COMPARATIVE DYNAMIC ANALYSIS OF R.C. FRAMES WITH AND WITHOUT SMA DAMPERS

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SUMMARY:
The term shape memory alloys (SMA) is applied to the group of metallic materials that demonstrate the ability to return to same previously defined shape or size when exposed to the appropriate thermal procedure.
In this paper the procedure for designing and modeling of diagonal damper made with combination of steel and shape memory alloys is given. Geometrical characteristics of damper main parts are calculated for given design parameters and for known material properties. The applicability of shape memory alloys in a system for structural control was analyzed with comparative dynamic analysis of two reinforced concrete frame structures with and without SMA braces, for a given acceleration history.
From the analyzed results can be concluded that built-in diagonal damper performed a dual role in the structure - it increases the lateral stiffness and it increases total structural damping in the case of dynamic loads.

Keywords: shape memory alloys, dampers, dynamic response

1. INTODUCTION

The term shape memory alloys (SMA) is applied to the group of metallic materials that demonstrate the ability to return to same previously defined shape or size when exposed to the appropriate thermal procedure. Main reason for this unusual thermomechanical response is martensitic transformation of the crystal structure, on the microscopic point of view. At macroscopic level, the martensitic transformation reflects with two characteristic effects: superelasticity and shape memory effect. These phenomena and unique characteristics of SMA: high damping possibilities, high recovery stress and strains, recentering capabilities, and high corrosion resistance, make this material attractive for many engineering applications, especially for application in the passive structural control systems for new and existing structures (DesRoches et al. 2004). In the recent years, many individual studies and several internationally collaborative research projects have been conducted to explore the SMA's potential for seismic protection (Janke et al. 2005), such as MANSIDE – Memory Alloys for New Seismic Isolation and Energy Dissipation Devices, and ISTECH – Shape Memory Alloy Devices for Seismic Protection of Cultural Heritage Structures. However, wider use of shape memory alloys in the field of earthquake engineering is still limited, mostly due to the high material cost and complex manufacturing process.

The development of diagonal steel damper, which will contain an element made of shape memory alloys of a certain length, can significantly reduce cost and at same time can be effective in reducing the seismic response. Such diagonal structural element composed with serial connection of a steel part with an appropriate length and cross section and part made of shape memory alloys (SMA) in the austenite phase, also with its length and cross section, will increase the lateral structural stiffness, and in the case of strong earthquake, through hysteretic damping, will dissipate a part of input seismic energy. Because it's known that amount of hysteretic damping depends of the deformations that occurs in structural elements, the question that arises is what are the optimal dimensions of the two constituent parts of such hybrid damper and how will it behave during cyclic action.

2. DEFINITION OF SMA DAMPER GEOMETRIC CHARACTERISTICS

The determination of geometric characteristics of the diagonal damper components can be done by few preliminary analysis based on the conditions for forces equilibrium and deformations compatibility, Fig. 2.1. For the required design parameters (length of the diagonal, maximal force and maximal deformation of the diagonal at a certain level of earthquake action) and for known material properties of both elements, Fig. 2.2, the geometric characteristics of main damper parts can be calculated (Todorov and Oncevska, 2007).

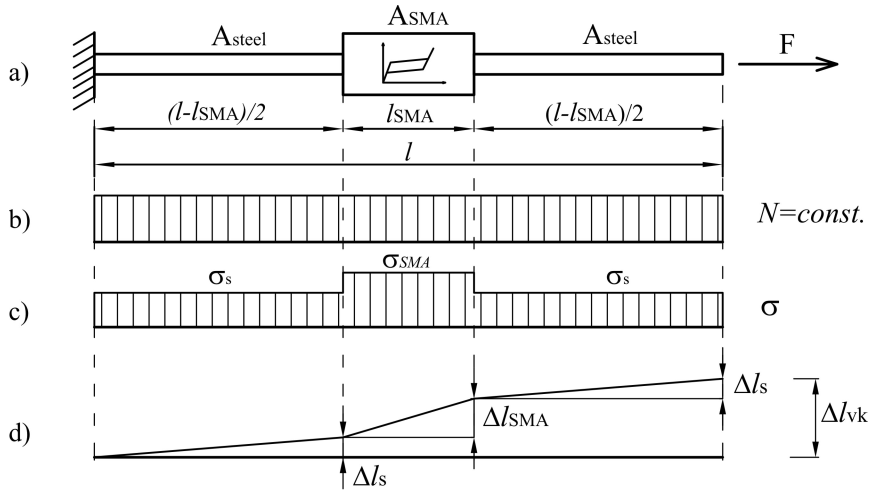

Figure 2.1. State of stress and deformation at axially loaded hybrid damper made with serial connected elements

