DEVELOPMENT AND APPLICATION OF PASSIVE STRUCTURAL CONTROL SYSTEMS IN THE MODERATE-SEISMICITY MEDITERRANEAN AREA: THE CASE OF SPAIN.

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ABSTRACT :

Considerable attention has been paid in recent years to research and development of passive control devices for both new and existing buildings. Most research effort has been carried out in high seismicity countries such as Japan, USA and New Zealand, where these devices have been increasingly used during the last decade. However, with regard to low-to-moderate seismicity regions such as the Mediterranean area, passive systems are still rarely applied (with some exceptions like Italy). This paper presents a brief overview of the application of passive structural control systems in the moderate-seismicity Mediterranean area, and the work carried out by the author to introduce this technology in Spain. The results of several tests on reinforced concrete wide beam-column subassemblages, and waffle flat-plate structures equipped with a particular brace-type hysteretic damper consisting of steel plates with slits are summarized. Furthermore, information is provided about the first application in Spain of hysteretic dampers to a new building for seismic protection.

KEYWORDS: energy dissipators, passive control, Mediterranean area, slit plate.

1. INTRODUCTION

For several decades, the loading effect of an earthquake was characterized by a set of horizontal forces which were obtained by multiplying the weight of the building by a shear force coefficient. The seismic design consisted merely of providing the structure with the strength required to resist such forces (strength-based elastic methods). However, the experience of past quake disasters and overall progress in seismic engineering made it clear that the forces induced by a severe earthquake in terms of an elastic response can be extraordinarily large, and providing the structure with sufficient strength to sustain such a demand is not feasible for economic reasons. Current seismic codes allow us to design conventional structures below the calculated elastic force levels, provided that the structure can deform inelastically without a significant loss of strength (i.e. without collapse). The importance of providing structures with plastic deformation capacity is now recognized as a key factor for achieving seismic safety at a reasonable economic cost. However, allowing for plastic deformations implies accepting damage.

The product of strength and plastic deformation capacity constitutes the plastic strain energy; thus lending the structure the required (and balanced) amount of both strength and plastic deformation capability means giving the structure enough energy dissipation capacity. Characterizing the seismic resistance in terms of energy dissipation capacity is the basis of the so-called energy-based seismic design approach, which is gaining extensive attention since the earliest works by Takanashi (1956), Housner (1956), Berg and Thomaides (1960), Kato and Akiyama (1975), or Housner and Jennings (1977), etc. Later, Akiyama (1985) showed that the energy input exerted by an earthquake on the structure is a very stable quantity, mainly dependent on the total mass and the fundamental natural period of the construction. For the structure to survive an earthquake, ultimate energy dissipation capacity must be larger than the portion of the total energy input by the earthquake that is not dissipated by the inherent damping mechanism.

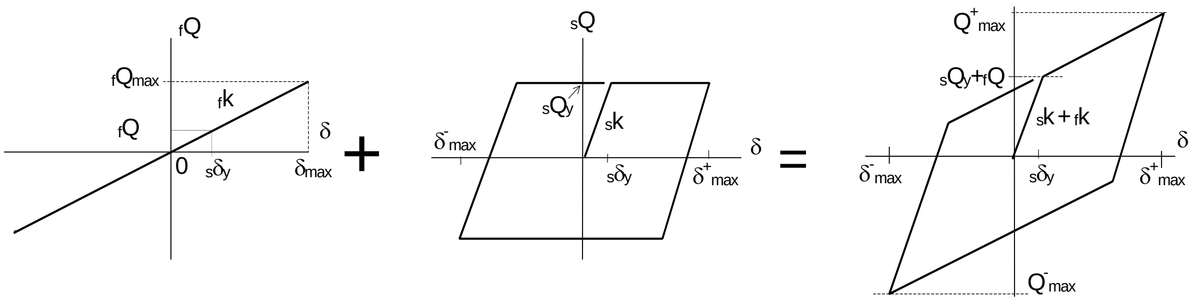
In the prevailing conventional seismic design practice, the energy absorption capacity of the structure relies on the plastic deformation ability of structural components, such as beams and columns in the case of frame structures. When the energy input by the earthquake is absorbed by inelastic deformations at beam and/or column ends, important damage must be expected in the primary structural members, which translates into property loss, the need for substantial repairs or even demolition after the earthquake. The advances in earthquake engineering and the huge damage caused by recent earthquakes, as in Northridge (US, 1994) or Hyogo-ken Nanbu (Japan, 1995), have unveiled important disadvantages of this conventional seismic design approach: (1) the structural damage is difficult to inspect and evaluate, (2) repairing the structure is very expensive; (3) the energy dissipation capacity of beams, columns, beam-column connections, etc., can be dramatically reduced by factors such as stress concentration in the case of steel structures; (4) designing beams and columns for sustaining gravitational loads and simultaneously dissipating energy reduces the flexibility of the design and hinders its optimization; and (5) strengthening the structure in order to reduce structural damage can increase the acceleration response of the building, resulting in the overturning of equipment and important non-structural damage.

