SEISMIC RESPONSE OF SIX- STORY STEEL FRAME BUILDING WITH SELF-CENTERING ENERGY-DISSIPATIVE (SCED) BRACES COMBINED WITH LINEAR VISCOUS DAMPERS

J. Erochko¹ and C. Christopoulos²

ABSTRACT

The self-centering energy-dissipative (SCED) brace is an innovative cross-bracing system that eliminates residual building deformations after seismic events and prevents the progressive drifting that other inelastic systems are prone to experience under long-duration ground motions. Previous studies of SCED braces have focused on the use of friction dampers as the primary energy-dissipating element within the brace. This study uses a six-story prototype building model to determine whether the addition of viscous dampers to the SCED-braced frame can efficiently reduce the accelerations while providing similar or better drift and base shear response. Two main design cases were studied: one with viscous damping only and one where viscous damping was combined with the friction damping within the SCED brace. The viscous damping constant at each story was calculated by determining the equivalent damping necessary to match the energy dissipation provided by a SCED brace with full friction damping at a design drift and modal frequency. The resulting hysteretic behavior of the structure was then modeled using the nonlinear structural analysis package OpenSees to determine the dynamic response of the structures. The best dynamic response was achieved by using 50% of the full SCED brace friction damping combined with viscous damping equivalent to the remaining 50% of the friction damping evaluated at the first modal frequency. This design resulted in a modest 15% increase in base shear while achieving significant performance improvements, decreasing accelerations by 30% and drifts by 20%.

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The self-centering energy-dissipative (SCED) brace is an innovative cross-bracing system that eliminates residual building deformations after seismic events and prevents the progressive drifting that other inelastic systems are prone to experience under long-duration ground motions. Previous studies of SCED braces have focused on the use of friction dampers as the primary energy-dissipating element within the brace. This study uses a six-story prototype building model to determine whether the addition of viscous dampers to the SCED-braced frame can efficiently reduce the accelerations while providing similar or better drift and base shear response. Two main design cases were studied: one with viscous damping only and one where viscous damping was combined with the friction damping within the SCED brace. The viscous damping constant at each story was calculated by determining the equivalent damping necessary to match the energy dissipation provided by a SCED brace with full friction damping at a design drift and modal frequency. The resulting hysteretic behavior of the structure was then modeled using the nonlinear structural analysis package OpenSees to determine the dynamic response of the structures. The best dynamic response was achieved by using 50% of the full SCED brace friction damping combined with viscous damping equivalent to the remaining 50% of the friction damping evaluated at the first modal frequency. This design resulted in a modest 15% increase in base shear while achieving significant performance improvements, decreasing accelerations by 30% and drifts by 20%.

**Introduction**

The self-centering energy-dissipative (SCED) brace is a high performance seismic force resisting system for structures that combines an internal restoring force that eliminates residual drifts after an earthquake with supplemental damping to reduce the maximum earthquake response [1]. The hysteretic response of a SCED brace that includes a friction or hysteretic energy dissipating device is shown in Fig. 1. The mechanics of a SCED brace that would produce such a hysteresis are also shown in Fig. 1; this behavior is fully described in [1]. The point on the hysteresis where the stiffness changes from \(k_i\) to \(k_a\) is called the activation force \(P_a\). The amount of energy dissipation that is provided by the friction or hysteretic damper is characterized by the energy dissipation capacity parameter \(\beta\) which is expressed as a percentage of \(P_a\). This \(\beta\) parameter is typically designed to be 80-90% to provide the maximum energy dissipation without resulting in

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residual deformations due to the resistance of structural members that are not part of the lateral load resisting system and non-structural components. This hysteretic response of the SCED brace shown in Fig. 1 provides significant energy dissipation and results in zero residual drift when the applied force in the brace returns to zero. This elimination of residual drifts provides overall performance benefits to the structure, since residual drift has been shown to be an important metric of post-earthquake building performance [2-5].

