more important. One of the issues that have been recently explored by researchers is Self-Centering structures. Combining Earthquake-Self-Centering Systems in addition to the ability to dissipative energy, the building to return to its original position after the earthquake. Figure 1 illustrates the hysteresis behavior of the Self-Centering system. Self-Centering systems are generally divided into three major categories: (A) Self-Centering Moment Frames with horizontal post-tensioned steel elements used at the bending joint to increase the structural flexibility during earthquakes, (B) The Rocking Walls system with or without vertical retracted members allowing the structure to move up and down from the foundation during the earthquake, C) Bracing system with Self-Centering braces which reduce the relative displacement of the building after the earthquake [1]. In 1993, Nims et al at the University of California, Berkeley introduced the first example of a Self-Centering braces. In the brace introduced by them, a series of friction springs had the task of dissipating energy and restoring the brake after loading [1]. The main problem with this brace was the difficulty of making it and having a low axial force capacity (about 1.5 kN). The fluid restoring force/ damping device is a self-centering bracing member that was originally developed for the United States Military in the 1970s but adapted for use in combination with base isolation systems for civil engineering structures. In unpublished military applications, these devices have been built to have axial capacities of up to 1500 kN; however, the devices presented by Tsopelas and Constantinou (1994) have a maximum axial capacity of only approximately 15 kN [2]. The friction spring seismic damper is similar in concept to the EDR but instead of using friction wedges and an axial spring, the functions of both of these elements are provided by a ring spring (also called a friction spring). Although the friction spring seismic damper can resist higher axial loads than the EDR, the axial capacity of the prototype damper is still an order of magnitude lower than the capacity that would be required for use in full-scale building applications [3]. A third notable self-centering brace that has been developed is the self-centering friction damping brace. This brace relies on the inherent self-centering behaviour of a new class of materials: shape memory alloys (SMAs). Although the concept for the self-centering friction damping brace works in principle, similar to the other two previous self-centering braces, the axial capacity is too low for use in a real structure and no fullscale prototype has been designed or tested [4]. prior self-centering braces have all shared the same problem: they are difficult to scale up to the axial capacities that are necessary for them to be used in a full scale building. The self-centering energy dissipative (SCED) brace solves this problem by reversing the self-centering mechanism of the EDR. Instead of relying on a spring in compression to provide the self-centering restoring force, which has a low stiffness and a low capacity for precompression, the SCED brace uses a cable or tendon in tension to provide this restoring force. This allows the use of relatively high stiffness, high strength tendons which can accommodate the high axial capacities that are necessary for a building cross-brace application [4, 5, 6, 7, 9]. In 2011, Erochko et al began work on a Telescoping Self-Centering Energy-Dissipative Brace, they attempted to design a Self-Centering brace prototype to allow for more flexibility in the structure by creating a Self-Centering property of the structure and to significantly reduce the relative displacement of the residual structure [9, 10].

2. Introducing Double Telescoping Self-Centering Energy-Dissipative Brace (DT-SCED)

After reviewing all previous centrifugal brackets, considering the available material and manufacturing facilities in Iran, a Double Telescoping Self-Centering Energy-Dissipative Brace (DT-SCED) was proposed. As mentioned earlier, the previous proposed braces all had several disadvantages, including difficulty in manufacturing, high cost, low energy Dissipation, and low axial force capacity. The proposed brace incorporates telescoping performance (Erochko et al 2014), with much simpler connections being used to build it [11]. The idea presented in Zhu and Zhang's research brace in 2008 was used to create tensile performance of cables during tensile and compressive loading. The brace has 4 series cables, two of which are activated in tension and the other two in compression. Figure 1 schematically shows the brace behavior. As shown in Figure 2, the DT-SCED uses an I-shaped member as an inner member and a Box as an outer member. Each cable is connected to the internal and external members by two angles. In the tensile and compressive loading, the cables are activated after the axial force reaches the frictional force between the internal and external members. The advantage of this type of brace over the previous models is the use of fewer cables and halved fatigue in the cables due to the separate tension and compression cables. Simplicity of construction and ease of installation are the other advantages of this brace compared to previous models, which makes it easy to manufacture in Iran. The important parameters of the proposed brace briefly described as: high axial load capacity, use of shorter brace cables, simplicity of construction, use of separate cables for compression and tension modes, less fatigue in cyclic loads and Allowing for more dynamic loading cycles.

