



Trends in research and design of structures with seismic protection systems

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Abstract

This article describes some of the new trends observed in research and design of structures equipped with seismic protection systems (SPS). This field of earthquake engineering has almost 40 years of formal development and techniques have gained increasing acceptance through time in design practice, especially due to the successful performance of these structures during the severe ground shaking of recent earthquakes. The time window considered in this investigation of the field is 10 years, defined mainly by trends observed after the important cluster of severe earthquakes starting with Sumatra in 2004, Haiti and Chile in 2010, and Japan and New Zealand in 2011. A brief overview of the research done in the field around the world is presented first to provide a general context to the reader, and also identify possible trends in research and practice that could lead the future development of the field. The article then highlights some results and applications derived from current research in earthquake behavior and seismic protection of buildings in Chile, followed by an overview of the design methodologies available in the literature. Furthermore, some details and results are provided for a robust design procedure that has been used to design a number of buildings equipped with SPS technologies in Chile. And finally, a list of the Chilean structures known up to now to be equipped with seismic protection was generated as future reference for the local development of the field.

Keywords: seismic protection, state of the art, seismic isolation, energy dissipation, structural control

1 Introduction

Structural and nonstructural damage is intrinsic to the current earthquake design philosophy of conventional structures when subjected to moderate and severe earthquake motions. The total cost worldwide attributed to earthquakes in the last 10 years amounts to about 220 billion dollars [1]. In Chile, the Superintendence of Values and Securities (SVS) in a report ([2]) estimated damage in the last Chilean earthquake in 2010 in about US\$ 30 billion, or an equivalent annual cost of 18% of the country's GDP. Some other simpler estimates show that average annual earthquake damage in the last 50 years in Chile goes easily above a billion dollars per year, i.e., of the order of half of a point of the national GDP. The normalization with GDP is important since as the country develops, the value exposed to earthquake damage also increases.

Although structural and infrastructure damage have important societal and environmental consequences, as critical as this damage is the loss of function of structures. Unfortunately, preserving functionality during a severe earthquake is difficult in general if the system has been designed by conventional building codes that are intended to dissipate the vibration energy by plastic deformation of the structural members, i.e. through damage. Seismic protection systems are used to tackle this problem by providing structures with supplemental devices that substantially reduce or avoid damage depending on the chosen solution. The design goal is to guarantee continuous functionality in earthquake loading cases a conventional structure does not.

Several previous studies have assessed states-of-the-art and states-of-the-practice in the use of seismic protection systems in civil structures. An comprehensive review of seismic protection systems was presented earlier by Housner et al. [3]. This review linked structural control with other fields of control theory, and suggested future high-priority research topics on the field. Some of these topics were: (1) devices and algorithms for passive, active, semi-active, and hybrid control of nonlinear systems; (2) development of innovative, high-performance, and intelligent material systems; and (3) near-field strong earthquake ground motion issues impacting structural control applications. Another similar state-of-the-art on seismic protection systems presented a brief historical outline of the technologies and highlighted their advantages and limitations [4]. A more recent work summarized the current practice and recent development of passive energy dissipation systems [5], and discussed the current code-based approach used to analyze and design structures that incorporate these systems. Other more specific state-of-the-art reviews are available in the extensive literature on the field, and are dedicated to specific seismic protection systems such as semi-active control [6], seismic isolation [7], shape memory alloy devices [8], and piezoelectric materials [9].

The field of seismic protection technology has over 40 years of development, and it would be impossible to achieve an insightful overview within the space limitations of this article. Consequently, the strategy followed herein is to concentrate in the developments of the last 10 years, motivated in part by the cluster of important earthquakes that have occurred along the Pacific Rim since the Sumatra earthquake in December 2004. Because of the several manuscripts that have addressed in depth the state-of-the-art in this field, our goal is to complement such work with some of the newer ideas contained in more recent publications.

The reader is probably familiarized with the customary classification of SPS into three categories depending on their requirement of external power: (1) passive, (2) semi-active, and (3) active. In turn, passive seismic protection systems are classified into: (i) seismic isolation systems, which filter out the high frequencies of the input and damp out the motions by usually placing an interface with low lateral stiffness and high internal damping between a super and substructure; and (ii) energy dissipation, which transforms and dissipates the vibration energy of a structure into heat (e.g., friction

dampers) or plastic deformation (e.g., metallic dampers). One special class of energy dissipators are tuned mass dampers (TMDs), which are inertial dampers connected to a single point of a structure and usually synchronized with one of the natural frequencies of the structure. TMDs can also be interpreted as a structural element (dissipator), which is an important dynamic amplifier of internal damping.

On the other hand, practical applications of semi-active systems are becoming more common today. These systems have the capacity to adapt to the changing conditions of the motion in the structure by continuously modifying their own mechanical behavior based on some feedback signal. They need very low external power supply to work, but require some feedback signal to feed into a control algorithm, which in turn generates the control signal that modifies the constitutive behavior of the passive device. One can conceptually understand them as a large collection of passive dampers from which the structure can choose the most convenient one at each instant of time. Furthermore, the combination of a passive and active system is known as a hybrid system [10]. Because forces (and power requirements) are extraordinarily large in active systems, the direct use of active control in structures has been very limited.

Elastomeric, lead-plug, high-damping, and sliding bearings are the most frequently used devices. Rubber isolators with steel plates were first implemented in a school in Macedonia in 1969 [11], and lead-plug rubber isolators in New Zealand in the late 1970s [12, 13]. Later, high damping rubber bearings (HDRB) appeared and used different compounds to increase the internal damping ratio to the 10-20% range at 100% shear strain [10]. These HD materials were first produced in 1982 by the Malaysian Rubber Producers' Research Association in the UK [14], and their first implementation occurred in 1985 for the Foothill Communities Law and Justice Center in California [15]. Sliding bearings, which basically use friction between surfaces to resist lateral loads, are also widely used nowadays. The best known of these devices is the friction pendulum system (FPS), developed and tested in the late 1980s, and has evolved into its current variations (double and triple FPS). Other common types of isolation systems include pot-type bearings, which combine elastomeric and friction type bearings, other kinematic bearings, and rubber isolation in combination with passive energy dissipation [11], e.g., spring-type systems, sleeve-pile isolation, and resilient-friction base-isolation. Isolators can be understood as a combination of a component that provides lateral flexibility acting in parallel with any kind of an energy dissipator.

