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SELF-CENTERING CAPABILITY OF SHAPE MEMORY ALLOY (SMA)-BASED SUPERELASTICITY-ASSISTED SLIDER (SSS)

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ABSTRACT

The self-centering capability, emphasized in design codes as a fundamental feature of aseismic isolation systems, is investigated for the Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS).

Restoring force in SSS is associated with austenitic SMA wires in order to properly re-center flat sliders. Energy considerations are examined first as an insight into the problem, revealing also the governing parameters. The self-centering capability is then investigated through an extensive parametric study of the isolated structures idealized as single-degree-of-freedom systems subjected to a large group of recorded earthquakes. According to the results obtained from extensive nonlinear time-history analyses,residual displacement after an earthquake and the cumulative build-up of displacements after a series of successive earthquakes depend on both structural properties and ground motion characteristics. SSS exhibits an acceptable self-centering capability, satisfying code provisions.

INTRODUCTION

The self-centering capability is identified by the current design codes as a fundamental requirement for seismic Isolation Systems (ISs). Systems with sufficient self-centering capability demonstrate a tendency to return towards the origin during the seismic event. Insufficient restoring capability is manifested by: (a) substantial residual displacements after the end of the seismic event, (b) accumulation of displacements during a sequence of seismic events, and (c) increased maximum and residual displacements for earthquake input histories containing substantial one-sided pulses. The self-centering capability of the ISs is increased by restoring forces that always act towards the origin, such as the rubber stiffness force of elastomeric bearings and the restoring force due to the concave sliding surface of spherical sliding bearings (e.g. the friction pendulum system or FPS). The self-centering capability of the ISs is decreased by forces that can act away from the origin, such as hysteretic forces (hysteretic dampers, yielding of lead in lead rubber bearings) and friction forces in sliding bearings. The balance of these counteracting components defines the self-centering capability of an IS (Katsaras et al., 2008).

The restoring force in SMA-based sliding ISs is provided by superelastic SMA devices, while the friction reduces the self-centering capability.

Most of the previous researches on the self-centering capability of nonlinear systems have been focused on the residual displacements of low-ductility systems that are not typical for ISs (Cardone, 2012). Riddell and Newmark (1979) showed that the magnitude of the residual displacement may be strongly affected by the hysteresis loop shape of the nonlinear system. Mahin and Bertero in a paper in 1981 (as cited in Cardone, 2012) found that, for some elasto-plastic systems, the residual displacement averaged more than 40% of the peak displacements with significant scatter. Kawashima et al. in a paper in 1998 (as cited in

Katsaras et al., 2008) proposed a residual displacement prediction procedure for bilinear ductile systems based on the results of a parametric study of various bilinear single-degree-of-freedom (SDOF) oscillators. According to MacRae and Kawashima (1997) the bilinear oscillators with positive stiffness ratios generally have small residual displacements, while those with negative stiffness ratios tend to undergo little inelastic reversal of deformation and have larger residual displacements. Medeot (2004) proposed the evaluation of the self-centering capability of bilinear hysteretic isolation systems based on the energy criterion ES ≥ 0.25EH, where ES is the stored elastic energy and EH is the hysteretic dissipated energy at a given maximum deformation. DesRoches et al. (2004) showed that increased loading rates lead to decreases in the equivalent damping, but have negligible effects on the recentering properties of the shape memory alloys. Dicleli and Buddaram (2006) studied the effects of isolator and substructure properties as well as the frequency characteristics and intensity of the ground motion on the performance of seismic-isolated bridges. Berton et al. (2007) presented the results of parametric studies on bilinear hysteretic ISs that show the importance of the characteristic strength of the system on its self-centering capability. Katsaras et al. (2008) presented the results of parametric studies on bilinear hysteretic isolation systems, showing that the main parameter that affects the re-centering capability of the isolation system is the ratio dmax/drm, where dmax is the absolute value of the peak displacement over the entire time history and drm is the maximum static residual displacement, which depends on the shape of the hysteretic cycles of the IS. Krishnamoorthy (2008) studied the seismic performance of a symmetrical space frame structure resting on sliding type of bearing with restoring force device concluded that the sliding bearing with restoring force device is effective in reducing the earthquake response of the structure. Cardone (2012) studied the re-centering capability of flag-shaped seismic isolation systems and from the statistical analysis of 50 seismic ground motions concluded that flag-shaped isolation systems with dmax/drm>3 experience negligible residual displacements compared with their maximum displacements.

