# KINETIC STRUCTURES IN ARCHITECTURE

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**ABSTRACT :**
In the frame of integrated architectural design, the structural building design plays a most decisive role in supporting the areas of interdisciplinary development as regards form, construction and energy efficiency of the building. In earthquake endangered areas the design of the structure includes an additional level of complexity within the integral development, for achieving from an early design stage optimized characteristics in respect to the functional requirements and the dynamic behavior of the system. The capacity design approach that leads to the development of appropriate structural areas with energy dissipative characteristics, included in most national codes for earthquake safety, serves as the basis of the designs. In extending the "classical" structural design approach for earthquake resistance, the present paper examines innovative, alternative control methods for achieving dynamic adaptable structural systems. The control concepts rely on the integration of passive damping mechanisms within the structural systems. The analysis of kinetic structures presented herein addresses primarily configuration and dynamic behavior issues of the systems and aims at promoting within the integrated architectural design approach the development of adaptable earthquake resistant structures from an early design stage. The new control systems are based on a dual function of the damper-bracing components. The bracing mechanism has a kinetic closed circuit, working only in tension. Three different bracing configurations of a frame with plastic hysteretic devices are investigated in their dynamic behavior under actual earthquakes of the Greek-Mediterranean region.

**KEYWORDS:**
DUAL SYSTEMS, HYSTERETIC DAMPERS, PASSIVE CONTROL

## 1. INTRODUCTION

In conventional seismic design, earthquake resistance is based on primary structural elements of the structure being able to absorb and dissipate energy in a stable manner for a large number of cycles. Earthquake inputs energy to specially detailed ductile plastic hinge regions of beams and column ends (capacity design). However this results in severe structural damage. The integration of damping devices into the structure with the main purpose of transforming them into mechanisms that can produce specified objective damping for avoiding damage of the primary structural elements provides a promising strategy.

A number of researchers have investigated braced frame systems with integrated shear hysteretic dampers, Symans et.al (2008). In conventionally passively controlled systems the bracing components consist of steel members, whose application under compression loads leads however to a relatively inefficient behavior of the system, since in every half-loading cycle the compression diagonal does not participate in the energy dissipation process. An alternative concept in this respect with a dual damper-cable bracing mechanism has been introduced by Phocas and Pocanschi (2003). The new control bracing system consists of a closed cable bracing mechanism with hysteretic dampers of steel plates. Since the closed control mechanism does not practically affect the initial stiffness of the system, the particular control concept relies on two completely "separate" systems: a primary for the vertical- and wind loads and a secondary for the earthquake loads.

In the present study, the dual system is developed through three different bracings configurations. The results from nonlinear time-history analyses of the idealized frame indicate its clear and so important dynamic behavior under selected earthquakes. They also clarify the role of the passive control mechanisms described in this paper, in preventing catastrophic failure, i.e. in protecting the system through managing the input energy by means of the yielding of mild structural steel. The dynamic vibration absorbers used as added damping devices are composed of a specific number of steel triangular plates that are effective in sustaining a large number of yielding reversals without any degradation. The paper examines the hysteretic energy dissipation ability of the plate-fusers placed in optimal places in the three selected configurations and compares the behavior between the bare frames, the frames with only the bracings and the frames bracings with the dampers to absorb a large proportion of the input seismic energy.

## 2. STRUCTURAL SYSTEMS

In all three static configurations of the dual system, the diagonals are fixed at the bottom of the columns and are capable to move at the top corners of the frame, through rotations of connecting eccentric discs. The bracing system forms a kinetic closed circuit, so that all braces remain at deformation state under tension. A hysteretic damper of triangular steel plates is connected between the frame and the respective bracing mechanism (Fig. 1).