TMDs are inertial devices that use a small mass (as compared to the weight of the structure) connected to a single point of the building through a linear or non-linear damper. The concept of TMD dates back to the early 1900's ([16, 17]). Their use was extended to control multiple modes by using multiple TMDs as first proposed in 1988 [18]. Moreover, TMDs have been used in conjunction in some cases with seismically isolated buildings [19] since these structure have the advantage of presenting an strongly predominant isolated mode. Several strategies for optimally placing and tuning the TMDs to the structure have been developed and can be found elsewhere [10]. Another related application are Tuned Liquid Dampers (TLDs), which dissipate energy through turbulence and friction of a fluid interacting with the wall or other elements within a container. Its civil engineering applications began in the 1980s [20], and TLDs are further divided into: (1) sloshing dampers, which dissipate energy by the flow through meshes and rods, and are tuned by modifying the container size or depth of the liquid; and (2) column dampers, which generate damping flowing through an orifice, and are tuned by changing the column shape or air pressure.

A concise mechanical comparison between friction, metallic, viscoelastic, and viscous fluid dampers can be found in the literature [5]. Friction dampers were first proposed in the late 1970s [21, 22]. The

concept came from car brakes, and has been applied to concrete shear walls [23, 24], and to braced frames [25]. After successful experiments, several types of these devices have been implemented, such as the Sumitomo friction damper, which uses a copper alloy lining pad typically connected to a chevron bracing [26]; slotted bolted connections, where the slots of the bolts are aligned to the direction of loading [27]; and energy-dissipating-restraint [28], which is a self-centering device where the sliding force is proportional to the displacement. On the other hand, metallic dampers use the hysteretic work of yielding metals to dissipate the vibration energy. This concept was first proposed in the early 1970's [29, 30], where several configurations of mild steel dissipators were tested, such as torsion of rectangular bars, flexure of short beams, and rolling of U-shaped strips. Among many typologies, a well-known type of metallic damper is the ADAS [31]. Another more recent metallic damper that has been extensively investigated and used in practice is the unbonded buckling restraint brace (BRB) used mostly in braced structures to limit axial forces on the braces and protect connections by allowing axial yielding of a steel section confined by an external casing with a small slack between the yielding element and casing [32]. Its popularity comes mainly from its symmetrical behavior in tension and compression.

Viscoelastic dampers dissipate energy through shear deformations of materials such as rubber, polymers, and glassy substances. One of their first applications in civil engineering was the wind-induced vibration reduction system of the Twin Towers of the WTC in New York city in 1969 [33]. Closely related to these dampers, viscous fluid dampers produce work through the motion and shearing of a highly viscous fluid, which also produces heating of the fluid. The first implementation of these devices in civil engineering was in the 1970s [34]. The first industrial device was made by GERB Vibration Control in the 1980s, and was used together with base isolation [35]. Many other viscous devices exist, such as the viscous damping wall [36] developed by Sumitomo (Japan), which requires very high viscosity fluids.

Semi-active systems were proposed as early as the 1920s as automobile shock absorbers [37]. Civil engineering applications began in the 1980s, and include: semi-active TMDs to counteract wind induced vibrations in tall buildings by changing the damping force of the tuned mass [38]; sloshing TLDs consisting of baffles orientated in real time in order to change the tuning of the device [39]; semi-active column TLDs, where a variable orifice controls damping [40]; semi-active friction dampers, which use electromechanical actuators [41]; and piezoelectric friction dampers [42]. Other types are the electrorheological (ER) and magnetorheological (MR) dampers. ER dampers use fluids containing dielectric particles that align when subjected to an electric field offering flow resistance; this change can occur within milliseconds and is completely reversible. In the early 1990s, ER dampers were proposed to protect base-isolated structures from long-period motions [43], usually attributed to near-source earthquakes, and to reduce the acceleration of a shock isolation platform for naval applications [44]. Similarly, MR dampers use the power of a coil to change the shear characteristics of an MR fluid, and in the 1990s several experiments were carried out to show their usefulness [45–49]. MR dampers have been proposed to control the vibration of train suspension systems [50] and have been used in scaled models of bridges to evaluate their effectiveness [51–53]. MR fluids have also been used to control damping in column TLDs designed for wind-induced vibration mitigation of tall buildings [54]. Furthermore, semi-active viscous fluid dampers may also change their properties by controlling the opening of orifices inside the piston and were first discussed in the early 1990s for bridge applications [55, 56] based on prior successful laboratory tests [38].

Given this general overview of some developments of the field, it is convenient to start with a very brief description of the equations of motion that govern the vibration and seismic protection problem of structures. Indeed, seismic protection may be understood as an automatic control problem of a

structure (plant), which seeks passive or semi-active forces to equilibrate the moving masses by modifying directly or indirectly the stiffness, damping, and mass of the system. After that, a brief overview of the developments in seismic protection over the past 10 years is presented with the goal of identifying future trends in the field. Some recent local research results associated with these new trends are also presented and discussed. The article concludes with a presentation of the advances in design of structures with Seismic Protection Systems (SPS) with especial emphasis on a methodology that has been recently proposed, and a summary of the Chilean implementation of SPS.

2 Formulation of the problem

The equation of motion of a MDOF linear structure with inelastic SPS can be written as a dynamic equilibrium problem:

$$\mathbf{M}\ddot{\mathbf{u}}_t(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) + \mathbf{L}^T \mathbf{f}_d(t) = \mathbf{0} \quad (1)$$

where \mathbf{M} , \mathbf{C} , and \mathbf{K} are the mass, viscous, and stiffness matrices, respectively; \mathbf{L} is the kinematic transformation matrix between the DOFs \mathbf{u} and the damper deformations $\mathbf{v} = \mathbf{L}\mathbf{u}$, and $\dot{\mathbf{v}} = \mathbf{L}\dot{\mathbf{u}}$; \mathbf{f}_d is the vector of damper forces; $\mathbf{u}_t(t) = \mathbf{u}(t) + \mathbf{r}\mathbf{u}_g(t)$ is the vector of total displacement of the masses relative to an inertial frame; \mathbf{u} is the vector of relative displacements of the building masses relative to the ground; \mathbf{u}_g is the displacement of the ground relative to an inertial frame; and \mathbf{r} is the kinematic transformation matrix between the ground displacements and the DOFs \mathbf{u} of the structure. Multiplying Equation (1) on the left by $\dot{\mathbf{u}}^T$, and integrating with respect to time, the following absolute energy equation is obtained [57]