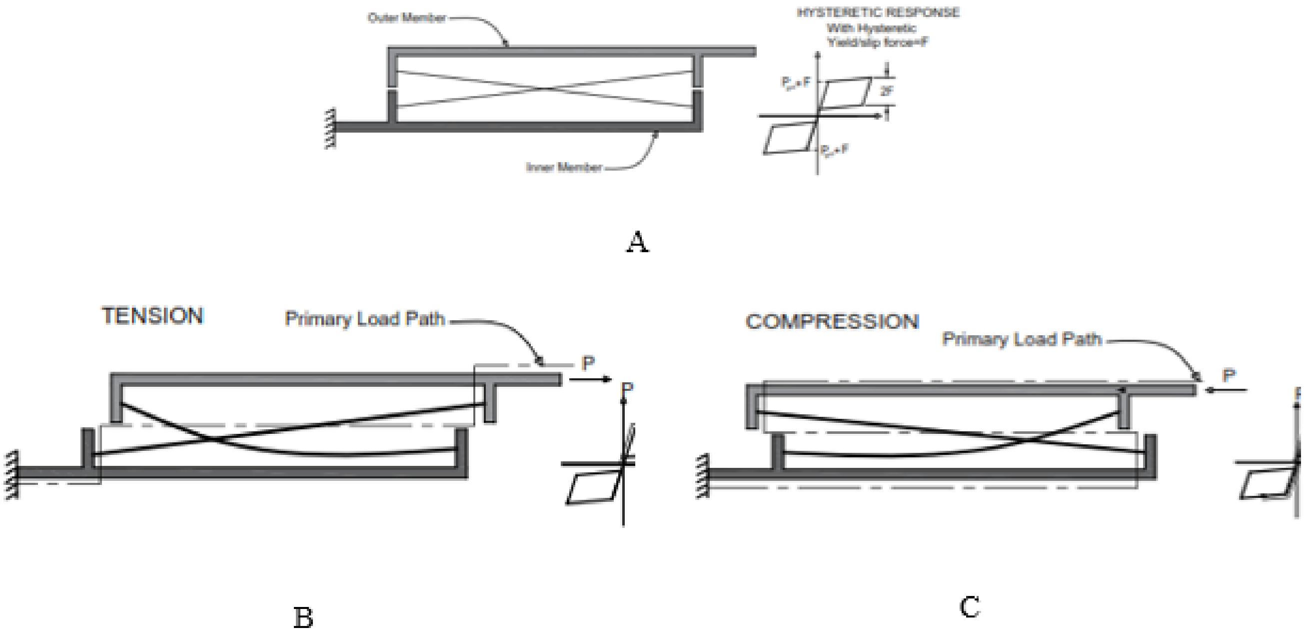


Figure 1: Schematic shape of the DT-SCED. A) no-load mode B) tensile loading C) compressive loading.

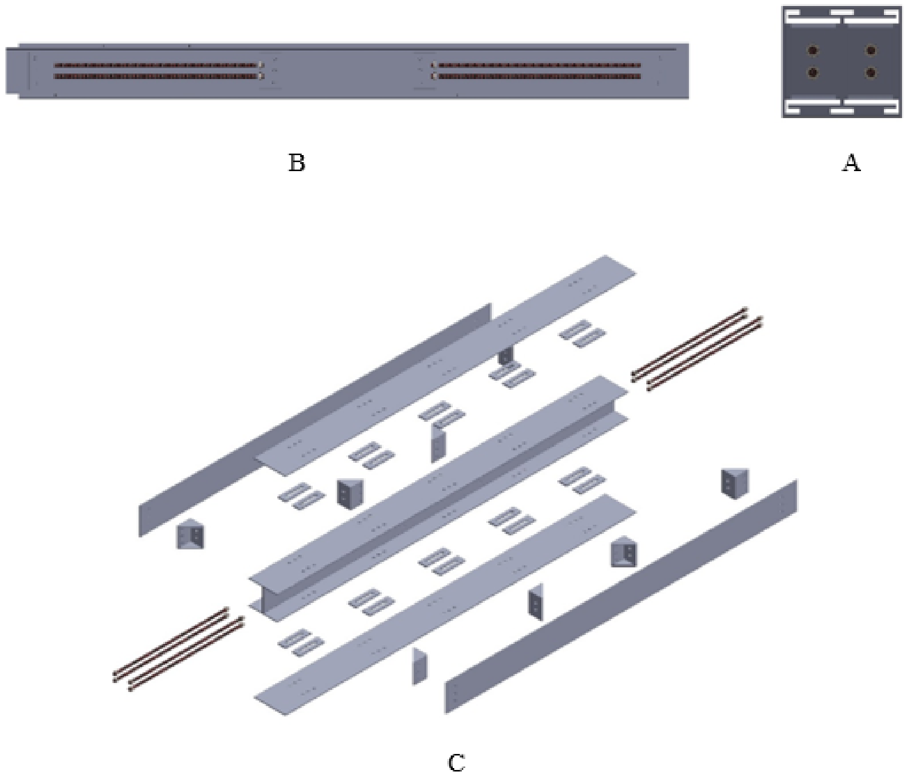


Figure 2: Detail of the DT-SCED. A) Bracket cross section B) Bracket sidewall C) Components required in bracket construction.

3. The Design of Laboratory Sample DT-SCED

The DT-SCED brace was directly tested for cyclic load. The dimensions of the Structural Laboratory of Ferdowsi University of Mashhad-Iran and its force capacity, the DT-SCED brace test set details are as shown in Figure 3. The relative displacement was assumed to be 12 mm. Assuming the axial capacity considered for the brace, the details of the brace design are presented in Table 1. Further details of the DT-SCED brace design are shown in Figure 4.

