DESIGN, TESTING AND DETAILED COMPONENT MODELING OF A 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. The results are compared with numerical relationships that were in good agreement.

Keyword: Telescoping Self-Centering Energy-Dissipative Brace (DT-SCED), Cyclic Load Test, Nonlinear Incremental Stiffness Analysis.

I. 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 [VIII]. 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 [VIII]. 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 [X]. 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 [VII]. 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 behavior 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 [II]. 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 [II, III, IV, IX, VI]. 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 [VI, I].
II. Introducing Double Telescoping Self-Centering Energy-Dissipative Brace (DT-SCED)

After reviewing all previous Self-Centering braces, 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 [V]. 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.
Fig. 1: Schematic shape of the DT-SCED. A) no-load mode B) tensile loading C) compressive loading.

III. 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.

Fig. 2: Detail of the DT-SCED. A) Bracket cross section B) Bracket sidewall C) Components required in bracket construction.
Fig. 3: Schematic shape of the test set-up (DT-SCED)

Table 1: DT-SCED Target Design Parameters

| Parameter                  | Value     |
|----------------------------|-----------|
| Ultimate axial force       | 280 kN    |
| δ                          | 12 mm     |
| cable length               | 80 mm     |
| Pre-tensioning Force $P_0$ | 5 kN      |
| friction force             | 80 kN     |
| DT-SCED Activation Load    | 240 kN    |
| $\beta$                    | 0.95      |
| Estimated Initial Stiffness $K_1$ | 83 kN/mm |
| Estimated Post-Activation Stiffness $K_2$ | 3 kN/mm |
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. The construction steps of the DT-SCED and its transfer to the structural laboratory of Ferdowsi University of Mashhad are shown in Figure 6.

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 mm²  |
| External organ cross section      | 3888 mm²  |
| Internal organ length            | 1050 mm   |
| External organ length            | 1050 mm   |
| Cable length                     | 842 mm    |
Fig. 5: the details of the DT-SCED section.
IV. 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 [V]. As seen in Fig. 7, a steel plate is positioned between two other metal pieces by 3 bolts which generates frictional force and energy dissipation by applied force.
V. 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 Fig 8, 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 mm² |
| Young's modulus                  | 44 GPa    |
| Modulus of elasticity            | 102 GPa   |
| Cable length                     | 842 mm    |
VI. 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 Fig 9. All cycles are completely stable and the flag hysteresis behavior is fully implemented.

![Hysteresis diagram DT-SCED](image)

**Fig.9:** Hysteresis diagram DT-SCED

VII. Simulation of DT-SCED Brace Response

The DT-SCED behavior was modeled using nonlinear stiffness analysis. Figure 10 shows the DT-SCED stiffness matrix. The model is one-dimensional, but it is shown here separated into two dimensions for clarity. The elements that represent the inner and outer members \( K_i, K_o \), and the tendons \( K_p, K_r \) 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 11. 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.

![Stiffness matrix DT-SCED](image)
Table 4: Mechanics Simulator Model Inputs.

| 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   |

Fig.10: DT-SCED structural model for calculating hysteresis diagram.
VIII. 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.

Fig. 11: Numerical and laboratory hysteresis diagram of the DT-SCED.
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