COADAL PROVISIONS

In recent years, several countries have started to be concerned about the self-centering capability of ISs designing based on the codes. AASHTO (2010) is one of the mostly referred codes that requires some specific controls on the self-centering capability of ISs. Similar regulations are addressed in the other codes such as the International Code Council (ICC); International Building Code - IBC (2006), the California Building Code – CBC (2001), and the European norm for earthquake-resistant design of structures - Eurocode 8; EC8 (2005).

AASHTO requires that (i) the difference between the re-centering forces at the design displacement (Dd) and at the half of the design displacement (ΔFr) shall be greater than 1.25 percent of the structure weight (W), and (ii) the period corresponding to the tangent stiffness based on the re-centering force alone at any displacement (Tt) up to the design displacement shall be less than 6 s. These mandatory specifications can be expressed as the following inequalities:

$$\Delta F_r \geq 0.0125W \tag{1}$$

$$T_t \leq 6s \tag{2}$$

It should be added that the requirements above need to be satisfied by ISs with displacement dependent re-centering force. If the re-centering force is constant (such as the ISs using compressible fluid springs with preload) the combined constant re-centering force shall be equal or greater than 1.05 times the characteristic strength. IBC and CBC specify self-centering capability requirements that are largely based on the AASHTO.

EC8 follows a more precise rule in order to control the self-centering capability. To this purpose, a secondary parameter is defined as the static residual displacement (dr) corresponding to the static equilibrium reached after the system is unloaded under quasi-static conditions from its displacement capacity (Dmax). In an IS designed based on EC8, following condition should mainly be met (Cardone, 2012), guaranteeing enough self-centering capability that can also prevent cumulative build-up displacements:

$$\Delta F_r \geq 0.025(d_{rm} / D_{\max})W = \sqrt{0.0125q}W \tag{3}$$

where q is equal to the ratio of the characteristic strength of the isolation system to the weight of the structure (Cardone, 2012). For sliding ISs, q is the friction coefficient at near zero velocity μmin (Dolce et al., 2005). Since the characteristic strength is included, the self-centering capability controlled by EC8 seems to be more reliable (Cardone, 2012).

SYSTEM CHARACTERIZATION

In this paper, a modern base isolation system, referred to as Shape Memory Alloy (SMA)-based Superelasticity-assisted Slider (SSS), derived from a practical combination of a FSBs with auxiliary SMA devices is investigated for its self-centering capability. ISs using either SMA wires or SMA bars, arranged in different styles, have been previously proposed and used in practice (Dolce et al., 2000; Casciatti et al., 2007; Attanasi et al., 2008; Cardone et al., 2009; Khodaverdian et al., 2012; Ozbulut and Silwal, 2014). SSS is a practically devised IS, with SMA wires preferred to bars. The advantages of newly proposed SMA cables (Reedlunn et al., 2013) are adopted in SSS with practical configurations. The arrangement of SMA wire cables changes the overall behavior. Four different configurations can be considered for SSS, three shown in Figure 1 (based on the system proposed by Dolce et al., 2000, further detailed by Cardone et al., 2009) and the forth is the combination of them with continuous SMA cables, such as the case considered by (Ozbulut and Silwal, 2014).