Table 1: DT-SCED Target Design Parameters

parameter	Value
Ultimate axial force	280 kN
δ	12 mm
cable length	80 mm
Pre-tensioning Force P_{P0}	5 kN
friction force	80 kN
DT-SCED Activation Load	240 kN
β	0.95
Estimated Initial Stiffness K_1	83 kN/mm
Estimated Post-Activation Stiffness K_2	3 kN/mm

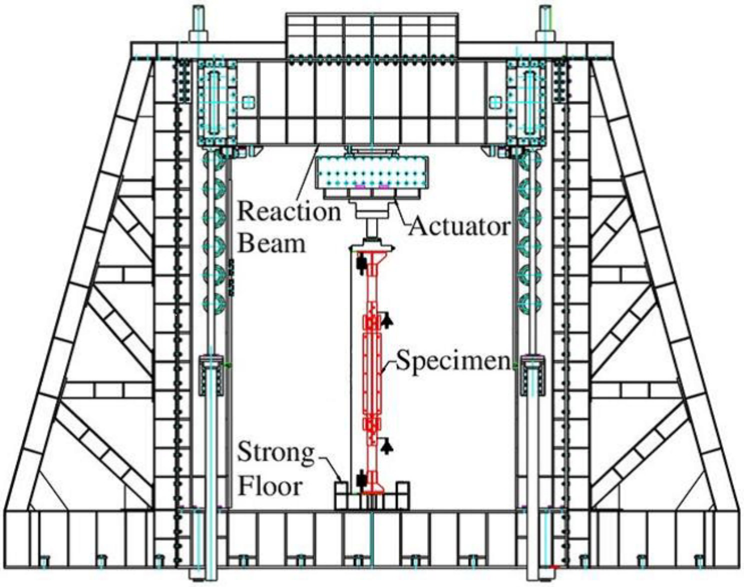
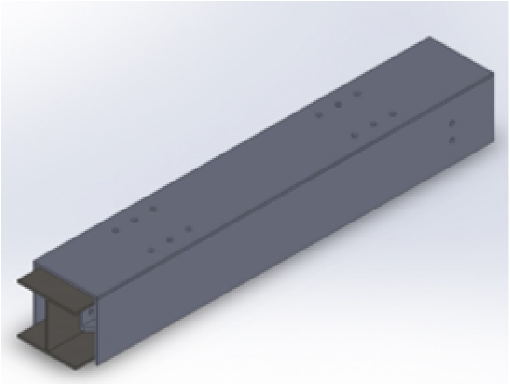


Figure 3: Schematic shape of the test set-up (DT-SCED).



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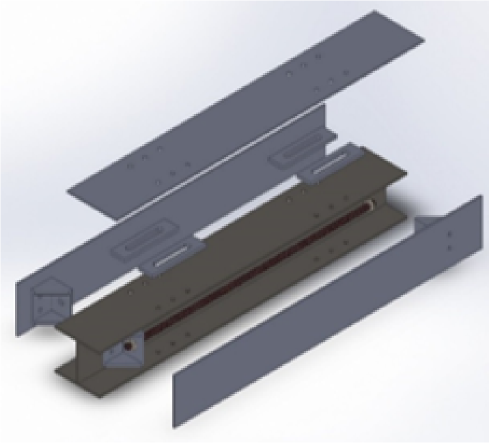

B

Figure 4: DT-SCED Schematic Image: (A) Closed, (B) with connecting components.

Details of the elements used in the construction of the DT-SCED bracket, including cross-sectional area, cable cross-sectional area, member length, modulus of elasticity, and others are presented in Table 2. To create frictional force and energy damping, 8 friction plates with 24 bolts were used. The friction plates were connected by 3 bolts between the inner and outer members of the DT-SCED. The details of the connection of these friction plates are shown in Figure 4. In the brace section, two cables have been replaced which are connected to the outer and inner members, for the installation and assembly operation, adequate space is provided for the wrench and mounting tool to be designed. The inner member was made of an I-Wide flange and the outer member of a Box member. Figure 5 shows the details of the brace section.

Table 2: Detail of the DT-SCED construction

parameter	Value
Elastic modulus of members	200000 MPa
Cable elastic modulus	102000 MPa
Internal cross sectional area	2580 mm^2
External organ cross section	3888 mm^2
Internal organ length	1050 mm
External organ length	1050 mm
Cable length	842 mm

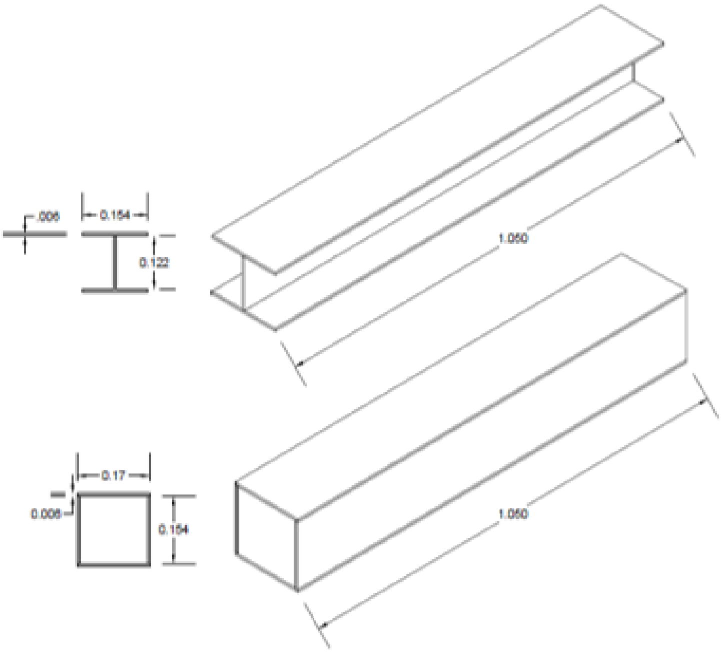

Figure 5: the details of the DT-SCED section.