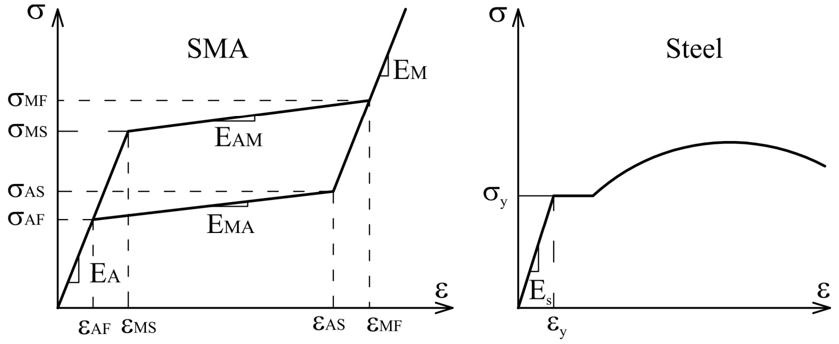

Figure 2.2. Stress strain diagrams for damper main parts

In this paper the diagonal damper geometric properties are calculated for element with total length of 5m and known material properties for the part made from shape memory alloys (modulus of elasticity in austenite and martensite phase, $E_A=E_M=60$GPa, dilatation at end of martensite transformation, $\varepsilon_{MF}=6\%$, stress at start of martensite transformation, $\sigma_{MS}=500$MPa, stress at end of martensite transformation, $\sigma_{MF}=600$MPa, stress at start of reversible transformation, $\sigma_{AS}=300$MPa and stress at end of reversible transformation, $\sigma_{AF}=200$MPa), and for the part made from mild steel with modulus of elasticity, E_{steel} =210GPa, and yield stress equal to $\sigma_y=240$MPa. Maximal elongation of diagonal at the end of martensite transformation was adopted to be $\Delta lmax_{mf}=20$mm, which is smaller than elongation of diagonal at interstory drift of 1%. Maximal force in the damper at the end of martensite transformation was restricted to Fmax=120kN. For these input parameters the following dimensions of damper main part are calculated: shape memory part with length of 32cm and cross section area of 2cm^2, and steel part with length of 468cm and cross section area of 30cm^2. Initial axial stiffness of element made with serial connection of these two main parts is equal to 30000kN/m. Axial force – deformation relationship for adopted material and geometric properties of damper main part is presented at Fig. 2.3.

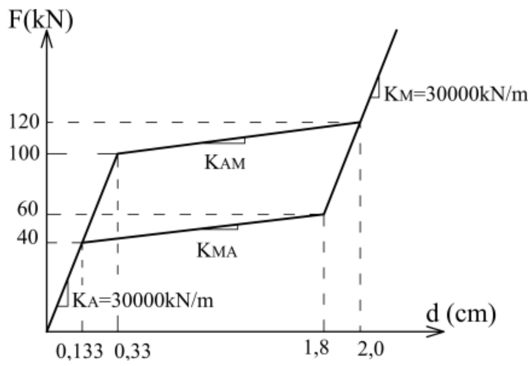

Figure 2.3. Force – deformation diagram for the designed damper

Numerical simulation of the resulting force-deformation diagram for the designed damper can be performed using specially developed hysteretic phenomenological models for simulation of the superelastic behavior of shape memory alloys (Lagoudas et al. 2001, Paiva and Savi 2006), or with the application of parallel and / or serial connection of two or more elements with well known hysteretic role of behavior.

3. APPLICATION OF EXISTING LINK ELEMENTS FOR SUPERELASTIC BEHAVIOUR MODELING

The development of finite element method, aided by the rapid development of information technology, in the last thirty years has contributed to the development of many sophisticated computer programs for analyzing of complex engineering problems. Nonlinear dynamic analysis, as one of the most complicated methods for analysis of structural systems in the structural engineering, is built in a number of three-dimensional computer programs, but material nonlinearity at the act of dynamic loads is still mostly limited to the level of line elements. Hysteretic behavior simulation in many of these programs is modeled through specially developed nonlinear line elements whose behavior is defined on the basis of known physical laws. Hysteretic complex models that are not embedded in computer code can be simulated with parallel and / or serial connection of two or more elements with known law of behavior. These elements are usually defined by two nodes with six degrees of freedom per node, where the number of required material parameters depends on the observed degree of freedom and from the type of element, i.e. material model with which it is defined.