$$\begin{aligned} & \underbrace{\frac{1}{2} \dot{\mathbf{u}}_t^T(\tau) \mathbf{M} \dot{\mathbf{u}}_t(\tau)}_{E_k(t)} \Big|_0^t + \underbrace{\int_0^t \dot{\mathbf{u}}^T(\tau) \mathbf{C} \dot{\mathbf{u}}(\tau) d\tau}_{E_v(t)} + \underbrace{\frac{1}{2} \mathbf{u}^T(\tau) \mathbf{K} \mathbf{u}(\tau)}_{E_s(t)} \Big|_0^t + \underbrace{\int_0^t \dot{\mathbf{u}}^T(\tau) \mathbf{L}^T \mathbf{f}_d(\tau) d\tau}_{E_d(t)} \\ & = \underbrace{\int_0^t \dot{\mathbf{u}}_g^T(\tau) \mathbf{r}^T \mathbf{M} \dot{\mathbf{u}}_t(\tau) d\tau}_{E_i(t)} \end{aligned} \quad (2)$$

where E_i is the seismic input energy; E_k is the total kinetic energy; E_v is the viscous damping energy; E_s is the elastic energy; and E_d is the SPS energy [57], i.e. $E_k(t) + E_v(t) + E_s(t) + E_d(t) = E_i(t)$. After enough time passed the end of the ground motion, say $t = t_f$, the kinetic and elastic strain energies vanish, and Equation (2) implies that $E_v(t_f) + E_d(t_f) = E_i(t_f)$. Therefore, for an elastic structure, the final input energy must be dissipated by the internal damping and the work done by the SPS. If the energy transferred to the structure exceeds this dissipation capacity, the structure will be damaged and ended with residual deformations. Seismic protection systems can significantly reduce these effects using two strategies: (i) by increasing E_v and E_d with energy dissipation devices, and (ii) by reducing the input (demand) through modifications of the dynamic characteristics of the system (e.g., seismic isolation).

3 World context in seismic protection

A detailed literature review was carried out by inspecting all seismic protection articles published in four leading journals of the field over the past 10 years. The journals studied were Earthquake Engineering & Structural Dynamics, Engineering Structures, Structural Control and Health Monitoring, and Earthquake Spectra. Shown in Fig. 1 is the number of articles on passive, semi-active, and active systems as the percentage of all published articles. It can be seen that passive seismic protection, which is the oldest, has been more studied than semi-active and active protection. Please note that

these percentages can add to more than 100% since a single article may contain more than one device. Although it is older than the rest, seismic isolation has been studied more than twice the next technology in the ranking, which are TMDs. The fourth highest is MR dampers, which is the most studied non passive system. This comparison is just a reference since energy dissipation is subdivided into many classes of devices, while isolation groups different families of devices. The plot on the right (Fig. 1) classifies these articles further into different observed thematic trends; those articles that did not fit into this classification were classified as “other”.

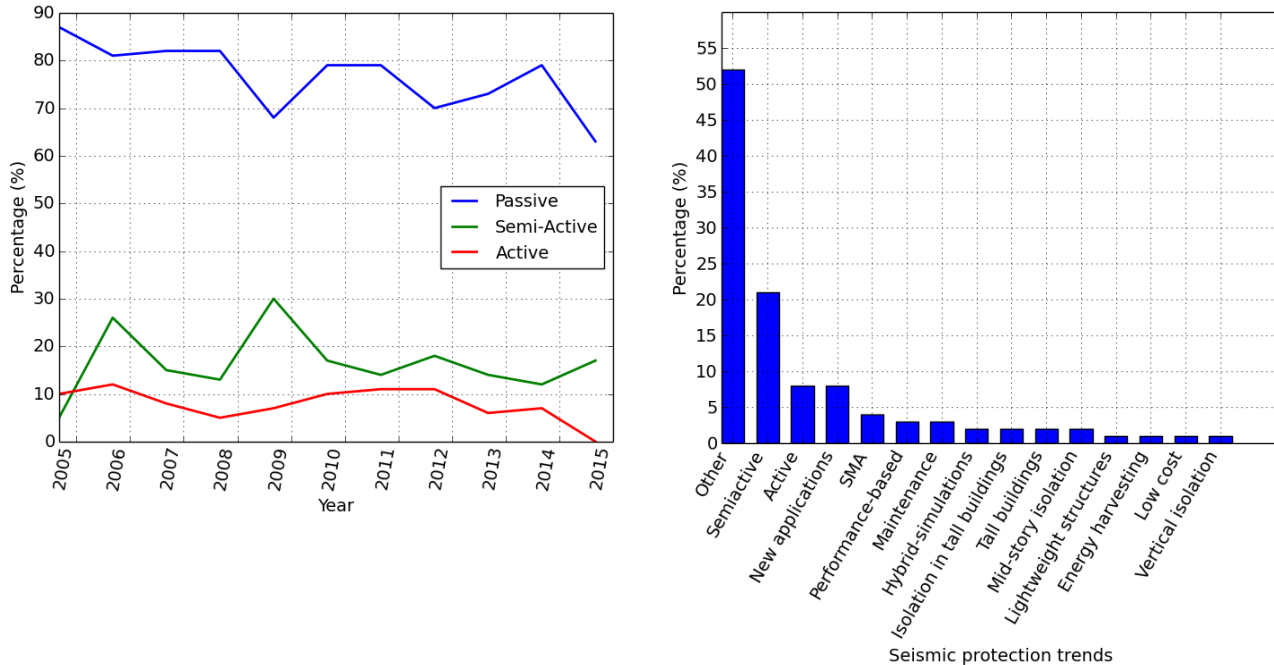


Fig. 1 – Publication trend in passive, semi-active, and active seismic protection over the last ten years

It is apparent that publication trends in Fig. 1 are quite steady over the last 10 years, and regardless of the successful performance of structures with SPS, it has not triggered any special concentration in research. Indeed, by grouping TMDs and TLDs, all the semi-active systems, and all the passive dampers, the distribution becomes more homogeneous (Fig. 2). In this case for example, energy dissipation as a topic, excluding TMDs and TLDs together that are the second highest, has been studied in average in 26% of the searched journal papers, while seismic isolation, which is the highest, in 36%.