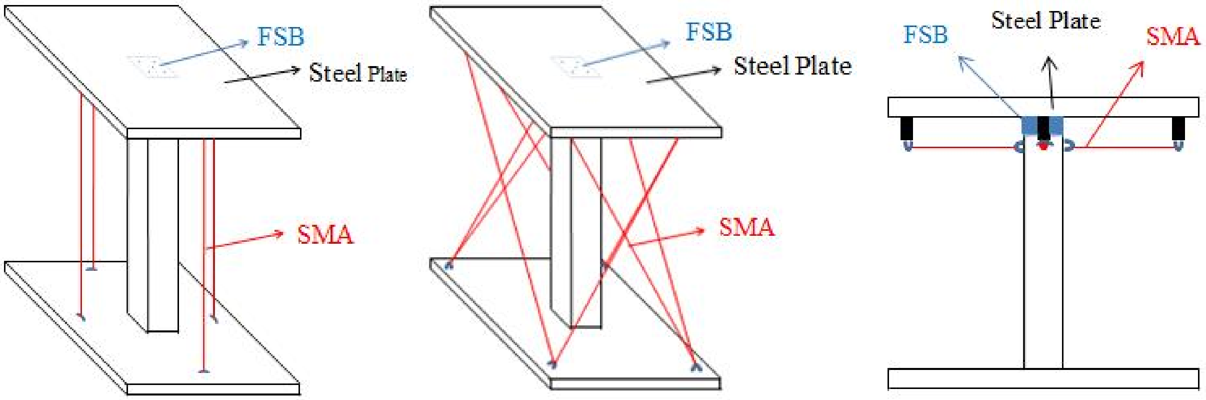

Figure 1. Schematic configurations of SSS with (a) vertically, (b) diagonally and (c) horizontally arranged SMA wire ropes

THEORETICAL CONSIDERATIONS

The behavior of the IS in terms of self-centering capability may be more clearly interpreted by dividing the seismic motion into two successive time stages. The first part is the strong-motion stage, in which the system absorbs energy from the seismic ground motion, and the second part is the free-vibration stage, in which seismic energy input can be considered insignificant compared with the variation in the kinetic and potential energies of the system. The free-vibration stage is mainly affected by the system properties and analytical considerations are possible, whereas the strong-motion stage is also strongly affected by the details of the ground motion which can only be investigated in a statistical manner. The self-centering capability of the IS is examined for each of these stages based on energy concepts.

The self-centering capability of the IS during the strong-motion stage depends on the entire displacement time history which is strongly affected by the details of the ground motion and cannot be fully described by the value of Dmax. The dependence on the details of the ground motion can be evaluated statistically for a large database of records. The seismic energy input during the free-vibration stage can be neglected. As a result of these examinations, the residual displacements (dres) can be estimated by Equation 4.

$$d_{res} = d_r[1+(1-\frac{(m+1)\sim(\sim+2\quad)}{2m}+\frac{\sim}{m})\frac{d_y}{d_r}-\frac{}{m}(\frac{d_{FV0}}{d_r}-1)] \qquad (4)$$

where d_y is the yield displacement, m is the order of force-displacement curve after yielding, d_{FV0} is the displacement corresponding to the beginning of free-vibration stage can be in general any displacement less than or equal to D_{max}. α and β are internal parameters defined by Figure 2, showing the force-displacement behavior of SSS with the austenitic SMA re-centering wire ropes arranged in vertical configuration, which is considered in this study.