Modeling of the hysteretic behavior of SMA damper element in this study is made by parallel connection of two link elements, multi-linear elastic link element and Wen plastic link element (Todorov, 2008). Thus, a hybrid element with complex hysteresis behavior is formed, where multi-linear elastic element has a role to raise hysteretic loop and execute recentering after unloading, while plastic Wen element has a role to form a hysteretic loop and allow dissipation of energy, Fig. 3.1. Both elements of this system, at a certain level of load, have the same deformation, and generate internal forces proportional to their stiffness. From the equilibrium condition, the total force at any moment is equal to the sum of the forces in both elements. It should be noted that this modeling approach provides an approximate simulation of the superelastic hysteresis obtained during cyclic loading and unloading in the direction of longitudinal axis of the elements.

Necessary parameters for defining the nonlinear characteristics of the two link elements can be obtained from the characteristic force – deformation diagram for SMA damper, formed on the basis of geometrical and material characteristics of both its constituent parts. The force that defines the horizontal plateau in the elastic element (point 1, Fig. 3.1) is equal to the mean of the sum of the forces that cause the beginning of martensite and end of austenite phase, $F_1 = (F_{MS}+F_{AF})/2$. Hardening during the martensite transformation can be simulated by a ratio of postelastic and elastic stiffness of Wen model. Yield force in Wen plastic element is equal to one half of the force which is defined the hysteretic loop, $F_y = (F_{MS} - F_{AF})/2$. End of martensite transformation is determined with second point of multilinear elastic element by the deformation at the end of martensite transformation, after which the element has stiffness equal to the stiffness in the martensite phase.

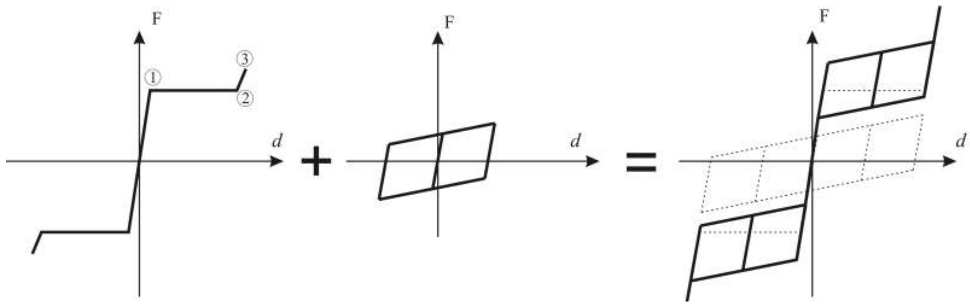

Figure 3.1. Schematic representation of the element behaviour obtained by parallel connection of linear elastic and Wen plastic model

4. COMPARATIVE DYNAMIC ANALYSIS OF FRAME WITH AND WITHOUT SMA DIAGONALS

In order to investigate the influence of the SMA diagonal dampers to the dynamic response of one structural system, a comparative dynamic analysis of reinforced concrete frame with and without SMA diagonals, for a given time history of acceleration was performed.

4.1. Description of analyzed structures

Analyzed structures are a five story three bay reinforced concrete frames with central span of 4m, and end span of 5m. Frames are designed with a total height of 15.0m. The distance between frames in transversal direction is 5m. Frame R_1, Fig. 4.1a, is pure, reinforced concrete frame, made from concrete C25/30, and reinforcement with yield stress 400 MPa. Geometrical characteristics of structural elements are calculated from the requirement in the current seismic code in our country. In order to reduce the deformation and to increase a dissipation of input seismic energy, the designed frame is enhanced with the incorporation of "X" diagonal SMA dampers in the middle span of the frame. Thus the frame structure R_2 was formed, Fig. 4.1b. For the purpose of the analysis it was adopted that all diagonals work with the same characteristics in compression and tension, i.e. the problem of buckling is neglected. For purpose of results comparison another frame R_3 is included in dynamic analysis, which has the same stiffness characteristics as frame R_2, but it was analyzed using linear dynamic analysis.