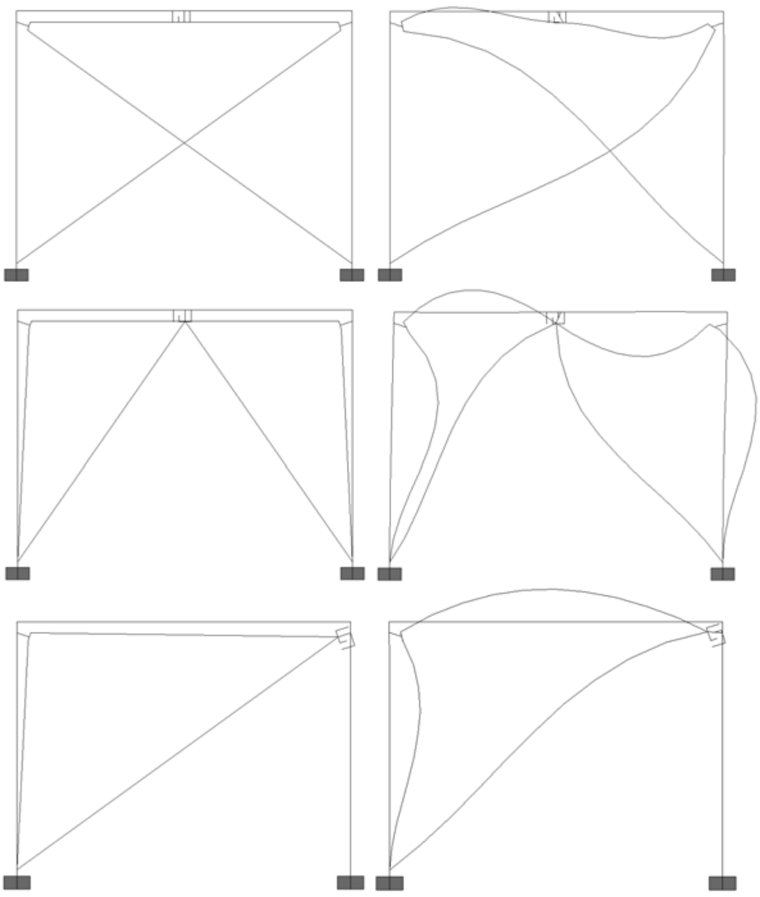


Figure 1 Static configuration and deformation of dual system 1, 2 and 3

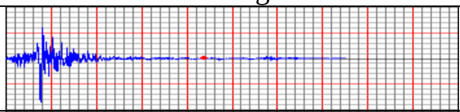
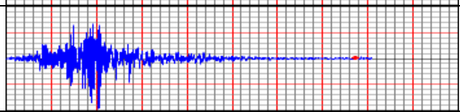
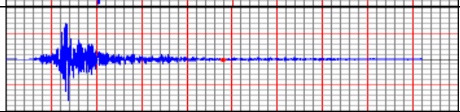
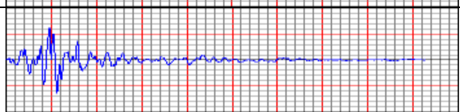
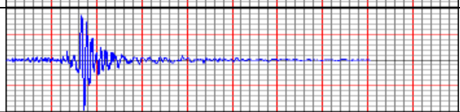
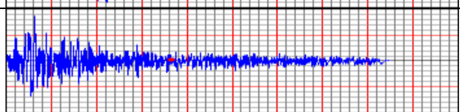
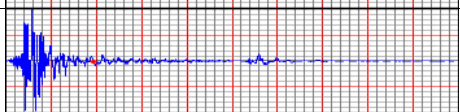
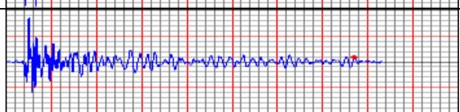
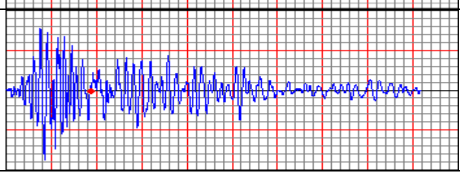
The control systems suggested, develop motion control forces at the points of attachment of the damper-bracing system. The relative motion of these points of attachment determines the amplitude and direction of the control forces. As the deformation shape indicates, bracings are tensioning during every cycle of earthquake movement, maximizing the yielding potential, compared to the possible buckling of the steel members at a lower stress, if subjected to compression. Additionally the bracing's ductility increases when the metallic dampers are supplemented at their optimal places. The steel damper utilizes the relative movement between the bracings and the frame, to yield under its shear or bending stress action, and dissipates a large proportion of the input energy.

Dimensioning of the primary beam and columns was the result of a static analysis without dynamical effect, only based on Eurocode 3 guidelines. IPBv 500 section was selected for the columns and IPBv 550 section for the beam to elastically resist a 1200 kN vertical load and a 15 kN horizontal. The frame structure height is 4.50 m and its opening 6.00 m. All the structural member connections in the static models are fixed supported preventing any rotation. Circular sections with a 25.0 mm diameter were selected for the bracings to activate the earthquake resistant mechanism. The dual system 1 has a fundamental eigenperiod of $T_1$= 0.367914, the dual system 2, of $T_2$= 0.36291 and the dual system 3, of $T_3$= 0.52895.