A preferable alternative to the aforementioned conventional seismic design approach exists, which consists of applying the concept known as “flexible-stiff mixed structures” (FSMS) (Akiyama, 1985). The FSMS are composed of two parts working in parallel as illustrated in Fig. 1. One is the elastic part (flexible part) that supports the gravity loading, which must be provided with low rigidity as well as strength great enough to remain essentially elastic under the severest earthquake. The other is the elastic-plastic part (stiff part) that dissipates the input seismic energy, and which must be provided with high rigidity, relatively low strength and large plastic deformation capacity (i.e. large energy dissipation capacity). The FSMS exhibit optimum response characteristics (Akiyama, 1998): the seismic energy input is initially stored in the “elastic part” in the form of elastic vibration energy, and then transferred to the “stiff part”, where it is finally dissipated. Numerous non-linear dynamic response analyses and tests have proven the advantages of this type of structure: (1) the damage (plastic deformation) is concentrated in the “stiff part” which can be designed to be easily repaired; (2) the cumulative plastic deformations in positive and negative domains are nearly equal, meaning the residual deformation after the earthquake can be reduced considerably; (3) the maximum deformations in the positive and negative loading domains are nearly equal; and finally, (4) the efficiency of energy dissipation with respect to maximum deformation is high. In a real structure, the concept of the “stiff part” of an FSMS is materialized in the form of a passive energy dissipation system (PEDS). The PEDS is defined here as the set of special elements or devices installed in the structure, commonly called energy dissipators (ED), in charge of absorbing the bulk of the energy input by the earthquake. Seeing the PEDS as a part of the more general FSMS concept provides a broader and better understanding of their possibilities for attaining enhanced performance in existing or new structures. Figure 2 shows a materialization of the concept of the FSMS in the context of reinforced concrete frames.

Much work has been accomplished over recent decades to provide structures with special elements (i.e. ED) that are “disposable” (i.e. structural “fuses” that can be easily replaced without disturbance of the main system) and that possess high energy dissipation properties. Viscous and hysteretic dampers have been used, in the last two decades, in North America and Japan as energy dissipation devices in the design of new buildings and for seismically upgrading existing structures. More recently, viscous and hysteretic dampers have been increasingly used in Europe, mainly for seismic retrofitting purposes. One of the early applications in the Mediterranean area was the seismic retrofit of an reinforced concrete framed school in Italy that was damaged by the 1997 Umbria-Marche earthquake. This paper focuses on the use of hysteretic and viscous/viscoelastic dampers for seismic applications in building structures located in countries of the moderate-seismicity Mediterranean area, and particularly in Spain. Other structures where the PEDS are equally important such as bridges and viaducts, or the structures with seismic isolation are not included for the sake of brevity.

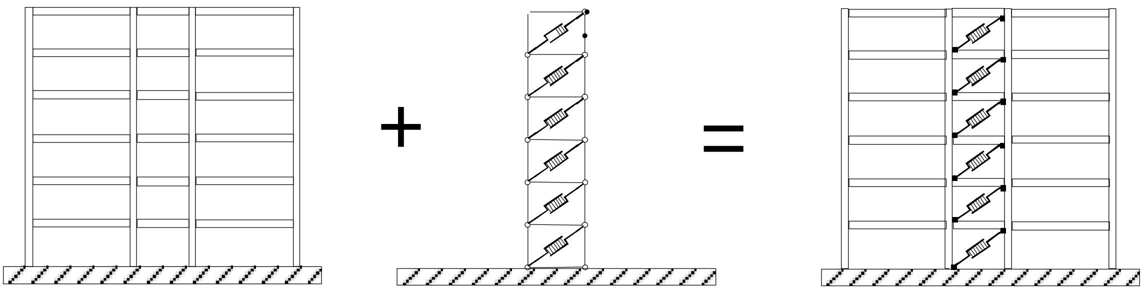
2. SEISMICITY AND CONCERNS IN THE MEDITERRANEAN AREA