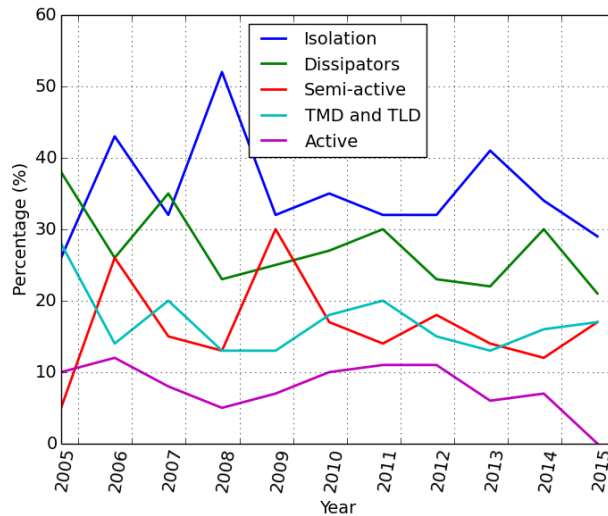


Fig. 2 – Trends of SPS publications over the last ten years and grouped as indicated in the legend

3.1 Future trends in the field

The study performed on the bulk of literature not only included a statistical analysis in terms of the publications according to the classes shown, but also searched for plausible future trends in the field. Although it could be debatable how identify such trends, since they are not only a result of a statistical analysis but rather, more often than not, from seminal work that creates fertile lines of research that lead to advancing knowledge. At the risk of being somewhat speculative in some cases, the ideas that come up in several publications and are more frequently been discussed these days in the field are:

(a) **Seismic isolation of tall buildings.** The construction of tall buildings is naturally increasing in earthquake regions worldwide as a result of population growth. Although not as effective as in massive squat structures, and within physically reasonable limits, seismic isolation may be effective in reducing the earthquake response of tall buildings. In such buildings, the uplift forces generated at the isolation system need to be limited to prevent stability failures and cavitation of rubber [58]. Several solutions can be proposed to reduce tension besides increasing the size of the isolators [59] such as outrigger elements or a grid of RC walls capable of distributing forces at the foundation and isolation system [60]. In these studies it was proven that horizontal displacements of the isolation system remain within the displacement capacity of conventional bearings. Another case [61] showed that soil inelasticity provides supplemental energy dissipation, and that the effects of rocking isolation may play a relevant role in building survival providing extra dissipation.

Another possibility for tall buildings is intermediate-story isolation. Some studies have dealt with multi-story structures suggesting the use of FPS [62], or semi-active[63] and active control [64] of nonlinear base-isolated structures. Intermediate-story isolation has to account for the specific characteristics of the isolation system and its location in height [65]. A building structure tested with base and mid-height isolation systems showed that the latter has smaller fundamental modal quantities than base-isolated buildings [66–68]. Some recent studies have tried to minimize the maximum floor acceleration of buildings, while constraining the maximum interstory drift, the maximum base displacement, and the total seismic isolation cost [69].

The protection toward vertical motions is also critical for some nonstructural systems [70], and cannot be achieved by conventional elastomeric and frictional bearings. The vertical response still

remains as a topic of study for base-isolated buildings, perhaps more so than in conventional fixed-base buildings since isolation is used in some structures to attain high performance requirement levels [71]. It can be shown that vertical isolation can reduce the vulnerability of nonstructural components in base-isolated buildings [72], and some innovative isolators have been developed for that purpose [73]. Earthquakes, but also human behavior [74, 75] and machine vibrations [76] also induce vertical vibrations in a structure, and vertical TMDs has also been proposed.

- (b) **Semi-active systems.** Structures are becoming increasingly complex systems in their operation, with the structure becoming less and less important in terms of cost. As a consequence, structures need to adapt better to different environmental conditions, among them, earthquake induced vibrations. Because semi-active systems use small amounts of energy to change the system properties in real time, they are an excellent alternative to control the building response as long as they are usually implemented in conjunction with other systems, such as TMDs [77, 78]. Since TMDs are large mechanical amplifiers of deformation and damping, the use of semi-active systems together with TMDs may be an important application in the future.
- (c) **Industrialized and precast structures.** Industrialized and precast structures are attractive construction technologies that increase productivity and quality in building construction. Almost inevitably, the resulting structures are prone to non-ductile behavior due to the types of connections used among components, unless conventional wet connections are emulated at the site. This results in a strong design and construction disadvantage of prefabricated structures in seismic countries. The use of SPS provides a tremendous opportunity to improve the seismic behavior of such structures by providing two important conditions: (i) a reduced seismic demand, and (ii) the necessary energy dissipation capacity [79]. Many technical issues still need to be investigated in order to effectively generate a methodology that fully takes advantage of the merge of precast construction and seismic design technologies.
- (d) **Self-centering protection systems.** Because one of the main goals in implementing SPS is to get rid of structural and non-structural damage and guarantee operational continuity for the structure, the residual condition of the building after the earthquake turns out to be very important. Although dampers are designed as true *fuses* within a structure, and after a strong earthquake should be replaced, in some cases the inelastic condition of the dampers may keep the structure from returning to its initial condition. Moreover, users are not familiar in general with the seismic design philosophy, and relate any kind of damage as a design failure. Consequently, the development of self-centering SPS has brought substantial attention from a number of researchers [80, 81].

One case of self-centering devices are the shape memory alloys (SMAs), which can be passive, semi-active, or active components [82]. SMAs have two advantages: (i) they return to their predetermined shape upon heating, and (ii) they present super-elasticity and can undergo large inelastic deformations without residual deformations upon unloading. This phenomenon provides ideal centering capabilities that can be used in passive control of structures subjected to earthquakes [83–86]. Besides, it can be shown that SMA wires supply recoverable hysteretic behavior [87, 88] and serve as an additional restoring force [89–92]. Several researchers have studied the behavior and performance of structures with SMAs [93, 94].

- (e) **Seismic protection of low-cost and lightweight structures.** Perhaps one of the most relevant challenges in the development of future SPS technology, is to make it accessible to everyone, like

any other construction material or construction technology available. Low-cost seismic isolation for instance has been a subject of research over the years [95, 96] and solutions range from complete foundation interventions [97], the use of friction and rubber-soil mixture interfaces [98], and also lower cost devices [99, 100]. In general, the energy dissipation solutions available cover a larger range of prices, and it is simpler to foresee low-cost SPS ideas implemented in the future. The application of seismic protection to lightweight structures is directly related to low-cost protection, and still has several technical and cost challenges, since these structures are less significant in size and cost, and conventional solutions are prohibitive for these structures. Technically, to be able to isolate lightweight structures, devices with stiffness independent of their height and kinematic isolators seem most appropriate [101]. Moreover, the large improvement observed in very low friction materials represents an interesting avenue to develop solutions for future lightweight structures.

4 Recent research results in SPS technology

This section contains a quick overview some of the most relevant research results obtained by the principal author and a group of master and doctorate students over the past 5 years. The emphasis is in this research group, but some appropriate references are made when needed to the results of other national researchers. This research is strongly related to the trends presented earlier and can be classified in the following three aspects: (i) building performance; (ii) new devices; and (iii) design methodologies.