## 3. SEISMIC INPUTS

The structural performance of the three dual systems was examined against the ten time varying loads of actual earthquakes of the Greek-Mediterannean region, as shown in Table 3.1. Nonlinear time history structural analysis was carried out integrating SAP2000 program. Zero damping was considered for all excitations loading. As the analyses results revealed, the structural performance depends strongly on the dynamic characteristics of the seismic excitations.

Table 3.1 Seismic inputs

| Earthquake | Max Acceleration (g) | Accelerogram |
|---|---|---|
| Aigio 95 (Aigio, $0^0$) | 0.50 |  |
| Ionian 83 (Argostoli, $90^0$) | 0.24 |  |
| Athens 99 (Sepolia, $0^0$) | 0.33 |  |
| Gulf of Corinth 93 (Nafpaltos, $90^0$) | 0.10 |  |
| Aigio 90 (Aigio, $90^0$) | 0.20 |  |
| Killini 88 (Zakinthos, $90^0$) | 0.15 |  |
| Etolia 88 (Valsamata, $90^0$) | 0.18 |  |
| Kalamata 86 (Kalamata, $0^0$) | 0.22 |  |
| Heraklio 84 (Heraklio, $90^0$) | 0.21 |  |
| Preveza 81 (Preveza, $0^0$) | 0.14 |  |

## 4. ENERGY DISSIPATION

Reaction forces on the primary frame elements in dual systems are neutralized, as in each load cycle the lengthening of a diagonal bracing tension member results to the shortening of the same length magnitude of the other bracing compression member. Energy dissipation takes mainly place through the hysteresis of the steel dampers. The suggested mechanisms incorporate hysteretic devices that dissipate energy with no significant rate dependence and operate on the principles of yielding of metals. The hysteretic dampers used in the dual systems consist of triangular steel plates, installed in parallel rows, typically within the respective idealized frame bay, between the bracing configurations and the primary frame elements. The steel dampers considered in the present study differ from the rectangular ones used in Phocas and Pocanschi (2003). Due to the triangular section shape, the bending curvature produced by the transverse force applying at the end of each plate is uniform over its full height, so that all steel triangular shaped section lines reach at the same time their yielding potential. The steel dampers dissipated much of the earthquake input energy and protected the more flexible ductile configuration system, in dependence to the characteristics of the ground motion (Fig. 2).

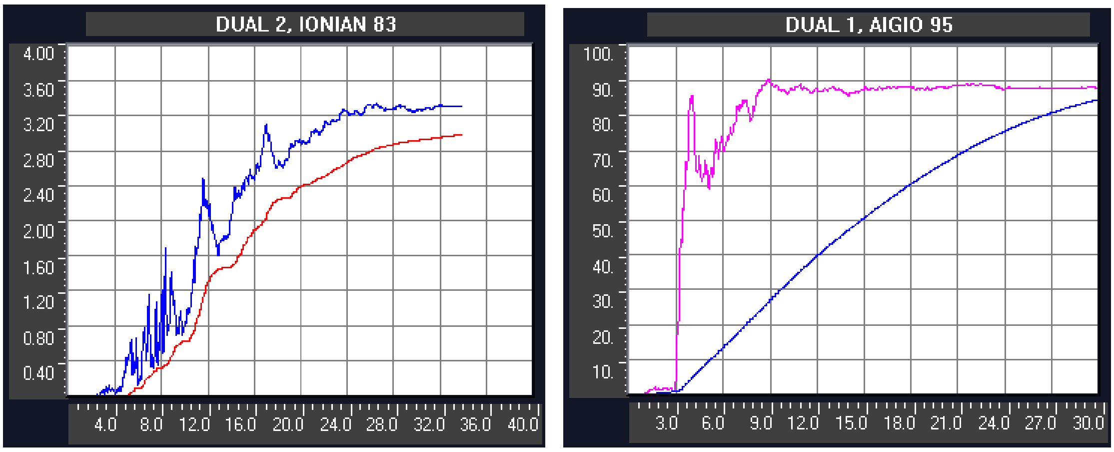



Figure 2 Energy dissipation behavior of the controlled systems according to earthquake characteristics

Defining the variables t, b and h for the thickness, width, and height of a plate section respectively, and n, for the number of damper plates, the elastic lateral stiffness of the damper is given by the following equation:

$$k_d = \frac{nEbt^3}{4h^3} \tag{4.1}$$

The plastic yield force, $P_y$, of the device is given by

$$P_y = \frac{nf_y bt^2}{6h} \tag{4.2}$$

where $f_y$ is the yield stress (S 235, E= 2.1 x $10^4$ kN/cm$^2$, $f_y$= 24 kN/cm$^2$, $\rho$ = 78.5 kN/m$^3$).