Several countries of the Mediterranean region such as Italy, Spain or Greece are located within a medium-to-high seismicity area, where the peak ground acceleration (PGA) ranges approximately from 1.3 to 4 m/s^2. In this region in particular, social and economic development after World War II led to the construction of many buildings and civil structures as a result of the huge economic growth of the early 50´s, 60´s and 70´s. Many of these structures were designed without seismic criteria, or applying earlier seismic codes which used purely strength-based elastic methods and paid no attention to the plastic deformation capacity of the structure.



a) Flexible part b) Rigid part c) Mixed structure

Fig. 1: Concept of the flexible-stiff mixed structures.



FLEXIBLE PART (RC frame) STIFF PART (Passive energy dissipation system) MIXED STRUCTURE (Overall structure)

Fig. 2: Materialization of the concept of a flexible-stiff mixed structure.

In the case of Spain, the first “modern” seismic code that included ductility requirements and capacity design considerations appeared in the late 90´s. Of special concern are the reinforced concrete structures, particularly those with wide beam-column connections and waffle flat-plates, or masonry buildings. The safety of these structures in the event of a severe earthquake is a matter of serious concern. The recent European Code Standard for structures in seismic zones Eurocode 8 (CEN, 2003) deals with specific aspects such as analytical methods and strengthening techniques. Also concerned with this matter is the recent Italian Seismic Code enforced in 2003 through Ordinance Nr. 3274/2003 of the Prime Minister. Using passive energy dissipation systems for the seismic upgrading of existing structures is a very promising solution that is receiving increased attention, particularly in Europe. PEDS are also economically feasible in the design of new structures located in moderate seismicity regions such as the Mediterranean area, because the increase in cost in comparison with conventional structural configurations is relatively minor (especially in the case of using hysteretic dampers), and is compensated by a drastic enhancement of the seismic performance of the structure.

3. APPLICATIONS OF PASSIVE SYSTEMS IN ITALY, GREECE, TURKEY AND CYPRUS

This section succinctly summarizes the applications of PEDS in Italy, Greece, Turkey and Cyprus. Other countries such as France are not included here for the sake of brevity, and because their seismicity is in general lower. France, however, was one of the first countries to develop and apply the base seismic isolation technique. The information sources used, aside from the literature, include the proceedings of the recent 10th World Conference on Seismic Isolation, Energy Dissipation and Active Vibrations Control of Structures and data collected by the author. In general, it should be noted that the number of applications of PEDS in the Mediterranean region is far below countries such as Japan, currently the worldwide leader, followed by the Russian Federation, China or the US. The reasons behind this delay in Europe are the lack of updated design rules and the excessive cumbersomeness of the already existing ones. Such difficulties have been assuaged in recent years in some countries like Italy.

3.1. Italy
Within the Mediterranean region, Italy is at present the leading country in the use of PEDSs for seismic applications. One of the reasons is the existence of a new national seismic code, enforced in May 2003, which frees and simplifies the adoption of these innovative techniques. The new code was mostly a consequence of the tragedy of the San Giuliano di Puglia, during the Molise and Puglia earthquake of October 2002. Worldwide, Italy is also a leading country in the use of a particular kind of PEDS called the shape memory alloy device (SMAD), and fifth in the number of buildings protected with seismic isolation that are already open to activity (Martelli et al., 2007). The number of applications is increasing steadily to existing buildings, new buildings and the cultural heritage. By May of 2007, besides the structures with seismic isolation, Italy had 19 building structures protected with ED or SMAD, and 28 protected with shock transmitters (ST). The applications concern not only strategic and public buildings, including hospitals, emergency management centers and schools, but also dwelling buildings and those of the cultural heritage. Some examples of application are: (1) the new building of the Polytechnical University of Marche at Ancona, which is protected with 86 buckling restrained braces; (2) the seismic retrofit of the Sanctuary Madonna delle Lacrime at Syracuse, which is a dome that was uplifted to insert elastic-plastic dampers; (3) the bell tower of Badia Fiorentina in Florence, which was seismic-retrofitted with eighteen SMDA inserted in series to the ties; (4) the Dome of Siena where viscoelastic dampers were installed to avoid the overturning of the façade. A detailed description of these structures can be found in Martelli et al. (2007).