4.1 Building performance

Understanding the detailed performance of different structural systems under severe seismic conditions remains one of the main goals of earthquake analysis. Thus, the research performed during the last years has focused on understanding the behavior of two types of systems, the so-called free-plan buildings, and the typical Chilean shear wall buildings. Although it was not evident from the dynamic properties and design characteristics, the former performed without damage during the 2010 Chile earthquake, while some of the latter developed a brittle failure induced by excessive compression in shear walls [102, 103].

Because free-plan buildings have structures with small lateral stiffness—their fundamental period is smaller than that of a frame structure of the same height—initial research was dedicated to understand their earthquake behavior that was uncertain since no history on the performance of this typology was available. In particular, the research aimed to represent the dynamic response of these systems with a sufficiently simple model that would enable the designer to try out different structural configurations and SPS solutions at initial stages of the design process. In the model synthesis process, the relative importance of the different structural components was evaluated discovering the surprising effect of the warping stiffness of the shear wall core, and the very relevant bending stiffness of the floor slab that couples, especially for lower modes, the shear wall core and the perimeter frames of free plan buildings structures [103]. Thus, a new simplified column model was developed for free plan buildings that is significantly less time consuming and whose errors are in general less than 15% [104]. The second idea was to use an adaptive neural fuzzy inference system (ANFIS) model [105] to quickly predict the seismic response of these types of buildings. For that, the central idea was to model the structure as a linear combination—with combination factors to be determined—of two extreme structural modeling cases [105]: (i) a rigid out-of-plane floor diaphragm of beams and slab in bending, and (ii) and infinitely flexible out-of-plane floor diaphragm of beams and slab that would result in cantilever-like deformations for all vertical elements. Given a proper

calibration of the neural network, analyses can be carried out very fast due to the simplicity of the model, which is crucial when a large number of earthquake runs are needed as required for optimal SPS design.

In case of reinforced concrete shear wall buildings, several studies have been performed since February 27th, 2010. First, a detailed study of the seismic behavior of 8 buildings in the city of Concepcion was done after the earthquake and has been published [103, 106]. The purpose was to understand their failure, propose solutions for their stabilization, study patterns of damage and correlate those with the seismic code demand, and collect all possible perishable earthquake data. The data collection effort was then extended to a set of 43 buildings in Chile and a formal statistical analysis process of the data has been performed and published [107]. Results show that the axial load ratio (ALR) played a fundamental role in the brittle damage of these buildings. Furthermore, statistical analysis of the collected data from the suite of damage building shows that damage was localized generally at lower levels of buildings and that there was a strong correlation between damage and soil quality [103, 107]. A study of the performance of specific walls was also initiated using state-of-the-art inelastic modeling tools for shear walls (e.g., Diana). In order to reproduce this damage, two approaches were taken: (1) Two-dimensional finite element inelastic models; and (2) three-dimensional nonlinear fiber models. Results show that to reproduce the actual failure in 2D inelastic models, both vertical and lateral displacements need to be accounted for in the imposed displacement pattern [108]. Two dimensional models were carried out in DIANA using shell elements with well-known inelastic stress-strain constitutive laws for concrete, but using rather simple constitutive laws for steel.

Also, a three-dimensional inelastic fiber model for shear walls was recently developed [109]. The model is capable of generating objective results for a big range of loading conditions, and reproduces well very different experimental cyclic tests of different shear wall cross-sections reported in the literature. The model took into account the full nonlinear 1-D stress-strain constitutive relationship for concrete, and also fracture, buckling, and Bauschinger's effect on steel bars. Moreover, the model accounts for inelastic shear deformations depending on the current axial load in the element. The first part of this investigation related to the inelastic cyclic modeling of reinforced concrete shear walls has been published elsewhere [109], and currently the inelastic dynamic response of 3D shear wall buildings is being considered.

4.2 New devices

Although the global concept of seismic protection has gained important traction in the profession over the last 10 years, it is evident that certain device characteristics are key in facilitating the incorporation of seismic protection technologies in building construction. Of course, cost and efficiency are two of them, and though very important, the final decision to incorporate seismic protection resides also in other aspects, like applicability of existing solutions, maintenance characteristics, device durability, physical appearance, magnitude of the structural and architectural intervention needed, commercial availability of alternatives, life and replacement of devices, device residual deformations, etc. Therefore, the work in developing new devices, the so-called hardware component of the SPS, is extraordinarily important and will still evolve significantly in the future.

This research team has tested several types of devices, covering metallic dampers in steel and copper, elastomeric and self-centering isolation and sliders, passive and semi-active friction devices, MR-elastomers, and MR-fluid dampers. A very extensive research work was developed in electrolytic tough pitch (ETP) copper. Initially, Added-Damping and Stiffness (ADAS) copper dampers were developed and tested resulting in very stable cyclic behavior and large energy dissipation capacity

that when applied to 6-, 12-, and 25- story planar structures, resulted in drift reductions ranging from 20-40% [110]. Recently, a bi-directional ETP copper-based energy dissipation device has been proposed [111], which is capable of enduring more than one severe earthquake without reaching failure; a good number of other configurations such as shear panel, honeycomb have been designed and tested. These studies successfully reproduced the experimental behavior of copper devices by using different stress-strain inelastic constitutive models capable of representing the cyclic behavior of copper including large deformations and isotropic and kinematic hardening. Applications EDDs have been developed not only for structures but also for nonstructural components such as partition walls [112, 113].

Seismic isolation of lightweight structures has been addressed mostly with kinematic isolators. One idea for poor foundation soils was a self-centering precast pre-stressed pile (PPP) isolator, first introduced in 2006 as a solution for seismic protection of low-income people housing [81]. The PPP isolator, which crosses the bad layers of soil, consists of a reinforced concrete pedestal with end caps of prescribed rolling shape, and linked to a top and bottom concrete capitals by means of a pre-stressed steel cable which provides the self-centering capacity of the PPP, and bars or EDDs that provide the dissipation capacity. The shape of the rolling surface defines the force-deformation constitutive relationship of the device and can be controlled by the designer. The top capital is connected to the superstructure of the building, and the bottom capital to the foundation system. Different variations can be proposed also for self-centering lintels with the same idea. The cost of the PPP isolation systems was estimated to be around 25-50% of a typical rubber isolation system [81], and since low-income people housing is generally placed in bad soil conditions at the periphery of cities, the PPP isolators also works as a foundation pile. Following this idea, a tridimensional analytical formulation of the PPP isolator was proposed [97] and tested [101]. A simplified design procedure was also proposed, which combined PPP isolators with steel-PTFE sliders in parallel [101].