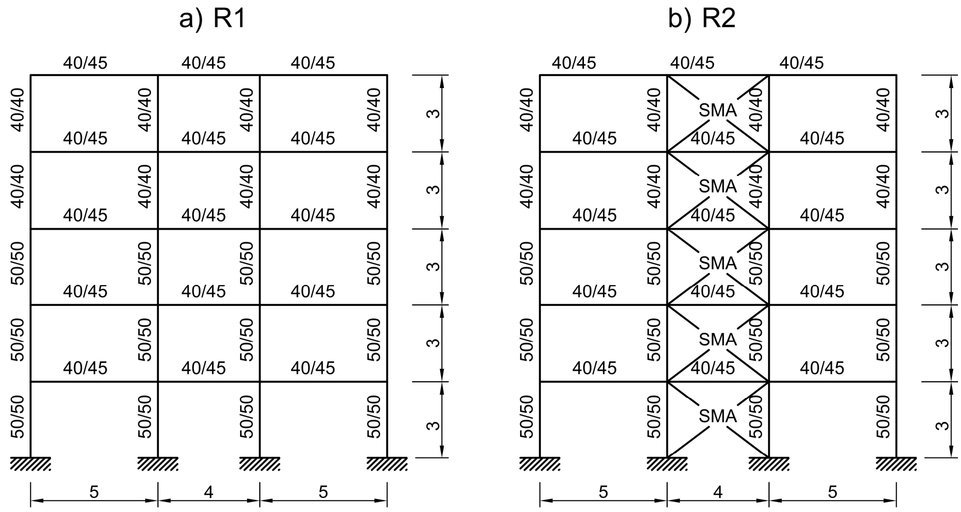

Figure 4.1. Geometric characteristics of the analyzed frames

The total mass of one floor is determinate for uniformly distributed load of 14 kN/m^2, i.e. 70 kN/m' line loads at every storey of a frame. So defined mass of 100t (70x14/9.81= 100t) is distributed on four nodes at one level of the analyzed frame, Fig. 4.2.

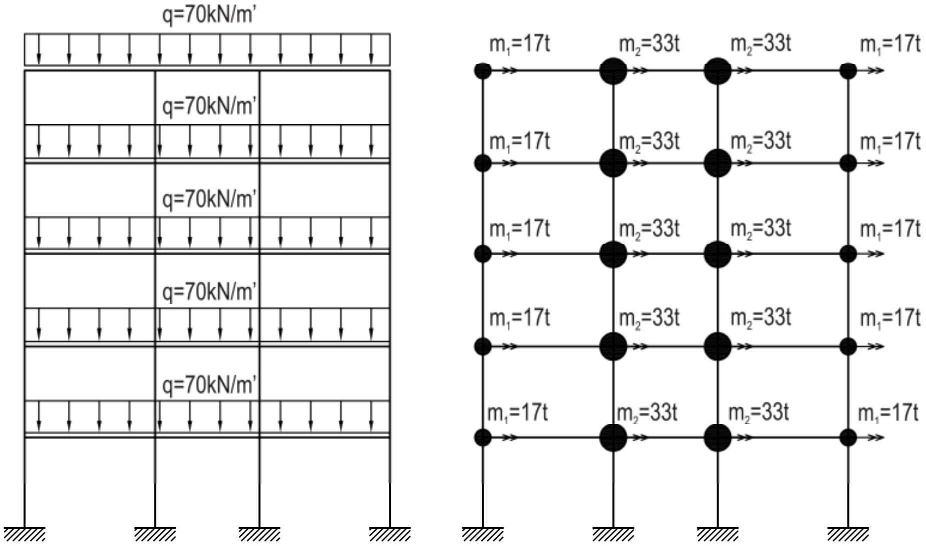

Figure 4.2. Distribution of loads and mass at the analyzed frames

A comparison of the dynamic behavior is first performed for harmonic acceleration time history at the base of structure with amplitude of 1m/sec^2 and period equal to the first period of oscillation of the considered structures, and then both structures are exposed to the acceleration time history on a real earthquake, El Centro time history with PGA = 0.313g. All analysis was performed for three different values of equivalent modal damping, 0, 2% and 5%. From the performed analysis a huge amount of data (time histories of displacements, accelerations, base reaction, force-displacement diagrams in non-linear elements, energy diagrams, etc.) are obtained, which show the behavior of analyzed structures of different scenarios of the ground motions.