3.2. Greece
The number of applications of energy dissipation devices in Greece is still very limited. Base isolation systems have been applied to a pair of LNG tanks and two buildings are currently under construction (Acropolis museum in Athens, and the Onasis House of Letters and Arts). The application of PEDS in the roof of a basketball stadium has been also reported. A detailed description can be found in Anagnostopoulos (2007).

3.3. Turkey
Energy dissipation devices have been used fairly recently in building structures, but only combined with rubber bearings to form structures with seismic isolation. These buildings include an airport terminal, several buildings and hospitals. A detailed description of these structures by Erdik and Mungan (2007) can be found in the references.

3.4. Cyprus
Besides three base-isolated buildings, only one multi-storey reinforced concrete construction (the Cyprus Sport Organization) is reported to include a PEDS consisting of steel braces and viscous dampers.

4. DEVELOPMENT OF PASSIVE ENERGY DISSIPATION SYSTEMS IN SPAIN

As indicated at the beginning, a main concern in the event of a severe earthquake in the moderate-seismicity Mediterranean region is posed by structures designed without seismic criteria, or under the application of earlier seismic codes. Particularly in Spain, most buildings constructed during the 60´s, 70´s, 80´s and 90´s were designed using strength-based elastic methods, and their plastic deformation capacity is very limited. Of special concern are the reinforced concrete frames with wide beam-column connections and the waffle flat-plate structures. Both types of structural systems largely populate the existing building stock in Spain, and past research has shown their deficient seismic behavior (Benavent-Climent, 2007). In recent years, research efforts have been made in Spain to seismically upgrade this type of structure by using PEDS. One proposed solution consists of installing brace-type hysteretic dampers (Benavent-Climent, 1998), whose energy dissipation source resides in the plastic deformation of steel plates with slits. Figure 3 shows the damper and Fig. 4 one solution for installing the dampers in an existing structure. In following paragraphs the results of past and ongoing experimental investigations are briefly summarized.

4.1. Seismic upgrading of existing RC frames with wide beam-column connections using brace-type dampers
In the context of a research project funded by the European Union, dynamic shaking table tests were carried out to investigate the influence of the hysteretic dampers in the seismic response of wide beam-column connections. The set up of the tests is shown in Fig. 5. The dampers reduced the maximum interstorey drifts by 60-80%, and increased the ultimate energy dissipation capacity of the exterior and interior connections by 12 and 4 times,

respectively. The RC elements of the connections equipped with brace dampers remained in nearly elastic conditions (i.e., with minor damage) until one of the brace dampers failed. A detailed description of the results can be found in Benavent-Climent (2006).