Recent studies have extended the elongation capacity of the SCED brace by introducing a new telescoping mechanism (called a T-SCED brace) [6], provided a more detailed understanding of SCED and T-SCED mechanics [7], and used shake table tests to prove that numerical models of multi-story SCED-braced frames provide a good prediction of the real dynamic behavior of SCED-braced frames [8]. Although it has always been suggested that there are many options for energy dissipation within a SCED braced frame, including hysteretic, viscous or viscoelastic damping [1], all of the previous SCED brace designs and models have utilized friction damping mechanisms to provide energy dissipation and supplemental damping.

The use of viscous damping in structural systems is attractive because the forces in viscous dampers are generally out-of-phase with the maximum forces elsewhere in a structural system. This is because the force in a viscous damper is velocity-dependent, whereas the force in structural members or in friction or yielding dampers is displacement-dependent. Therefore, if a viscous damper is used in place of a friction or yielding damper, in addition to reducing accelerations in a system, the viscous damper also has the potential to reduce maximum inertial forces in a system, compared to a friction system that provides an equivalent amount of energy dissipation. To take advantage of these properties, this study will investigate the use of linear viscous damping to either fully or partially replace the friction damping in a SCED braced frame.

There have been a few numerical studies that have been previously conducted into the use of viscous damping with other self-centering systems. Kim [9], conducted a numerical study of a fully-designed, six-story self-centering moment frame building that used viscous dampers for energy dissipation. His study found that the frame with the viscous dampers experienced smaller drifts and accelerations than a friction damped frame or a conventional yielding moment frame and was able to completely eliminate residual drifts. Kam et al. [10] conducted a dynamic
single-degree of freedom (SDOF) study of self-centering systems with either friction (hysteretic) damping, viscous damping, or a combination of the two. They found that the combined combining friction and viscous damping tended to have the best response in terms of maximum drift, residual drift and maximum acceleration without a causing a significant increase in base shear. A similar SDOF study which included both self-centering systems and bilinear elastoplastic systems with added viscous damping was conducted by Karavasilis and Seo [11]. They confirmed the results of the previous study and also found that increasing the strength ratio decreases accelerations, and that added damping is better at mitigating accelerations in self-centering systems than in elastoplastic systems.

**Six-Story Building Design [12]**

The six-story SCED-braced frame design for this numerical study was taken from a previous analytical study that was conducted by Choi et al. [12]. This prototype building was designed for normal occupancy on class D soil in downtown Los Angeles, California. The building was designed using the modal response spectrum analysis procedure. The SCED braces themselves were designed using the same response modification coefficient, overstrength factor, and deflection amplification factor as those prescribed for buckling-restrained braced frames in ASCE 7-05 [13]. All columns and beams were steel W-Sections. Concrete floor slabs acted as rigid diaphragms at every story. The total effective seismic weight of the structure was 32,100kN. Full design details may be found in [12]. The plan and elevation of the completed six-story building are shown in Fig. 2. 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 were analyzed in 2D and the contribution of the orthogonal SMRFs was neglected.

**Building Modeling**

A summary diagram of the 2D building model is shown in Fig. 3. The structure was modeled and analyzed using the structural seismic behavior modelling software OpenSees [14]. The SCED braces were modelled using the OpenSees ‘SelfCentering’ material model and the viscous dampers were modelled using the plain Viscous material. All columns were considered to be continuous with fixed column splices and pinned column bases. The column sections were modelled using a lumped plasticity model with hinges at either end of each column. The moment-curvature response and axial moment interactions of the column hinges were considered implicitly by using fiber sections at the hinge locations. The nonlinear steel material that was used for these fiber elements was assumed to have a post-yield stiffness equal to 2% of the initial stiffness. Beams were considered to be pinned and were modelled using truss elements. All beam and column ends were assigned fixed end offsets to account for beam and column depths at the connections.

To account for P-Delta effects in the model, four leaning columns were added. They each had the combined properties of all the gravity columns that share the same cross-section. For the model’s mass matrix, the story mass for half of the building which includes the mass that is supported by all the gravity columns, was lumped together and assigned to the master node on the frame (see Fig. 2). A rigid diaphragm constraint was modelled at each floor to simulate the
horizontal constraints applied by the floor slabs. Inherent damping was modeled using 3% of critical Rayleigh damping in Modes 1 and 2. This is the same amount of damping that was assumed in the study by Choi et al. [12].