4. Friction force

To calculate the amount of frictional force caused by the friction of metal plates between internal and external members, results from the experiment (Erochko et al 2013) were profitable [11]. As seen in Figure 6, a steel plate is positioned between two other metal pieces by 3 bolts which generates frictional force and energy dissipation by applyed force.

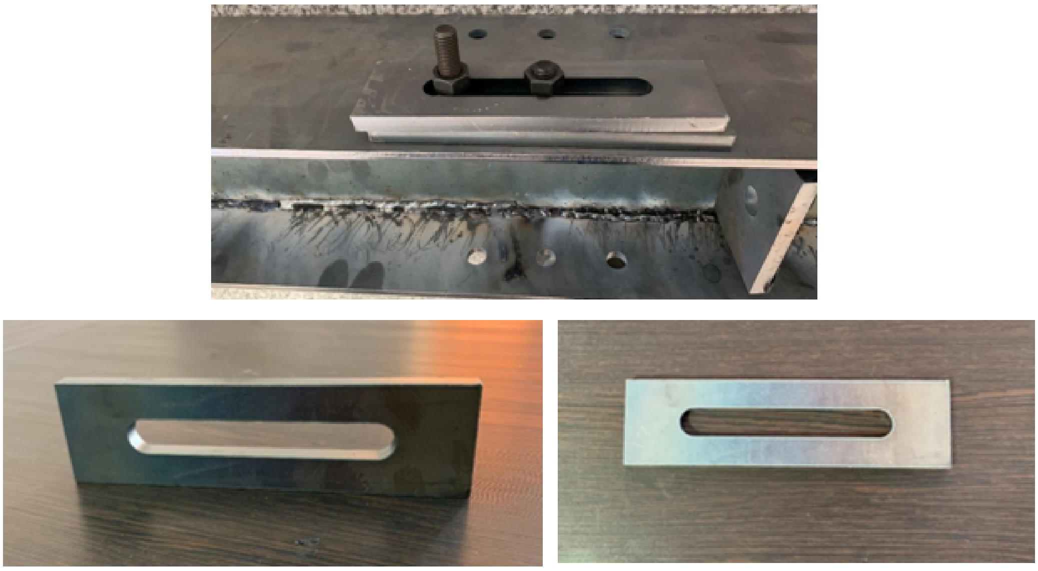

Figure 6: Friction plates used in the DT-SCED.

5. Pre-tension force

In this experiment 6mm cables were used. The cables are made of aramid fibers. The strain capacity for the cables was 1.8%. Further details of the cables are presented in Table 3. The pre-tension of the cables was assumed to be 5 kN. The failure rate and the displacement rate of the cables 285 kN and +/- 14 mm were considered. To pre-tension the cables, a connecting device was mounted on the ends of the cables that could be supported with adjustable beads. As seen in Figure 7, the cables were woven into a joint in an industrial workshop and pressed with a metal bushing and fastened in place.

Table 3: Details of the cables use in DT-SCED.

Parameter	Value
Nominal diameter of cable	6 mm
Nominal cross section of cable	28.26 mm^2
Young's modulus	44 GPa
Modulus of elasticity	102 GPa
Cable length	842 mm

6. DT-SCED Experiment

After placing the DT-SCED under the dynamic jack, a semi-dynamic cyclic loading was applied. In this experiment, the maximum displacement of the strap was assumed to be 12 mm in both compression and tensile modes, and loading was applied at 0.5 mm/s. The hysteresis DT-SCED diagram with two loading periods is shown in Figure 8. All cycles are completely stable and the flag hysteresis behavior is fully implemented.

7. SIMULATION OF DT-SCED BRACE RESPONSE

The DT-SCED behavior was modeled using nonlinear stiffness analysis. Figure 9 shows the DT-SCED stiffness matrix. The model is one-dimensional, but it is shown here separated into two

Figure 7: Woven cable around the connection tool to create the pre-tension force.

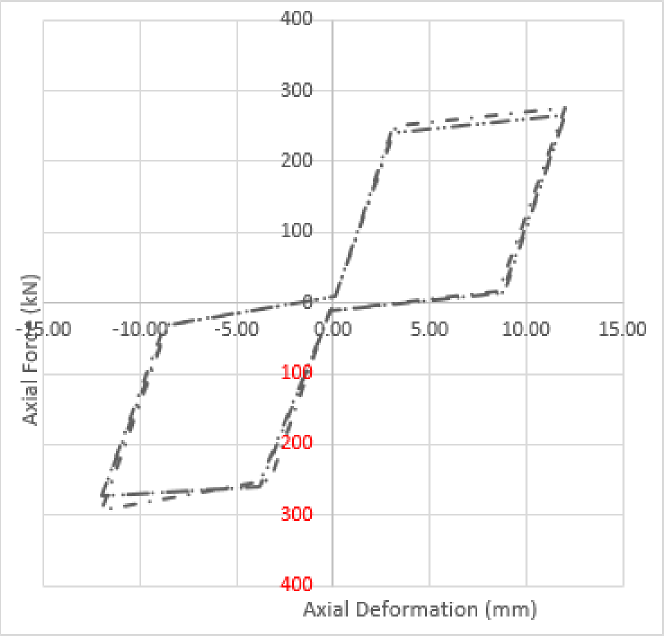

Figure 8: Hysteresis diagram DT-SCED.

dimensions for clarity. The elements that represent the inner and outer members (K_i, K_0), and the tendons $(K_p, K_{p'})$ have a permanent linear stiffness which is dictated by the input parameters. The connection stiffness element (K_{con}) also has a permanent stiffness dictated by an effective series connection stiffness provided in the inputs. The end members with K_g and the internal friction with K_{f1} and K_{f2} are also shown in the diagram.