More recent research on passive devices has focused on modeling the multi-physics of viscous and magneto-rheological dampers [114]. Models developed account for the complete fluid dynamics and thermal behavior inside the damper, and present excellent accuracy with experimental cyclic tests. Experimental evidence also shows that for high frequencies, the compressibility of the fluid must be accounted for in order to reproduce the experimental results. In those cases, the commonly accepted design formula of viscous force being proportional to a power of velocity needs to be modified to include the compressibility of the fluid.

Even though the application of more intelligent devices is just beginning in Chilean practice, research has been generated for semi-active systems, such as: (1) MR dampers [115–118]; (2) semi-active piezoelectric friction dampers [119]; and (3) MR elastomers [120]. MR dampers consists of an MR fluid which properties can be changed from a viscous fluid into a semi-solid material by subjecting the fluid to a magnetic field. One of the advantages of MR fluids relative to viscous fluids is its stable behavior over a broader temperature range [118]. Again, a multi-physics finite element model that couples the Maxwell equations of magnetism with the Navier-Stokes equations for the fluid was develop to parametrically study the effect of different physical geometric design characteristics of the dampers on the force-velocity constitutive relationship, and results were validated experimentally [115]. The design, build, test of a prototype MR-damper, specifically designed for one of the two TMDs of a 21-story building located in Santiago, led to the first real-life implementation of such a semi-active SPS in Chile [116, 117]. The experimental validation of the final TM-MR damper assembly on the building was carried out by subjecting the system to pull-back tests of 10 cm of amplitude [116], and the experimental results showed that the MR dampers decreased the peak displacement of the building by 22% relative to the TMD system with no dissipation devices. Another study considered

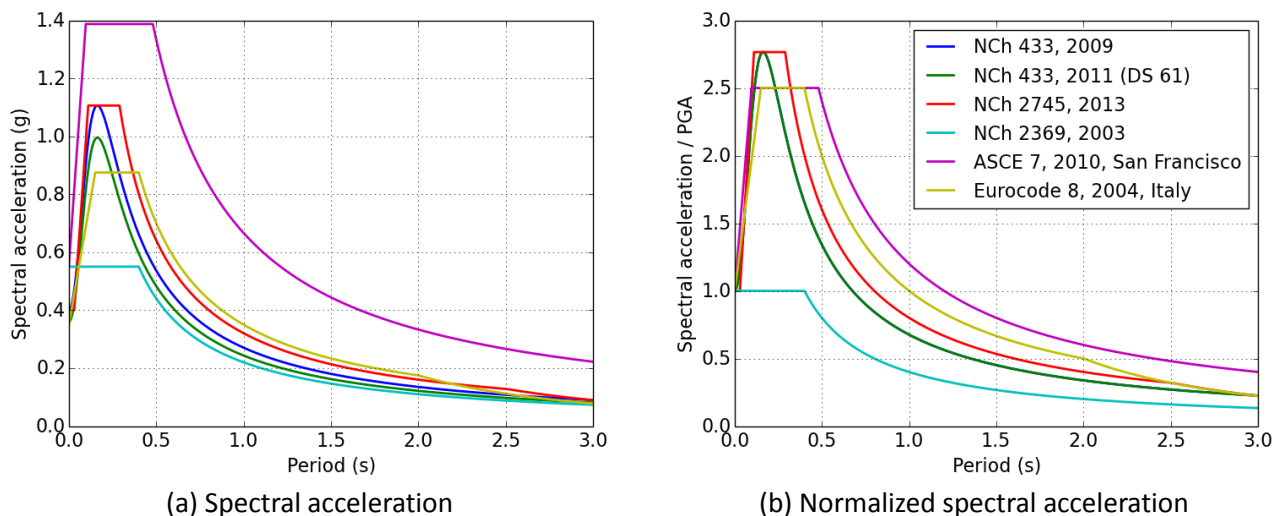
a semi-active elastomer, which consists of a composite material with an elastomeric matrix filled with micro-sized iron particles [120]. This is an initial investigation since the magnetic fields required are still large, but the material is capable of varying its force-deformation constitutive relationship when subjected to a magnetic field and in principle could vary stiffness and damping by means of a simple control system.

One of the drawbacks of regular friction dampers is that their efficiency depends on the selection of the activation force and the ground motion intensity. Semi-active piezoelectric friction dampers overcome this limitation by controlling the normal force of the contact surfaces using piezoelectric actuators. Recent research has proposed a new piezoelectric friction damper that can work in passive or semi-active mode using contact surfaces made of stainless steel and brake pad material [119]. The device is able to vary its initial normal force by a dynamic range factor of 1.9, and hence modify its dissipation force capacity by the same factor.

Other Chilean researchers have carried investigations in the field of shape memory alloys that includes experimental testing [121–125]. SMA bars have shown good dissipation properties with an equivalent damping of 12% [124] and they have also found applications in structural cables showing more energy dissipation and better re-centering capabilities [121]. A SMA damper was informed to reduce floor peak accelerations when tested as part of a braced system; the reduction obtained was around 60% [125]. Also, by means of genetic algorithms, an optimal control of the maximum acceleration in a building together with the roof lateral displacement was numerically studied for an isolated building with magnetorheological dampers [126].

4.3 Design methodologies

The true vehicle to transfer knowledge in structural engineering to the society is through a design algorithm, generally included in codes. Thus, any relevant analytical or numerical capacity to evaluate the structural performance and force-deformation constitutive behavior of the EDDs used in seismic protection need to converge into a formal and coherent design procedure, capable of producing physical solutions that work under the uncertain loading conditions of an earthquake.