TEST 108 parameters for the triangular plates were finally selected for the analysis; h= 200 mm, b= 50 mm, t= 10.8 mm and n= 10). The dampers were modeled as link elements and their nonlinear behavior as uniaxial plasticity (Wen model), whereas their nonlinear properties assumed to follow the plastic (Wen) type in which its force-deformation relationship involves the elastic spring constant, the yield force, the specified ratio of post-yield stiffness to the elastic stiffness and an internal hysteretic variable that evolves according to a differential equation. Based on the results from the research study by Phocas and Pocanschi (2003), initial values of a stiffness factor k (damper to structure stiffness) k= 0.1062, in combination with a cable's stiffness of $k_c$= 6433 kN/m ($d_c$= 25.0 mm), were selected for the beginning of the analysis tests.

The examination of the results on the relationship between the internal shear force at the ends of the damper model and the corresponding deformation for the three dual systems concluded that the dampers hysteretic loop can be grouped into three basic categories as indicated in Fig. 3. First representative example concerns the force-displacement relationship under the Etolia 88 earthquake for the dual system 3. It describes a rigid plastic behavior. Second group of behavior is represented by the loop developed by the dual system 1 under the Killini 88 earthquake. The behavior described by the graph is similar to an elastoplastic model. Finally a third group following the Ramberg-Osgood curve was distinguished, represented by the graph involving dual system 2 under the Ionian 83 earthquake.

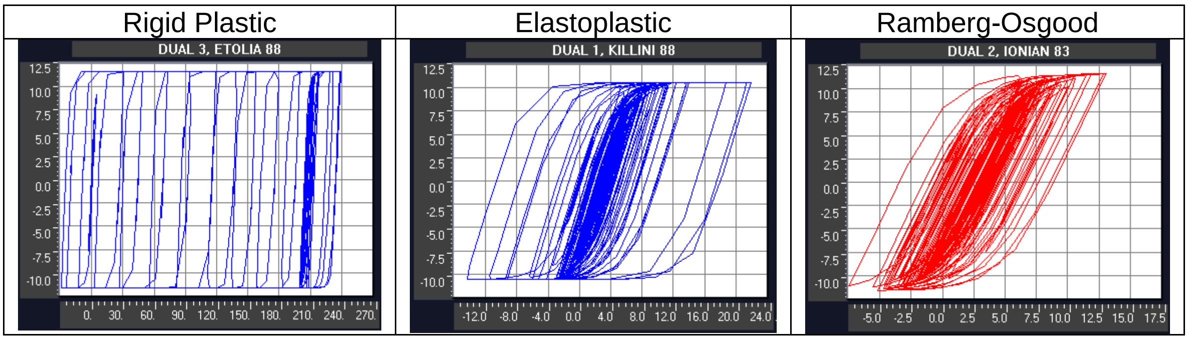



Figure 3 Basic groups of hysteretic behavior

In all cases, the dampers primarily resisted the horizontal forces through bending deformations of the individual steel plates. Beyond a certain force-level (approximately 12.5 kN), the plates yielded and thus provided a supplemental amount of energy dissipation. The shape of the plates promoted nearly uniform yielding throughout their length. The resulting inelastic force deformation curves can be easily compared with experimental conclusions from past research studies, Tsai et.al. (1993), confirming the same characteristics in output behavior. The research study assured that the basic parameters determining the hysteretic behavior of the steel dampers are the yield displacement and stiffness of the device and the stiffness of the brace, with which the device is connected. Although the selection of triangular plates for the present analysis proved to be workable, further research study is needed to succeed in a more stable hysteretic curve shape under repeated loading cycles.