The assumptions of this simulation are presented in Table 4. The results of the numerical simulation and the laboratory sample are shown in Figure 10. The hysteresis diagram obtained from the high-precision numerical simulation corresponds to the test results. The simulation mechanism also predicts the effective stiffness of the brace.

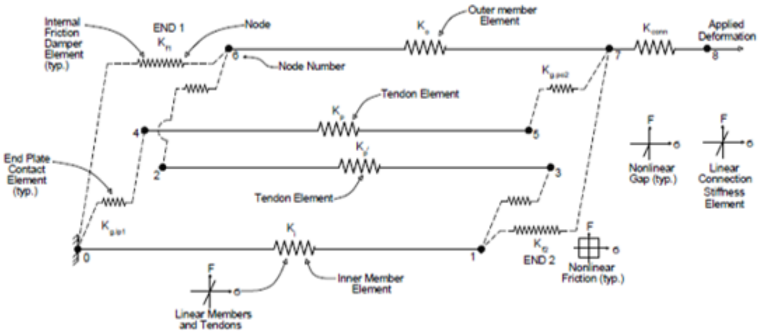

Figure 9: DT-SCED structural model for calculating hysteresis diagram.

Table 4: Detail of the DT-SCED construction

parameter	Value
Steel elastic modulus	200000 MPa
Cable elastic modulus	102000 MPa
Internal Member length	1050 mm
External Member length	1050 mm
Internal cross sectional area	2580 mm^2
External organ cross section	3888 mm^2
Internal friction	5 kN
Cross section of cable	28.26 mm^2
The amount of cables complexity	5 kN
Load rate per step	0.1 kN
The amount of movement per step	0.01 mm

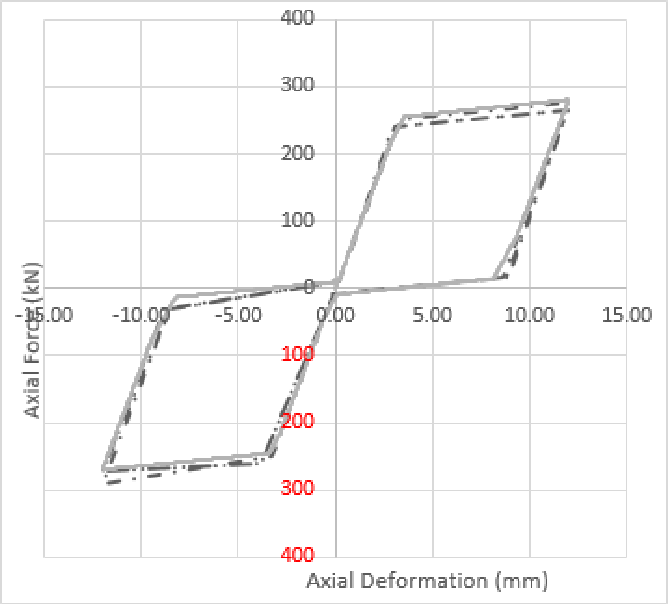

Figure 10: Numerical and laboratory hysteresis diagram of the DT-SCED.

8. Sample six-story building design

In this study, a six-storey prototype frame with a (DT-SCED) first examined by Christopoulos et al was used to investigate seismic behavior in real structures [16]. The results were compared with two other research samples. It should be noted that ASCE7-05 was used to design this structure [12]. This prototype building was designed for normal occupancy on class D soil in downtown Los Angeles, California. The design was done using the modal response spectrum analysis procedure. The SCED braces themselves were designed using the same response modification coefficient R=7 , overstrength factor $\Omega_0 = 2$, and deflection amplification factor $C_d = 5.5$ the same as those prescribed for buckling-restrained braced frames in ASCE 7-05. All columns and beams were steel W-Sections. Concrete floor slabs acted as rigid diaphragms at every storey. The total effective seismic weight of the structure W was 32 100kN. The plan and elevation of the six-storey building are shown in Figure 11. The building lateral force resisting system consisted of SCED-braced frames in the North-South direction and special moment-resisting frames (SMRFs) in the East-West direction. For the current study, only the SCED frame response will be considered, meaning that the SCED frames have been analyzed in 2D and the contribution of the orthogonal SMRFs has been neglected.