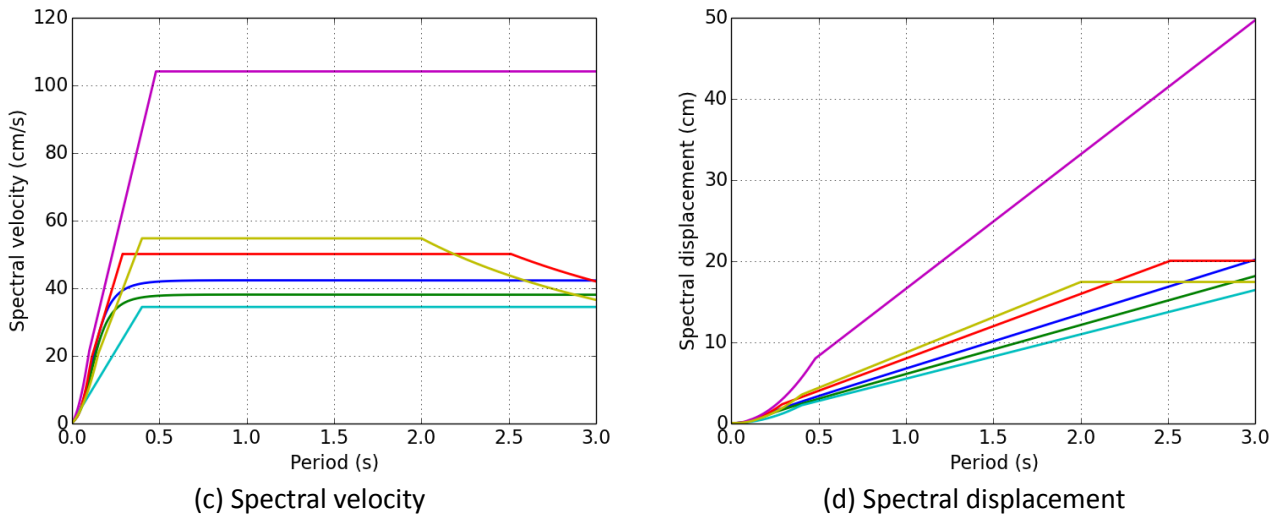


Fig. 3 – Design spectra for NCh 433, NCh 2745, and NCh 2369 Chilean codes for zone 3 and soil type A ($V_{S30} \geq 900$ m/s); ASCE 7 code for San Francisco and site class A (hard rock, $V_{S30} > 1524$ m/s); and from the Eurocode 8 for zone I in Italy and ground type A ($V_{S30} > 800$ m/s).

A key aspect in any structural design is the definition of the earthquake demand, which varies from site to site. In order to compute the structural response, earthquake excitations need to be taken into account using a design spectrum. Shown in Fig. 3 is a comparison of the design spectra of several building codes: Chilean codes NCh433 modified in 2009 [127], current NCh433 code modified in 2011 by Supreme Decree 61 [128], NCh 2745 code for base-isolated buildings [129], NCh 2369 for industrial structures [130]; ASCE 7 code [131] for the city of San Francisco, California; and Eurocode 8 [132] for Italy’s zone I. All spectra are calculated for the best possible soil (i.e., type A) and with an importance factor of 1. Each design spectrum has an associated return period and peak ground acceleration as indicated in Table 1.

Table 1 – Design return period and peak ground acceleration of each design code.

Design code	Design Return Period (years)	PGA (g)
NCh 433, 2009	-	0.40
NCh 433, 2011 (DS 61)	-	0.36
NCh 2745, 2013	475	0.40
NCh 2369, 2003	-	0.55
ASCE 7, 2010	475	0.55
Eurocode 8, 2004	475	0.35

The philosophy of current design methods states that the demand on the earthquake resistant structural system of a building with SPS can be reduced due to their incorporation into the design. In practical terms, the more supplemental damping is introduced into a building—which can be done by energy dissipation devices—the more the design spectrum is reduced [131, 133]. Given this demand, the design of EDDs consists of finding their mechanical properties and spatial distribution. This problem has been dealt with in literature through two approaches: (i) an optimization problem where the designer has to find the EDD distribution and capacities for minimizing some response related function; and (ii) a problem that given a spatial distribution of EDDs, find their optimal capacity.

Optimal damper distributions have been widely proposed in the literature, e.g. optimal placement of dampers in height by minimizing both the sum of amplitudes of linear transfer functions [134] and also their peak [135]. The effect of torsion for controlling the response of asymmetric-plan systems, where the geometric and rigidity centers do not coincide in plan—generating stiffness eccentricity—has also been studied in the framework of seismic protection. The idea is to find a spatial distribution on the plan of a structure that balances the response, and it has been suggested that more damping is required along the flexible edge of the plan, as it was shown for linear [136] and nonlinear [137] structures. Other studies have developed the concept of torsional balance as an optimal design criteria, and have found that the optimal eccentricity of dampers not only depends on the structural eccentricity, but also on the frequency content of the excitation and the amount of supplemental damping [138]. Shown in reference [139] is that for two-story frames with asymmetric plan, the EDD distribution is similar for linear and inelastic structural models, and the same applies to linear and inelastic damper models.

Speaking strictly about optimization methodologies, several methods have been proposed and used, such as those based on control theory, H_∞ and H_2 , which lead to optimal spatial distributions and capacities of dampers [140]. The advantage is that this solution neither depends on the loading conditions nor on the structural response. This is not the case of genetic algorithms that require multiple runs of structural analyses that are generally inelastic [141] or that deal with uncertainty in the seismic loading [142]. Genetic algorithms have not only been used for passive dampers but also for intelligent ones [143]. In the latter case, genetic algorithms were combined with fuzzy logic controllers and stochastic linearization method to allow an efficient solution. Reference [144] used genetic algorithms for magnetorheological dampers to solve a multi objective optimization problem given by several performance based design targets. There are other methods such as optimal control using a linear quadratic regulator [145], Cutting Planes Method for solving the optimization problem with Lagrange multipliers [146], and gradient based algorithms [135] among others.

ASCE 7-10 provisions define four procedures for the analysis and design of structures equipped with SPS: equivalent lateral force analysis, response-spectrum analysis, nonlinear static-pushover analysis, and nonlinear dynamic response history analysis. The latter can always be used, but other constraints apply for the other three methods that require much less computational effort. These other three procedures use a damping reduction factor for the building response which results from the effective damping of the EDDs. In design practice, the ASCE 7-10 provisions, which can be used for all kinds of dampers, imposes that the lateral resisting system withstands the nominal forces calculated for the unprotected structure, though if some special requirements are met, the minimum base shear can be reduced. On the other hand, the protection system can be accounted for controlling the displacement requirements [131].

If the design of structures with EDDs is not thought as an optimization problem, it can be done by using displacement or energy based approaches. In the former, if the structure and EDDs are modeled with their effective stiffness and damping properties, a linear iteration involving only static analyses can be used for design [147], where given a target displacement and an effective damping ratio, the strength and stiffness are obtained. Another displacement approach is that of performance-based philosophy, as shown earlier for bridge piers with hysteretic dampers [148]. In this case, a displacement or strain index performance is chosen and the structure is transformed into an equivalent single degree of freedom after performing pushover analysis. Then, by means of capacity-demand spectra, and given a required ductility, one can find the required stiffness and yield strength. Among other displacement based design methods, a very well-known one is the capacity spectrum method [133] where a performance point is obtained by equating the inherent equivalent damping of

the cyclic response obtained from a pushover curve with the associated damping used to reduce the demand spectrum.