4.2. Analysis of the obtained results

The presence of diagonal dampers in the frame R_2 increases the horizontal stiffness in the case of moderate earthquakes, and decreases the horizontal displacements. Results of the modal analysis indicate reduction of the first periods of the oscillations in the frame R_2 for about 19% compared with the frame R_1 (T_1 (R_1) = 0.827 sec compared with T_1 (R_2) = 0.671 sec.). A similar trend of reduction of the periods of oscillations is registered in the higher modes (T_2 (R_1/R_2) = 0.279sec. /0.225sec.; T_3 (R_1/R_2) = 0.151sec./0.127sec. etc) .

Time histories of displacement obtained by El Centro earthquake without modal damping, show that stiffer frame R_3 has larger total displacement (27cm.) compared with the more flexible frame R_1 (23cm), Fig. 4.3. These seemingly contradictory results are due to the frequency content of input earthquake which actuate the stiffer structure R_3 more unlike the more flexible R_1. Frame with SMA dampers, R_2, in this analysis shows much smaller maximal displacements on the fifth floor, which amounted to about 12 cm, i.e. about 2 times smaller than the corresponding frame R_1. This difference in obtained displacement is mainly due to variable stiffness of the frame R_2, which during the seismic action “escapes” from the dominant frequency range of the earthquake, and due to hysteretic damping which occurs in SMA dampers. From the analysis with 5% modal damping, Fig. 4.3 it is obtained that the frame R_2 has 40% smaller displacement compared with the frame R_1.

Maximal value for interstorey drifts obtained from the El Centro time history analysis without modal damping, Fig. 4.4, is 6.98cm at frame R_3, and it is 2.8 times larger compared with the interstory drift of frame R_2. In the analysis with 5% modal damping the frame R_1 has maximal interstory drift equal to

3.12cm and it is about 1.52 times larger than the corresponding frame R_2 and R_3. Relative interstory drifts of the frame R_2 are closely related with the deformations in diagonal dampers placed in the middle span of that frame. Optimal design of the geometric characteristics of the dampers constituent elements should be following the change of interstory drifts to the height of the building. Since the adoptions of the damper dimensions for all storey of the structure were chosen with the same values, force-deformation curves show a different state of deformation in dampers on separate storeys.