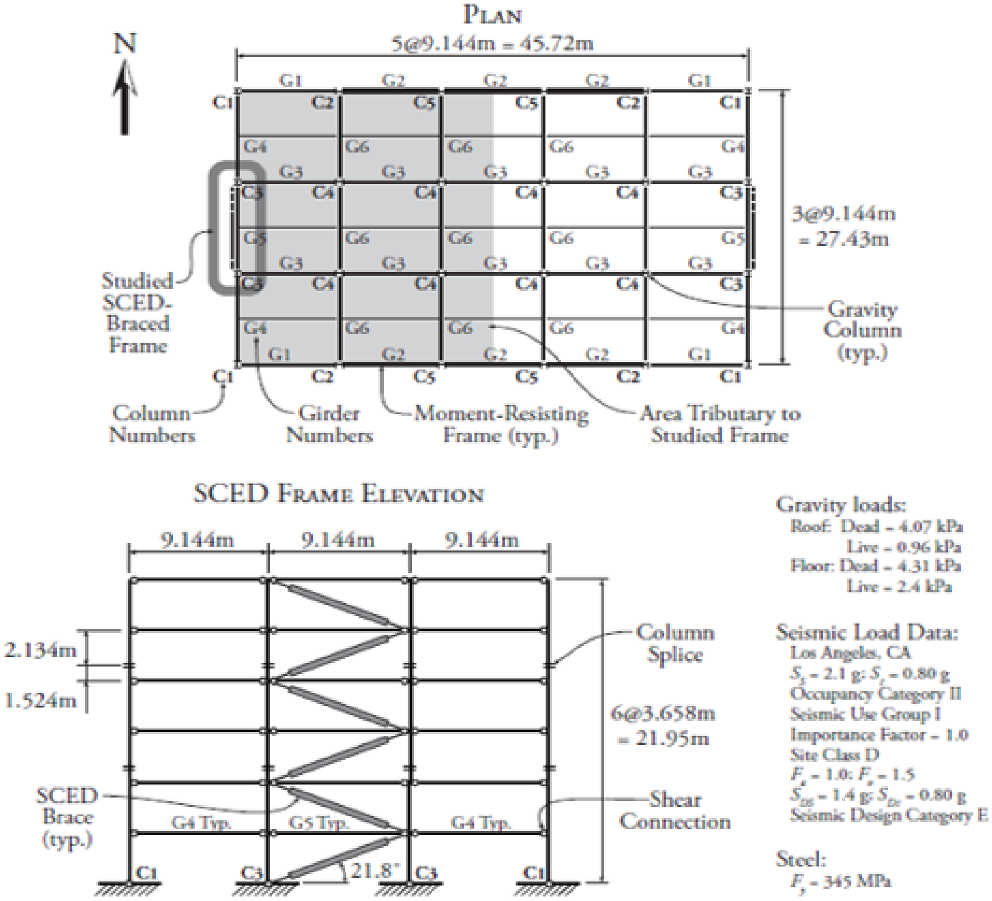

Figure 11: Six-Storey SCED Building Design [16].

9. BUILDING MODELLING

To model the DT-SCED, the hysteresis diagrams of each storey were calculated in the first step. the amount of lateral force was applied in each storey and the DT-SCED details were calculated according to the maximum axial force. Table 5 provides details of SCED, T-SCED and DT-SCED [17].

Table 5: Mechanics Simulator Model Inputs for Designed SCEDs.

Parameter	SCED	T-SCED	DT-SCED
Young's Modulus Steel	MPA 200000	MPA 200000	MPA 200000
Young's Modulus Tendon	MPA 102000	MPA 102000	MPA 102000
Inner Member Length	mm 6500	mm 7000	mm 6500
Inner Member Area	Table 6	Table 6	Table 6
Intermediate Member Length	-	mm 7000	-
Intermediate Member Area	-	Table 6	-
Outer Member Length	mm 6500	mm 7000	mm 6500
Outer Member Area	Table 6	Table 6	Table 6
Internal Damper Friction End 1	Table 6	Table 6	Table 6
Internal Damper Friction End 2	Table 6	Table 6	Table 6
Tendon Area Total Tendon Pretension	Table 6	Table 6	Table 6
Initial Pre-tensioning Force Step	KN 0.1	KN 0.1	KN 0.1
Analysis Deformation Step	mm 0.005	mm 0.005	mm 0.005

Table 6: SCED Brace Property Summary.

Brace/ Storey	Member Area (mm^2)			Internal Damper Friction (kN)		Tendon Area	Tendon Pretension
	A_i	A_m	A_0	F_{I1}	F_{I2}	(mm^2)	(KN)
	Inner	Interm.	Outer	End 1	End 2	A_{pt}	P_{p0}
SCED							
S1/S2	20100	-	20700	450	450	1830	1053
S3	20100	-	20700	450	450	1830	894
S4	20100	-	26770	350	350	1220	787
S5	20100	-	26770	250	250	1220	617
S6	13600	-	26770	200	150	912	398
T-SCED							
S1/S2	13600	26770	26431	250	250	912	557
S3	13600	26770	26431	200	150	912	398
S4	20100	26770	29050	300	300	1220	851
S5	20100	26770	29050	250	250	1220	617
S6	13600	26770	26431	200	150	912	398
DT-SCED							
S1/S2	18773	-	22432	450	500	1500	1050
S3	18773	-	22432	400	400	1500	780
S4	18773	-	25000	350	200	1100	635
S5	18773	-	25000	250	250	1100	635
S6	15900	-	21462	200	150	800	500

10. BUILDING PERIODS AND PUSHOVER ANALYSES

The elastic periods of the first three modes of the different design structures are shown in Table 7 It was observed that the period of the research sample building with DT-SCED is close to the comparable samples. Single direction pushover analyses were conducted for each design and the results are shown in Figure 12 These force-controlled pushovers were conducted using an ASCE-7 force distribution over the height (ASCE, 2005). The pushovers show that all of the full friction designs transition between the initial building stiffness and the post activation stiffness at approximately the same level of base shear. This shows that all of those analyses have the same activation base shear which was the design intention.