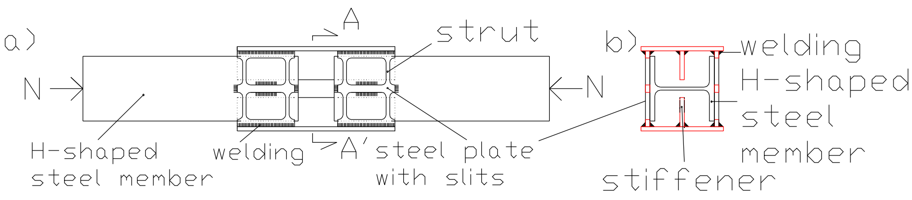


Fig. 3: Brace-type hysteretic damper: (a) elevation; (b) section

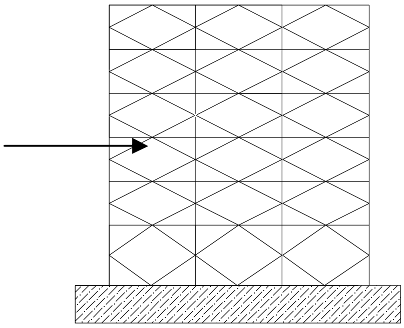


Fig. 4: Installation of brace-type hysteretic dampers in existing structures

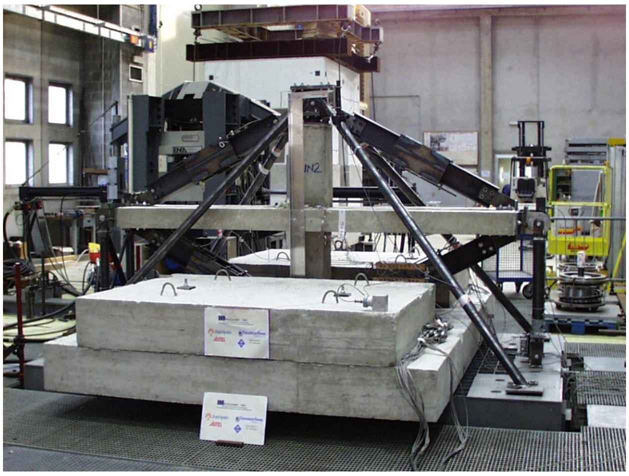


Fig. 5: Tests on wide beam-column connections

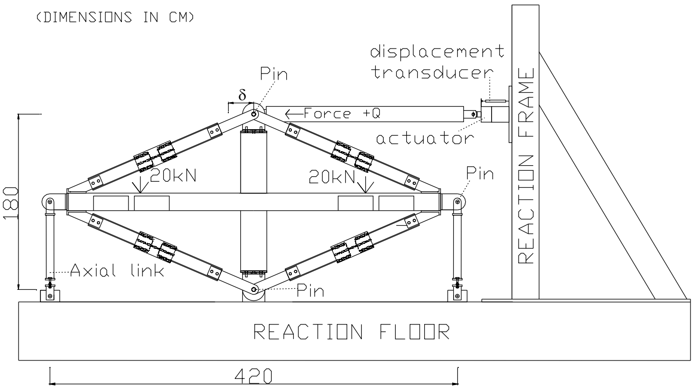


Fig. 6: Tests on waffle flat-plate connections with dampers

4.2. Seismic upgrading of existing RC waffle flat-plate-column connections using brace-type dampers

The use of the brace-type hysteretic damper of Fig. 3 was also investigated for seismic upgrading waffle flat-plate structures. Several specimens were tested under static cyclic loads. The set-up is shown in Fig. 6. The dampers increased the initial lateral stiffness of the connection by approximately three times, the lateral strength by about two times, and the ultimate energy dissipation capacity of the connection by about three and a half times. A detailed description of the results can be found in Benavent-Climent et al. (2008).

5. APPLICATIONS OF PASSIVE ENERGY DISSIPATION SYSTEMS IN SPAIN

Although energy dissipators (mostly viscous dampers) have been used in Spain for the control of vibrations caused by traffic in bridges and hospitals, currently there is only one realization of PEDS for seismic protection. This application is the new building of the Official College of Architects in Granada, just recently finished. Several reasons can be found for explaining this gap between Spain and Italy in the use of these innovative technologies. The first reason is that the current Spanish seismic code applicable to buildings (NCSE, 2002) lacks any guidelines or design method that might enhance the use of the PEDS. No reference is even explicitly made to this innovative technology. The second reason is that seismic design is required only in a quite limited area of the country, located in the south, and the seismicity in Italy is higher than in Spain. A third reason is the lack of severe earthquakes in Spain over the last 100 years or so; an actual seismic event could unveil the disadvantages of the conventional structural configurations, and urge the pursuit of innovative solutions. Certain changes effected recently are on the right track, however. First, the new Spanish seismic code applicable to bridges (NCSP, 2006) makes explicit mention of the possibility and the advantages of using PEDS, although neither guidelines nor design rules are provided. Second, in the past few years, local and central authorities have been generously funding research projects aimed at developing and using energy dissipators for the seismic protection of existing and new buildings. Below we offer a brief description of the first, and only, application of PEDS in Spain.