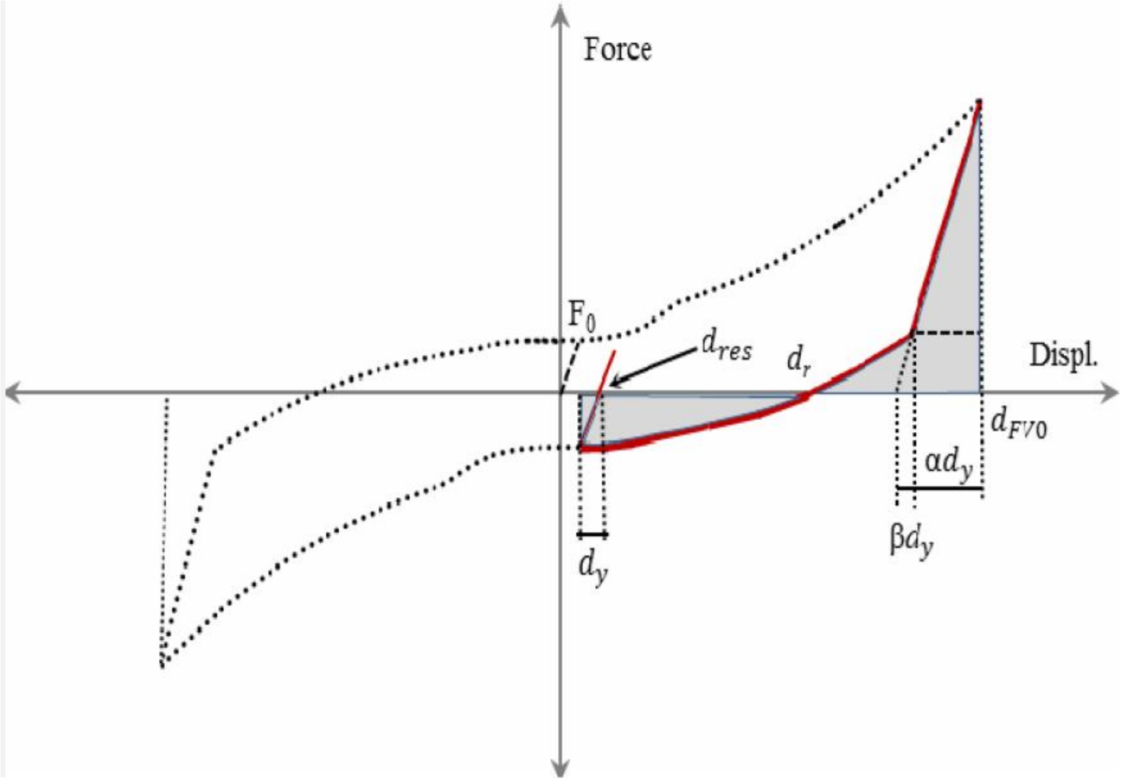

Figure 2. The force-displacement behavior of SSS, with vertically arranged SMA wire ropes, defining the parameters governing self-centering capability

NUMERICAL STUDIES

Self-centering capability of the IS is investigated in a statistical manner in terms of residual displacements after the earthquakes. The residual displacement after an earthquake does not scale up monotonically with respect to the scaling factor, unlike the maximum displacement (Katsaras et al., 2008). This leads to the conclusion that a limited number of dynamic time-history analyses cannot be reliable for the evaluation of the restoring capability. Moreover, the magnitude of the residual displacement depends strongly on the details of the ground motion and the complex behavior of the nonlinear system during the strong-motion stage. In order to derive reliable conclusions, a large and representative database of actual seismic motions should be used. The results of the time-history analysis should constitute an adequate sample in order to evaluate the restoring capability of the system in a statistical manner. The selected records do not need to be compatible with a design spectrum, taking into account the periodic nature of the residual displacement with respect to the earthquake scaling. On the other hand, the selected records should produce a wide variety of $D_{\max}$ values in order to take into account the effect of periodicity of the residual displacement.

A database of 222 ground motions, which corresponds to historic records from 24 different seismic events and includes many records with near-fault effects, is used in this study. Figure 3 shows the distribution of the characteristics of the 222 ground motions is presented.