Table 7: Analysis Model Periods.

Analysis	Mode 1	Mode 2	Mode 3
SCED	0.9	0.3	0.17
T-SCED	0.76	0.22	0.12
DT-SCED	0.81	0.24	0.14

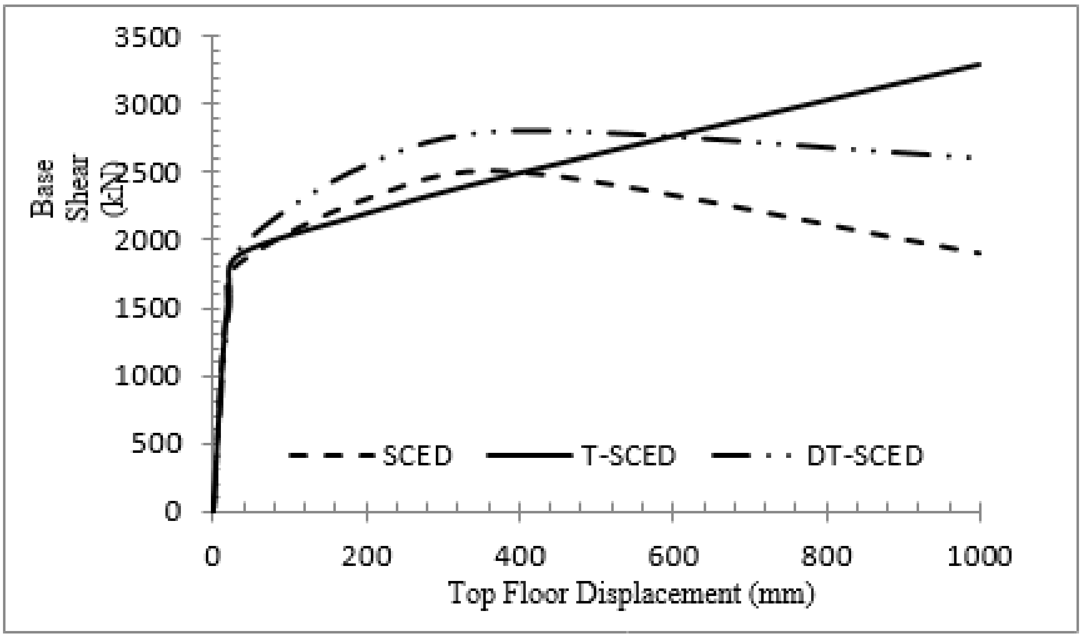

Figure 12: Building Model Pushover Analysis Comparison.

11. COMPARISON OF PUSHOVER ANALYSES RESULTS

In this study, the results of the research by Erochko et al [17]. were used to evaluate and compare seismic performance. The results of the Pushover Analysis on sample buildings are presented in Table 8 To investigate the effect of each Self-Centering brace on the seismic response of the sample buildings, the following parameters were compared: Peak Drift, Peak residual Drift and maximum base shear.

One of the most important parameters to investigate seismic behavior is DRIFT. Figure 13 shows the Drift of the sample buildings. The DRIFT of the building with the DT-SCED brace has a good

Table 8: Seismic Responses of Sample Buildings with SCED, T-SCED, and DT-SCED Brace.

Analysis	Peak Drift (%)	Peak Residual Drift (%)	Maximum Base Shear (Kn)
C-SCED	1.65	0.25	2460
T-SCED	1.63	0.011	3234
D-SCED	1.62	0.013	2676

seismic performance compared to the other two braces. It should be noted that Self-Centering behavior can act as a member or as a system in a structure. In this study, a Self-Centering member was used as a brace in the sample building.

The most desirable performance of Self-Centering braces can be expressed as its ability to create flagging behavior in the building. Figure 14 compares the Residual-Drift of the sample buildings. It is observed that the Residual-Drift in buildings with T-SCED and DT-SCED braces is close to zero.