## 5. DYNAMIC BEHAVIOR COMPARISONS

Triangular steel plate dampers exhibited a strong dependency on the displacement. Maximum values of the relative displacement between the roof and the base were calculated for the three dual systems and compared for the bare frame and the braced frame without the dampers, with the cases where the steel plates were attached (Fig. 4). The maximum relative displacement, $U_{max,}$, was reduced in all three systems for all ten records. Braced system 1 developed in three cases the same magnitude of $U_{max}$, whereas in the last record, $U_{max}$ was even increased. The benefit of adding the damper on the bracings was obvious. As regards braced system 2, the increase in $U_{max}$ was noticed in five cases, whereas in three cases $U_{max}$ remain in the more or less the same magnitude. The sixth case in the row was the only case where $U_{max}$ was reduced when the system was capable of absorbing the input energy within the bracings and the main frame. The graphs for dual system 3 confirm the certain reduction of maximum relative displacement magnitudes, when the dampers were supplemented. In addition, there were some cases (four for dual system 3), where the use of the bracings, increased the magnitude of $U_{max}$, compared to the bare frame. The benefit of increasing damping through the use of dampers attached to the bracings is quite obvious. Last graph in Fig. 4 presents the influence of the configuration of each dual system, on the reduction in the maximum relative displacement magnitude for the ten cases of earthquake loading. Dual 3 system performed better in 30 % of the cases, dual 2 in 20 % and dual 1 in 40 %. There was a single case (9th in the row), where compared to the dual system 1 and 2, the dual system 3 exhibited the worst reduction.

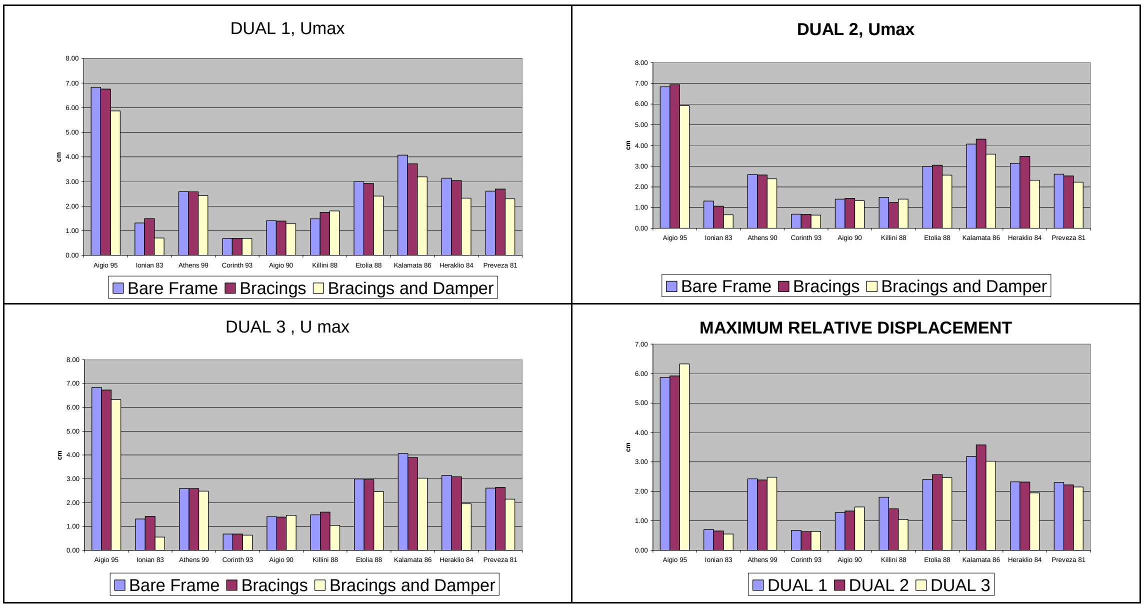



Figure 4 Relative displacements of dual systems

In all loading cases, the base shear was reduced when dampers were incorporated to form the dual systems (Fig. 5). The base shear of the braced frames was slightly reduced compared to the bare frames. Especially for the configuration characterizing dual system 2, keeping exactly the same section properties, the system with the bracings performed better in at least 50 % of the cases compared to the bare frame, but the reduction when dampers were used was remarkably effective. Last graph in Fig. 5 attempts a comparison between the three different dual configurations. In 20 % of the cases dual system 3 performed better, whereas in one case it resulted in the worst reduction compared to the other two configuration systems. Dual system 2 was clearly better in 40 % of the cases, whereas dual system 1, in 10 % of the cases.