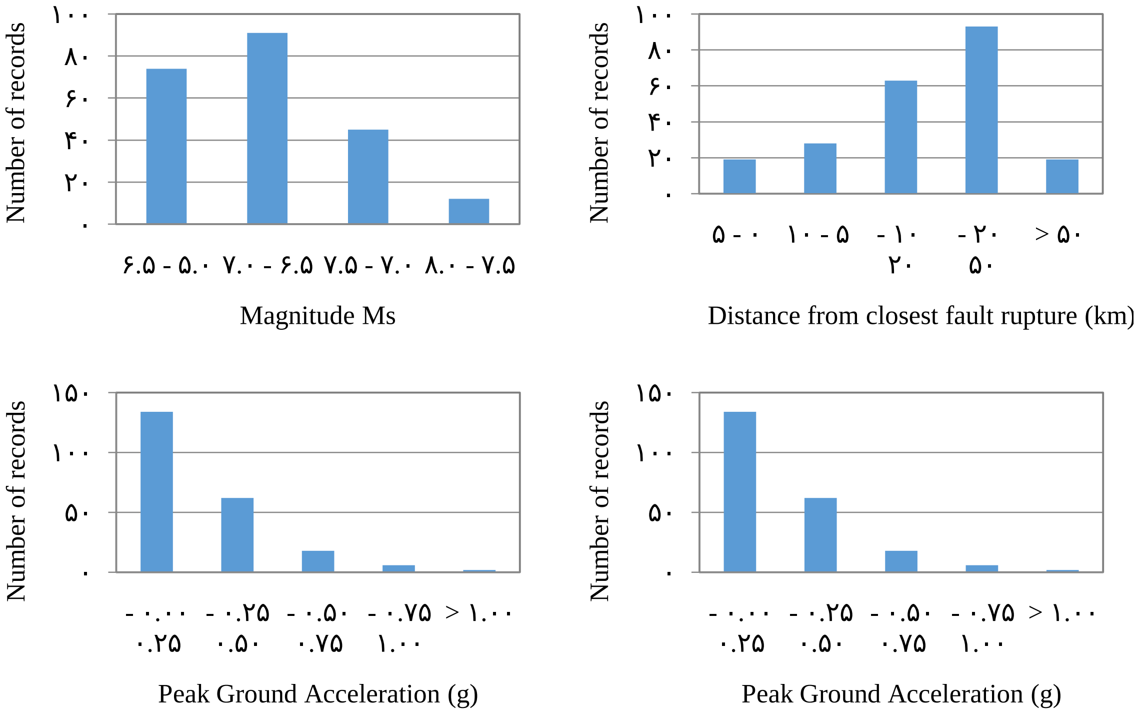

Figure 3. Distribution of the ground motion characteristics for the 222 records used in the analyses

A series of parametric studies was performed (D_d= 0.1, 0.3, 0.5 m; μ= 0.02 , 0.05; W= 8 MN; Number of ground motion records= 222; Number of consecutive ground motions= 1, 2, 3, 4, 5). For each case, a nonlinear time-history analysis was performed. The maximum displacement and the residual displacement after the earthquake were stored for further statistical processing. A total of 1332 different cases were examined and 1332 nonlinear time-history analyses were performed.

Based on the preliminary study of displacement response time histories of a number of selected cases the diagonal and horizontal configurations seem to be perfect in terms of self-centering capability, while furthur studies are required for the vertical configuration.