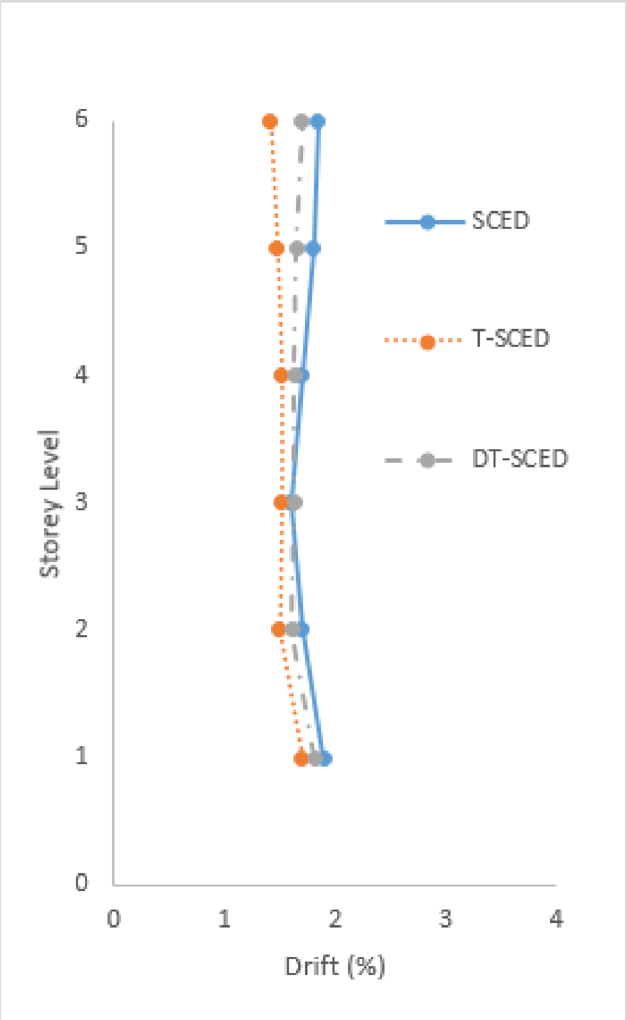

Figure 13: Maximum DRIFT diagram of sample buildings with Self-Centering braces.

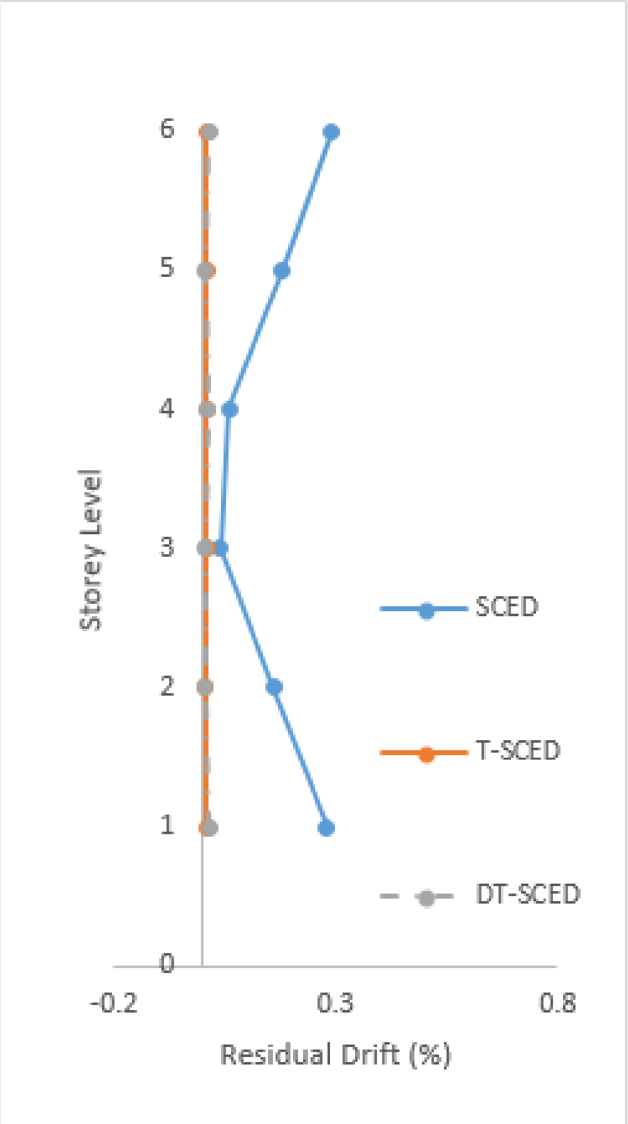

Figure 14: Maximum Residual-DRIFT diagram of sample buildings with Self-Centering braces.

12. Conclusion

In this study, the DT-SCED was introduced which has superior features over other telescopic braces. These include: high axial load capacity, use of shorter cables in brace construction, simplicity of construction, use of separate cables for compressive and traction modes, less fatigue in cyclic loads and, allowing for more dynamic loading cycles.

Details of the design and assembly of the brace have been provided in a detailed manner for real and laboratory dimensions. A laboratory sample was designed for an axial load capacity of 300kN. The brace was tested on a cyclic load and the experimental result showed complete Self-Centering behavior. The hysteresis diagram of this laboratory sample was drawn, which shows it is flag-shaped.

The laboratory specimen of the DT-SCED was modeled in finite element software and subjected to cyclic load testing. The actual and software hysteresis charts were compared which shows that the two graphs match together very well.

Design Dimensions of DT-SCED braces are executable and manufactured in Iran. These members were more economical than SCED and T-SCED braces in terms of outer, internal and cabling cross-sectional area.

The seismic performance of the DT-SCED brace is far better than the SCED brace in the prototype building. Unlike the SCED brace, the DT-SCED brace behaves completely Self-Centering and the Residual-DRIFT of the building is approximately zero.

The seismic performance of the DT-SCED brace is similar to the T-SCED brace. DT-SCED brace displacement is lower than the T-SCED brace, which can be due to the use of separate cables in compression and traction modes.

As a result, it can be concluded that the use of DT-SCED brace improves the seismic performance of the building. Also, due to the ease of construction and assembly of these braces (DT-SCED), they can easily create a Self-Centering behavior in buildings.

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