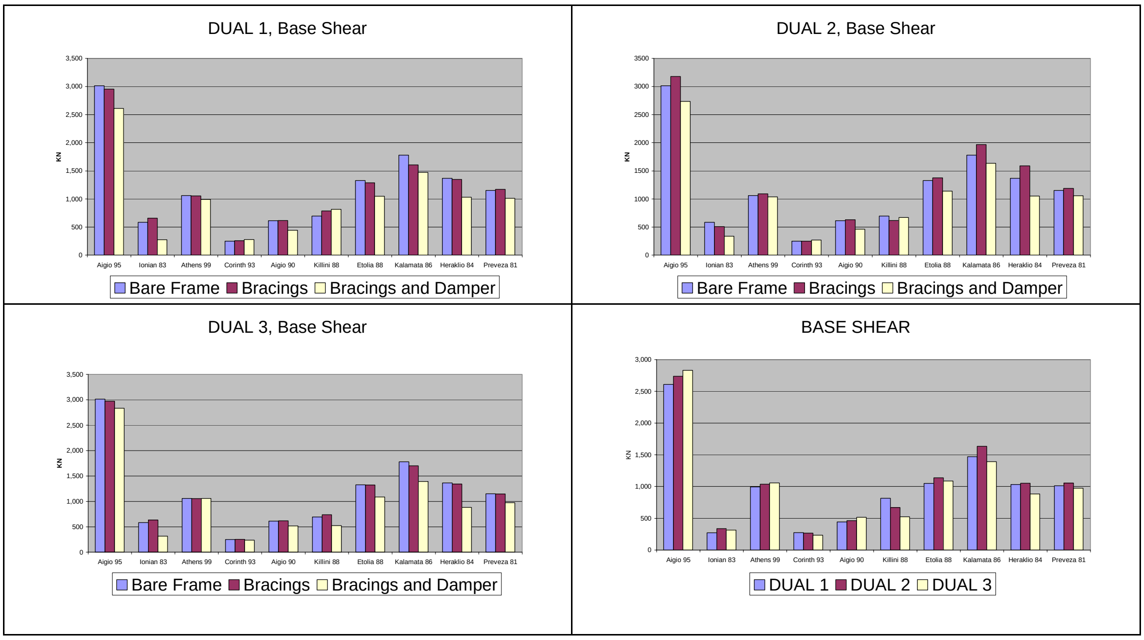



Figure 5 Base shear of dual systems

## 5. CONCLUSIONS

The present study includes the design and analysis of three dual systems with a closed damper-bracing control mechanism. The benefits of adding the control mechanism in different configurations to form the dual systems from an early design stage are presented in the study. Most important feature of the interaction-free control mechanism is that it practically enables the development of two completely "separate" structural systems: a primary for the vertical- and wind loads and a secondary for the earthquake loads. Further benefits are the reduction in both maximum relative displacement and base shear force. This effect was clearly shown for each of the three dual systems under the ten earthquake loadings. The displacement dependent damper added to the particular bracings was effective in developing satisfactory hysteretic behavior for all 30 cases under consideration (ten records for each of the three dual systems). There were a number of cases, where the portion of hysteretic energy dissipated exceeded 75 % of the input energy. In some other cases though, the dissipation through the damper hysteresis was very poor. Further studies might lead to the improvement of the devices behavior under repeated cycles of earthquake loading. The use of friction dampers instead of the hysteretic one used may result in very a similar behavior of the controlled system, since the hysteretic loop for a great number of the cases analyzed is that of a rigid plastic model. The use of velocity dependent dampers in dual systems is a future study subject, as well as the investigation of the systems behavior in respect to the earthquake characteristics.

## REFERENCES

Phocas, M.C. and Pocanschi, A. (2003). Steel frames with bracing mechanism and hysteretic dampers. *Journal of Earthquake Engineering and Structural Dynamics* **32**: 811-825

Renzi, E., Perno, S., Pantanella, S. and Ciampi, V. (2006). Design, test and analysis of a light-weight dissipative bracing system for seismic protection of structures. *Journal of Earthquake Engineering and Structural Dynamics* **36**: 519-539

Symans, M.D., Charney, F.A., Whittaker, A.S., Constantinou, M.C., Kirchner, C.A., Johnson, M.W. and McNamara R.J. (2008). Energy dissipation systems for seismic applications: Current Practice and recent developments. *Journal of Structural Engineering* **134(1)**: 3-21

Tsai, K.C., Chen, H.W., Hong, C.P. and Su, Y.F. (1993). Design of steel triangular plate energy absorbers for seismic-resistant construction. Earthquake Spectra **9(3)**: 502-528