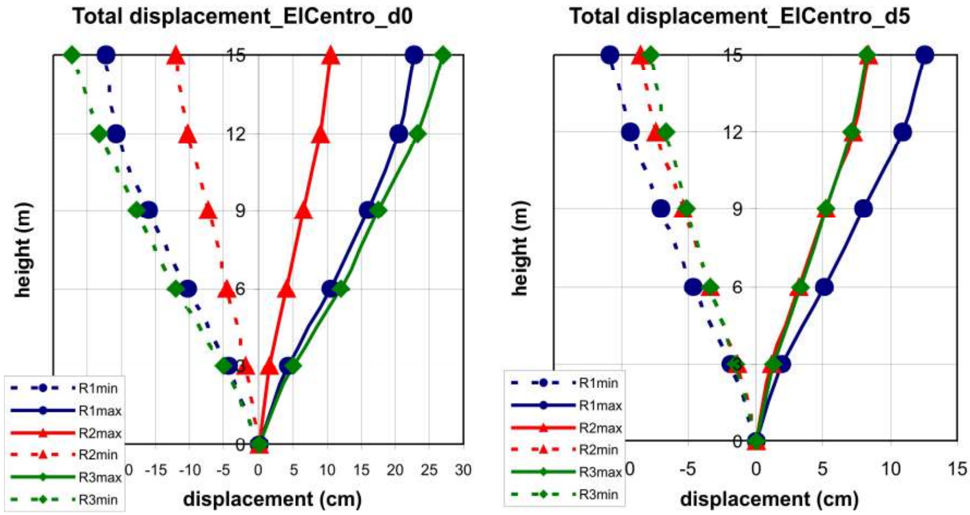

Figure 4.3. Distribution of loads and mass at the analyzed frames

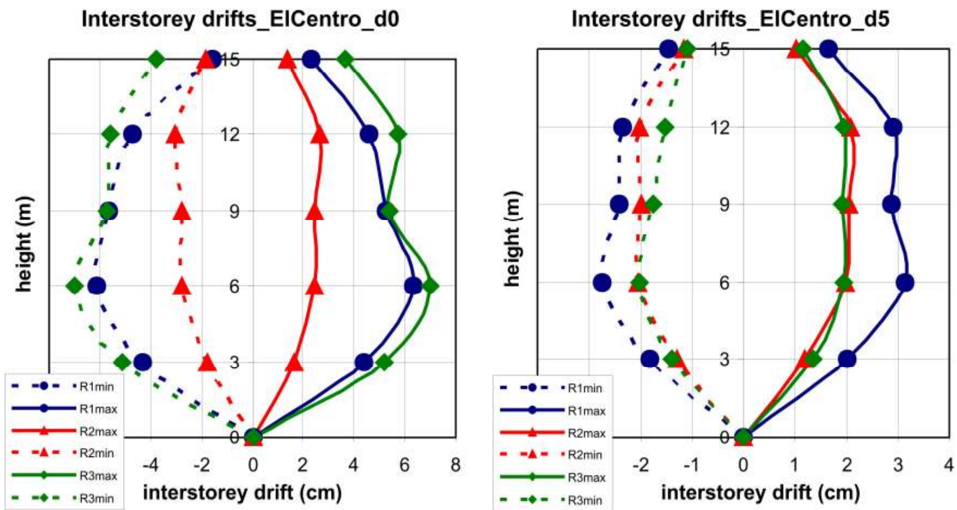

Figure 4.4. Distribution of loads and mass at the analyzed frames

Maximal deformation in the dampers occurs at the place with maximal interstory drifts, second storey of the structure in the case of periodic time history without modal damping, Fig. 4.5. A complete martensite transformation in that damper is finished, corresponding with maximal displacement of 2.35 cm, and force of 225kN. Complete martensite transformation is also finished at the dampers of third and fourth storey of the structure in the case of periodical input, and at the dampers of second, third and fourth storey in the case of the El Centro time history without modal damping. In the case of analysis with 5% modal damping, a complete martensite transformation is not finished in any damper. Maximal interstory drifts of the second, third and fourth storey are fairly uniform at about 1.5 cm, compared with the deformations of the first storey that are around 1cm, or deformations on the fifth storey equal to 0.75 cm. Force – displacement curve for the dampers at second storey in the case of time history analysis for periodical input without modal damping, and for El Centro earthquake with 5% damping are presented at the Fig. 4.5.

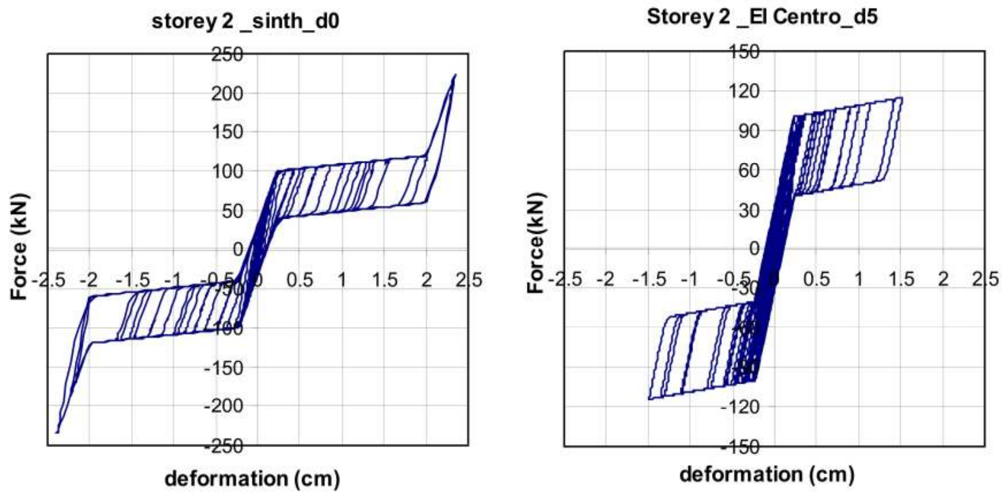

Figure 4.5 Force-deformation diagrams for the dampers at second storey of frame R_2

At the energy diagram for the frame R_2, Fig. 4.6, a participation of hysteretic damping in the total dissipated input energy can be observed. In the case of El Centro time history analysis without modal damping, total input energy is dissipated thru hysteretic damping. At the analysis with 2% modal damping, hysteretic damped energy is around 10% larger compared with the modal damped energy. A similar ratio can be observed from the energy diagram for 5% modal damping, where modal dissipated energy (224 kNm) is about 2 times larger compared with the hysteretic dissipated (113 kNm). According to these results, effective damping of designed hysteretic dampers is equivalent to 2.5% modal damping for analyzed structure.