Figure 2. Six-story prototype building design

Design of SCED Braces and Viscous Damping

The target design parameters for the SCED braces were chosen by matching the activation load $P_a$ of the new braces to the activation load of the SCED braces that were used previously by Choi et al. [12]. The SCED braces that were designed by Choi et al. [12] were designed to have the same axial force as a buckling-restrained brace at 2% story drift. All of the new SCED braces that were designed for this study were telescoping SCED braces (T-SCEDs) [6] and their behavior was modeled to include the effect of anticipated fabrication tolerances using the detailed SCED brace analytical model described in [7]. Since high capacity T-SCEDs would result in unreasonably large cross-sections, for the first two stories each side of the building was
considered to be able to have two T-SCED braces instead of one. The behavior of these two braces for the first and second stories were combined into a single brace element in the model.

Since the objective of this study is to compare the behavior of conventional friction-damped SCED braces (T-SCED braces) to SCED braces with viscous damping, five different SCED brace designs were considered. The first was the conventional T-SCED brace that was designed to be equivalent to the braces designed by Choi et al. as described above [12]. The remaining four designs had either all of their friction damping or half of their friction damping replaced by viscous damping. These designs will be referred to as V-SCEDs. Since this numerical study is the first of its kind, only linear viscous dampers were considered in order to reduce the number of design parameters. Hence, the goal of the design of the V-SCED viscous dampers was to determine a set of linear viscous damping constants ($C_L$) that results in reduced story accelerations, potentially reduced story drifts, and does not significantly increase the building’s base shear.

A traditional approach for designing viscous dampers for a structure would entail the determination of the effective stiffness and mass properties of the structure which would then be used in conjunction with a design response spectrum to determine the amount of viscous damping required to achieve a target displacement or force level; however, since the goal of this pilot study was to compare different combinations of SCED brace friction damping with added viscous damping, this simple method was not deemed to be appropriate. Instead of explicitly attempting to reduce target response quantities, this study aims to compare different SCED/viscous combinations to assess the response quantity reductions that are caused by the different combinations of friction and viscous damping. Therefore, the selection of the linear viscous damping constant for the V-SCED braces is based on an energy-dissipation equivalence between the design with the added viscous dampers and the baseline friction-damped T-SCED braced frame design.
To determine this equivalence, a target design drift level for the structure must be selected. For these analyses, this target was set to the ASCE-7 story drift limit of 2% [13]. This target drift determines the total amount of energy that is dissipated per loading cycle for the starting-point friction-damped T-SCED designs (i.e. the area within the hysteresis). Then, either one half of that friction energy-dissipation or all of it is removed from the T-SCED braces and replaced with an equal amount of viscous damping instead. To replace the removed T-SCED energy dissipation with viscous damping, an equivalent linear viscous damping constant $C_L$ must be selected for each brace. Since viscous damper energy is velocity dependent, the damping constant cannot be determined without the selection of a viscous damper loading frequency. Therefore, an effective frequency is determined based on the modal properties of the building and the effective secant stiffness of each T-SCED in the starting-point structure. Using this effective frequency and the target energy dissipation, the viscous damping constant $C_L$ for each V-SCED brace may be calculated using Eq. 1:

$$C_L = \frac{E_{flag}}{\pi \omega_{eff} \delta_d} \quad (1)$$

where $E_{flag}$ is the energy that was previously dissipated by the T-SCEDs friction damper that will be replaced by viscous damping, $\omega_{eff}$ is the effective angular modal frequency of vibration for the T-SCED brace, and $\delta_d$ is the brace deformation at the design drift of 2%. The first mode frequency seems to be the obvious choice for the design of the viscous dampers; however, since significant story velocities may be caused by the second mode of the building response, both the first and second mode frequencies were tested for the design of the viscous dampers in this study. The first and second mode periods for the T-SCED structure were 0.86 s and 0.27 s, respectively. This process resulted in four different sets of brace designs that combined T-SCEDs with viscous damping. The two designs with no friction damping will be referred to as V-SCED (0-M1) and V-SCED (0-M2) for the first and second mode effective frequency designs, respectively. Similarly, the two designs with half of the internal friction damping remaining will be referred to as V-SCED (50-M1) and V-SCED (50-M2). Sample T-SCED and V-SCED design results for the first story braces are shown in Table 1. See Fig. 1 for the definitions of the hysteresis parameters shown in the table.