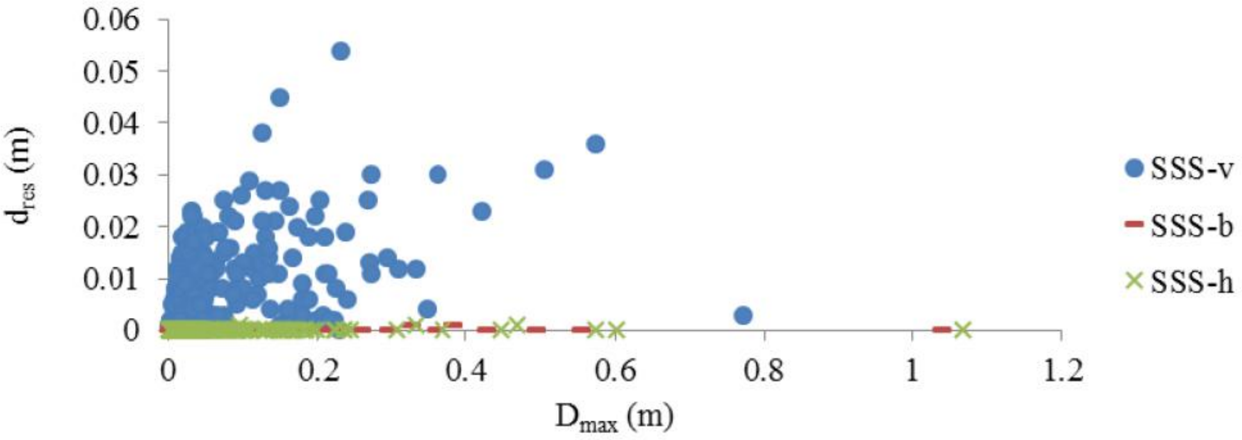

Figure 4. Residual displacements against maximum displacements for the vertical, diagonal, and horizontal configurations of SSS

Figure 4 shows the residual displacements against the maximum displacement occured in the cases studied. Details for the vertical configuration are given in Figure 5.

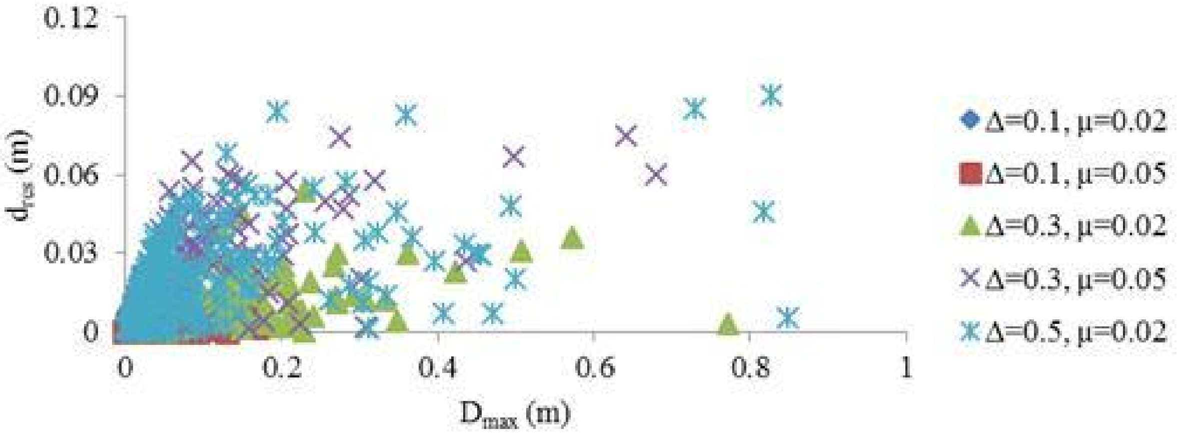

Figure 5. Residual displacements against maximum displacements for different cases of SSS with vertically arranged SMA cables

As can be seen, the residual displacements are mostly less than 10% of the maximum displacements and generally recoverable by exploiting the shape memory effect, as demonstrated in Dolce et al. (2000).

In order to investigate the effect of the consecutive ground motions a sequence of five successive identical ground motions was examined for each case in the parametric study. Figure 6 shows the values of the residual displacements against maximum displacements for a sample practical case (D_d= 0.3 m; μ= 0.02).