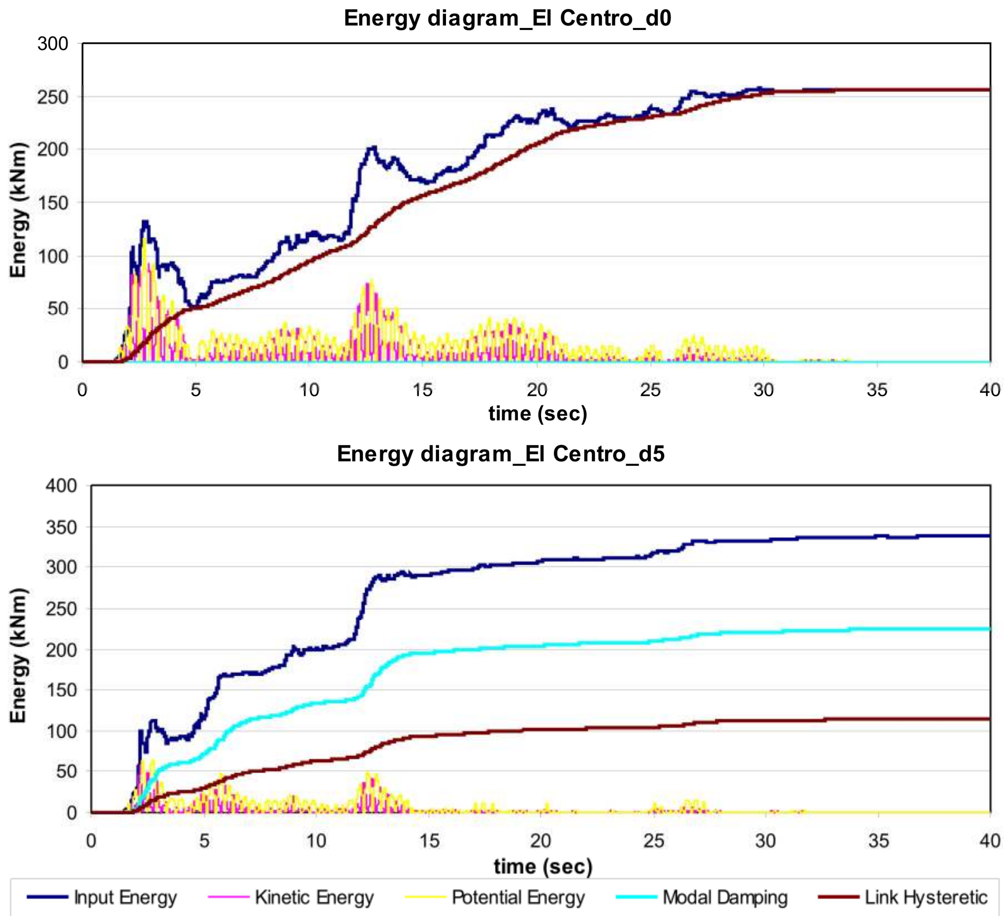

Figure 4.6 Energy diagrams for El Centro time history analysis with 0 and 5% modal damping

5. CONCLUSON

From the analyzed results it can be concluded that built-in diagonal damper performed a dual role in the structure, it increases the structural stiffness for lateral loads and increases total structural damping in the case of dynamic loads. From the diagrams of energy balance it can be concluded that effect of hysteretic damped energy is equal to energy damped with 2.5% of equivalent modal damping for analyzed structure. With proper design of the geometric characteristics of its constituent parts, diagonal damper can provide linear structural behavior with stiffness in the austenite phase at the act of minor earthquake, nonlinear hysteretic behavior with variable stiffness at action of moderate earthquakes and hardening with stiffness in martensite phase and control of interstory drifts, in the case of strong earthquakes. With its non-linear superelastic behavior, SMA-dampers change the dynamic characteristics of structure allowing shifts from the dominant frequency range of exposed earthquake.

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