4.1. Building description

The Official College of Architects is a professional organization that groups the architects working in the region of Granada. The old headquarters was recently extended by adding a new building of about 2000m^2. The architectural design was made by two Spanish architects, Rafael Soler and Francisco Martínez, and the author of this paper carried out the structural design. The building has five levels, three above and two below the ground. The structure is basically a reinforced concrete frame with beams spanning 7.5m in the main direction, and one way joist slabs spanning perpendicularly. The roof is a light steel truss. Energy dissipation devices consisting of steel plates with slits were installed in each floor and in both directions as shown in Fig. 3. The section of the structure is shown in Fig. 4, while Fig. 5 shows a photograph of the dampers. In order to materialize the concept of the FSMS explained in the Introduction section, the columns were intentionally made slender and were heavily reinforced in order to enhance their flexibility and lateral strength. In contrast, the substructure formed by the energy dissipating devices and the auxiliary RC walls that connect the dampers to the frame were made intentionally stiff.

4.2. Earthquake loading

According to the current Spanish code for earthquake resistant design NCSE (2002), the peak ground acceleration (PGA) of the design earthquake for regular buildings in stiff soil located within Granada is 0.23g (g being the gravity acceleration). This acceleration was used to scale a design energy input spectra proposed by the author (Benavent-Climent et al., 2002) that provided the maximum amount of energy that the design earthquake is expected to introduce in the structure.

4.3. Design method and criteria

The structure was designed by applying energy-based seismic design methods (Akiyama, 1985; Akiyama, 1999). Under the design earthquake, the following two conditions were imposed: (a) the inter-storey drift could not exceed the elastic deformation capacity of the frame; and (b) the hysteretic dampers had to be able to dissipate the input energy exerted by the earthquake that was not absorbed by the inherent damping mechanism of the structure.

6. CONCLUSIONS

An overview of the current status of application of passive energy dissipation systems to building structures in the moderate seismicity Mediterranean area has been described. At present, Italy is by far the leading country in the development and application of such systems in Europe. The works carried out by the author to introduce this technology in Spain are briefly reported, and finally, information is provided about the first application in Spain of hysteretic dampers to a new building for seismic protection.

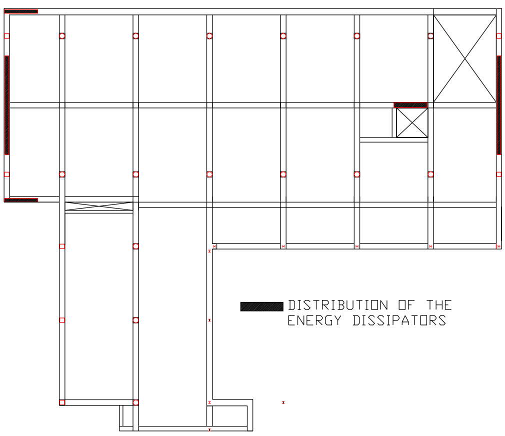


Fig. 3: Plan and position of dampers

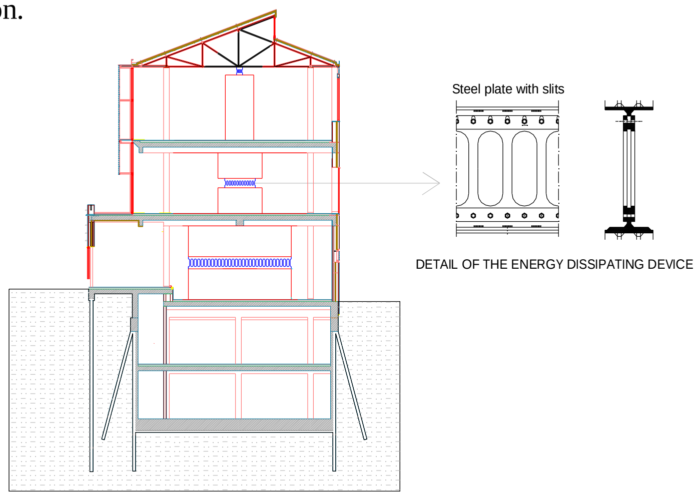


Fig. 4: Section of the structure and location of dampers

Fig. 5: Photograph of the energy dissipating devices in the first storey.

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