Table 1.  T-SCED and V-SCED brace sample designs (first story)

<table>
<thead>
<tr>
<th>Brace</th>
<th>Act. Force $P_a$ (kN)</th>
<th>Initial Stiffness $k_I$ (kN/mm)</th>
<th>Post-Act. Stiffness $k_a$ (kN/mm)</th>
<th>$\beta$ Param.</th>
<th>Damping Constant $C_L$ (kN·s/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-SCED</td>
<td>2140</td>
<td>674</td>
<td>13.0</td>
<td>0.900</td>
<td>-</td>
</tr>
<tr>
<td>V-SCED (0-M1)</td>
<td>1150</td>
<td>457</td>
<td>13.0</td>
<td>0.01</td>
<td>9.03</td>
</tr>
<tr>
<td>V-SCED (50-M1)</td>
<td>1646</td>
<td>578</td>
<td>13.0</td>
<td>0.58</td>
<td>4.52</td>
</tr>
<tr>
<td>V-SCED (0-M2)</td>
<td>1150</td>
<td>457</td>
<td>13.0</td>
<td>0.01</td>
<td>2.84</td>
</tr>
<tr>
<td>V-SCED (50-M2)</td>
<td>1646</td>
<td>578</td>
<td>13.0</td>
<td>0.58</td>
<td>1.42</td>
</tr>
</tbody>
</table>
To design a V-SCED brace, a similar approach could be used: design regular SCED or T-SCED braces based on seismic demands, and then replace some or all of the friction energy dissipation with viscous dampers as described above.

**Figure 4. Contributions to hysteretic response for the first story braces in the V-SCED designs (MCE Earthquake LA21)**

**Ground Motions used in Time-History Analyses**

The time-history analyses were performed using a suite of sixty total ground motions that were taken from the SAC joint venture project [15]. The SAC records are calibrated for the Los Angeles area and split into three different hazard levels. Twenty records (LA41 to LA60) represent the frequently occurring earthquake (FOE) seismic hazard level with a probability of
exceedence of 50% in 50 years. An additional twenty records (LA01 to LA20) represent the design basis earthquake (DBE) seismic hazard level with a probability of exceedence of 10% in 50 years. The final twenty records (LA21 to LA40) represent the maximum considered earthquake (MCE) seismic hazard level with a probability of exceedence of 2% in 50 years.

**Time-History Analysis Results**

The sixty different earthquake records from each of the three seismic hazard levels described above were applied to each of the different building designs and the results of these analyses and the trends that were observed from these results are described below.

**Individual Record Response and Hystereses**

The differences between the different building designs may best be seen by comparing sample hysteretic responses for the SCED braces in each different design. Sample hystereses for the first story braces (including the effect of the viscous damping) in each of the four different V-SCED designs subject to a typical maximum considered earthquake (MCE-LA21) are shown in Fig. 4. This figure shows that each total hysteretic plot for the V-SCED (the left column of plots in the figure) represents a superposition of two different hysteretic behaviors: the one of the SCED brace and the one of the viscous damper (the center and right columns of the figure, respectively). The two top V-SCEDs with no internal friction damping have a SCED hysteretic response that is effectively a bilinear elastic curve. This is a flag hysteresis with an energy dissipation capacity parameter ($\beta$) value of zero. The hystereses that are shown behind these plots in grey show the behavior of the regular T-SCED braces with 100% of the energy dissipation coming from friction for comparison. The activation load of the bilinear elastic curve is lower than the T-SCED because the activation force is equal to the sum of the SCED brace tendon pretension and the internal friction damper slip force. Without the internal damper force, the activation force drops. The two bottom V-SCEDs with 50% internal friction damping have a SCED hysteretic flag width that is half that of the starting-point T-SCED. The viscous damper hystereses that are shown in the right column of plots show the typical behavior of a linear viscous damper subjected to an earthquake-derived deformation history. The first mode period viscous designs resulted in higher viscous damping constants and, therefore, experience higher forces and also dissipate more energy than the second mode period designs; however, the first mode designs also result in greater floor shears.