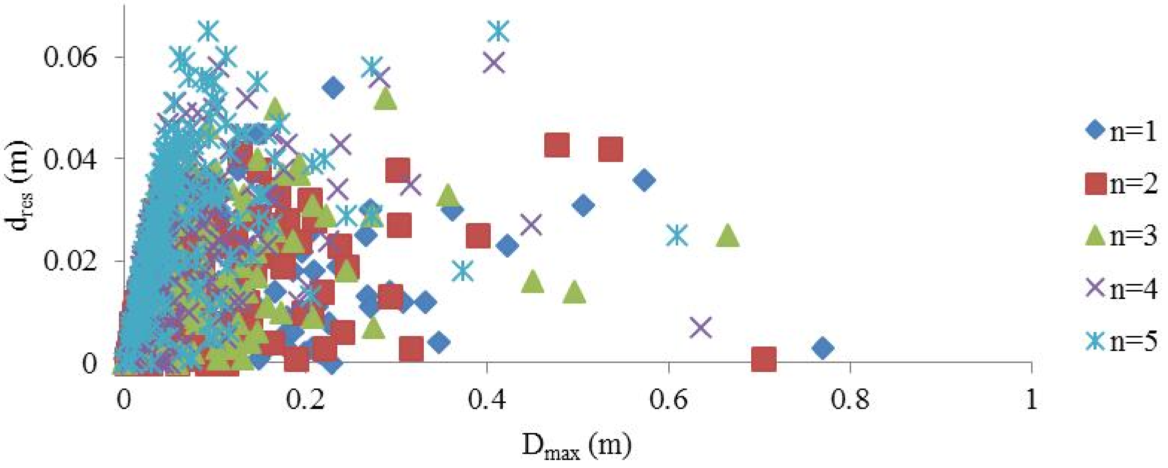

Figure 6. The observed values of residual displacement as a function of maximum displacement for a sample practical case of SSS with vertically arranged SMA cables (D_d= 0.3 m and μ= 0.02)

The results show that residual displacement increases with increasing the number of consecutive earthquakes.

CONSISTENCY WITH CURRENT CODE SPECIFICATIONS

As shown in Figure 7, the EC8 criterion is checked out for the self-centering capability of SSS, showing that that the force at the design displacement minus the force at half the design displacement (C_E) is acceptably greater than 0.025W multiplied by the ratio of static residual displacement to design displacement (the dashed line) in most of the cases.

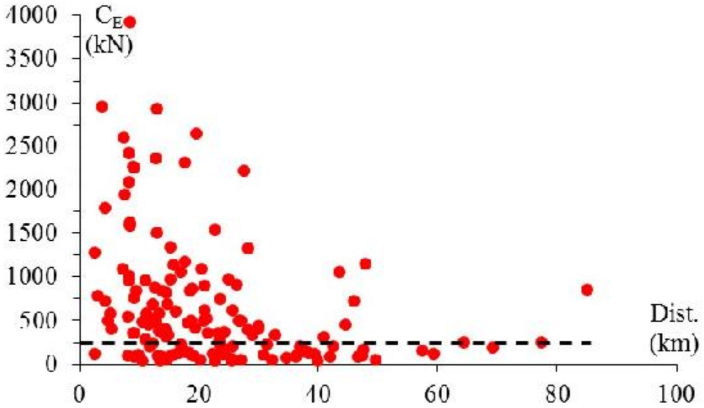

Figure 7. The self-centering capability criterion of EC8 (C_E) against fault distances of ground motion records (Dist.) checked out for a practical case of SSS with vertically arranged SMA wire ropes designed for a typical building, regarding the lubricated state of sliding interfaces (D_d= 0.3 m; μ= 0.02; W= 8 MN)

CONCLUSIONS

A parametric study, performed to evaluate the self-centering capability of the Shape memory alloy (SMA)-based Superelasticity-assisted Slider (SSS), was presented. Following outcomes can be stated according to the results obtained from extensive analyses:

1) Self-centering capability depends on both structural properties and ground motion characteristics.
2) The main parameter that affects the self-centering capability is the ratio D_{max}/d_{rm}, where D_{max} is the maximum seismic displacement and d_{rm} is the maximum residual displacement under which the system can be in static equilibrium.
3) D_{max} depends strongly on the details of the ground motions and decreases when the distance from rupture is increased.
4) Self-centering capability increases for seismic motions involving larger displacements.
5) SSS acceptably satisfies the main self-centering capability criterion required by Eurocode 8.

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