**Response Summary**

The median results for peak acceleration, peak story drift, and peak base shear are shown for all of the different designs in Table 2. All of the designs successfully eliminated residual building drifts. The results show that, as anticipated, the accelerations of the V-SCED buildings were significantly lower than the accelerations of the T-SCED building. This shows that adding viscous dampers to SCEDs produces the desired effect of reducing accelerations. These accelerations were reduced at the expense of increased base shear in the first mode effective frequency designs. For the second mode design with no internal friction, accelerations were reduced at the cost of modestly increased drifts at the DBE level. The only V-SCED design that improved relative to the T-SCED design in all categories was the second mode period design.
with 50% internal friction damping. Compared to the T-SCED, this design produced a modest decrease in accelerations, similar drifts and slightly reduced base shears.

These results suggest three main conclusions about the V-SCED behavior. First, designing using the second mode effective frequency of a six story building seems to provide viscous damping constants that provide the best match between the response of the resulting V-SCED building and the reference friction damper T-SCED building. This shows that higher modes influence the behavior of the viscously damped SCEDs. For taller buildings, it is expected that other higher modes should also be considered when selecting the damping constants if a comparable response to the reference T-SCED building is desired. Second, the 50% internal damping friction design seems to provide the best balance between controlling drifts and reducing accelerations. Third, if increased capacity design forces by around 10-15% are tolerable, the highest level of performance may be provided by designing using the first mode period with 50% friction and 50% viscous damping.

Table 2. T-SCED and V-SCED Response Quantities - Median Values
Percentages shown represent percentage relative to T-SCED value

<table>
<thead>
<tr>
<th>Model</th>
<th>Maximum Acceleration (g)</th>
<th>Peak Drift (%)</th>
<th>Maximum Base Shear (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FOE</td>
<td>DBE</td>
<td>MCE</td>
</tr>
<tr>
<td>T-SCED</td>
<td>0.83</td>
<td>1.39</td>
<td>1.82</td>
</tr>
<tr>
<td>V-SCED</td>
<td>0.36</td>
<td>0.62</td>
<td>0.99</td>
</tr>
<tr>
<td>(0-M1)</td>
<td>43%</td>
<td>45%</td>
<td>54%</td>
</tr>
<tr>
<td>V-SCED</td>
<td>0.52</td>
<td>1.00</td>
<td>1.26</td>
</tr>
<tr>
<td>(50-M1)</td>
<td>63%</td>
<td>72%</td>
<td>69%</td>
</tr>
<tr>
<td>V-SCED</td>
<td>0.62</td>
<td>1.05</td>
<td>1.29</td>
</tr>
<tr>
<td>(0-M2)</td>
<td>75%</td>
<td>76%</td>
<td>71%</td>
</tr>
<tr>
<td>V-SCED</td>
<td>0.83</td>
<td>1.26</td>
<td>1.52</td>
</tr>
<tr>
<td>(50-M2)</td>
<td>100%</td>
<td>91%</td>
<td>84%</td>
</tr>
</tbody>
</table>

Conclusions

The results from these analyses have provided some insight into the behavior of MDOF SCED-braced structures with viscous damping. The best match between the response of the T-SCED building and the V-SCED building was achieved by using 50% friction damping with viscous damping constants that were determined using the second mode effective frequency of the structure; however, the best dynamic response was achieved by using 50% friction, but increasing the viscous damping constant by using the first mode effective frequency for design. This first mode design resulted in a modest 15% increased base shear but significant performance improvements, with a decrease of accelerations by 30% and drifts by 20%.

The numerical study described here points to some avenues for further study. Particularly, the study should be extended to taller and shorter buildings to determine whether
the suggested viscous damper design would be applicable to a wider range of structures. For taller structures consideration of higher modes than the second mode may be necessary to develop a good V-SCED design. Since all of the viscous dampers in the study used linear viscous damping constants, nonlinear viscous dampers may also be investigated in the future to determine whether the response improvements that were provided by the viscous dampers could be further improved upon.

References