In case of the energy based approaches, they directly account for the accumulated hysteretic energy, and hence, accumulated damage, as opposed to the displacement based approaches. Reference [149] presents a method where an energy demand spectrum is used after transforming the system into a SDOF by using the two modes with the highest mass participation factors. The design can also include the assessment of the structural seismic risk, which is normally calculated using the Pacific Earthquake Engineering Research Center (PEER) framework [150]. This framework has been used to estimate the probability of failure of building equipped with viscous dampers [151], and of three different base isolation systems in a nuclear power plant [152].

5 Design of structures with SPS

This section contains a quick overview of the procedure that has been calibrated with the design of several structures with SPS in Chile. It has been developed over 15 years [153] and continuously improved by different research and real design cases. It would be impossible to describe the procedure in detail herein and the interested reader may look for further details elsewhere [154]. In this study the design flowchart shown in Fig. 4 is presented. This conceptual design procedure is developed for elastic buildings equipped with linear and non-linear EDDs, but it can be readily extrapolated to the case of an inelastic structure. The procedure consists of the following: (i) to select the building key design performance indices (KDPI) (*e.g.*, peak floor displacements, peak inter-story drifts, *etc.*); (ii) to reduce the order of the dynamic structural model through generalized modal or physical coordinates; (iii) to determine the most significant mode according to a significance ratio (*i.e.* the modal significance factor (MSF)); (iv) to reduce the response of interest until a second mode becomes the controlling mode, and so on until a suitable reduction factor for the response is reached; (v) to build iso-performance curves (providing the amount of supplemental stiffness and damping required to reduce the building response to a specific target value); (vi) to compute a height-wise damper distribution and obtain linear equivalent parameters for each story and device; and (vii) to select the EDD parameters and validate by computing the inelastic response of the structure.

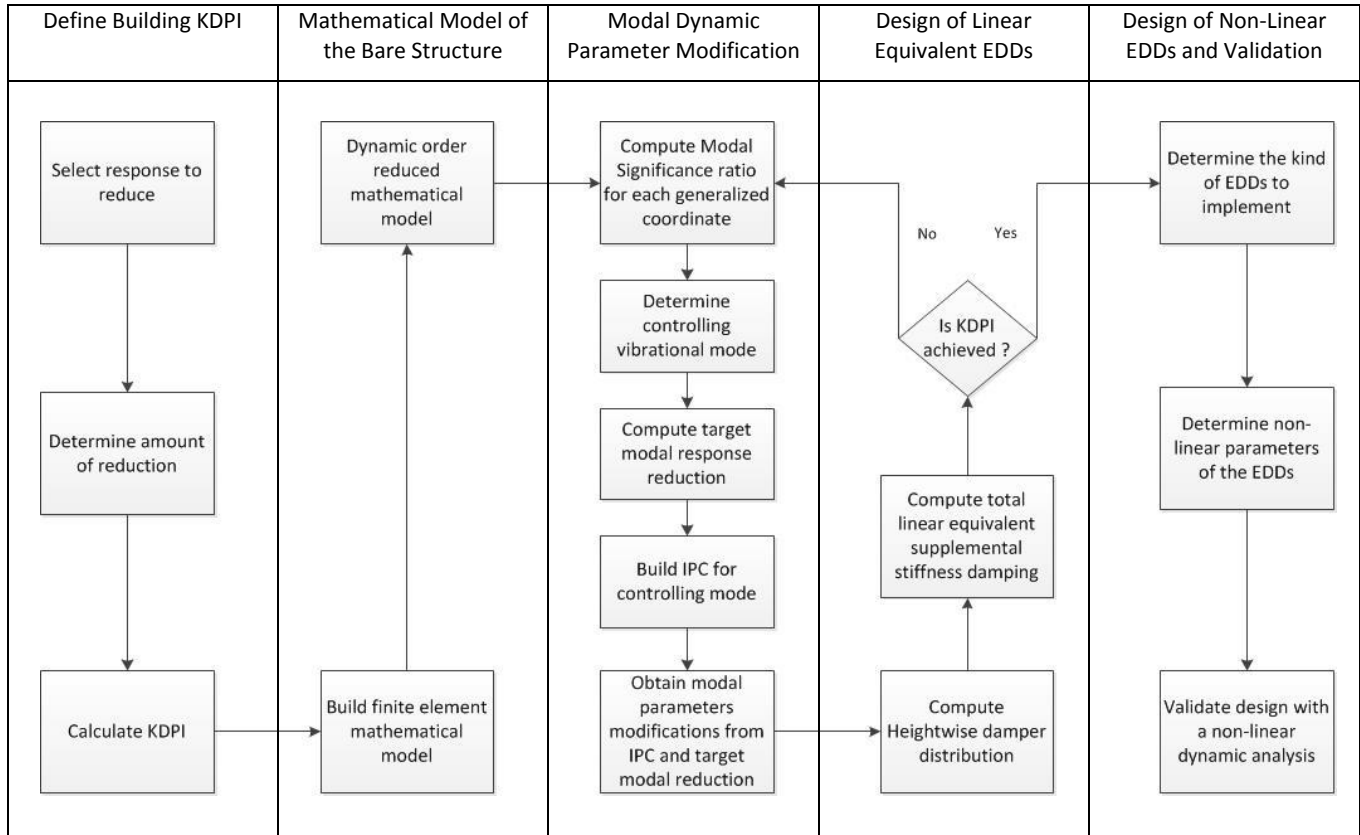


Fig. 4 – Schematic flow diagram of the proposed design procedure [154]

In what follows, only three key aspects of the procedure are highlighted in this article, which turn out to be critical to the procedure: the calculation of the modal significance factor (MSF), the global determination of stiffness and damping, and the definition of the optimal localization of damping.

5.1 Modal significance factor (MSF)

MSF are calculated by decomposing the selected KDPI on the different building modes and choosing the mode with the highest contribution to the KDPI. This parameter is proven to be a robust and extensively applicable method but should consider the non-classical nature of the problem. Thus, the peak response of the KDPI, $Z(t)$ at time t , is decomposed into m modal contributions $Z_m(t)$, where the $m - th$ modal contribution to the MSF, χ_m , is defined as:

$$\chi_m = \frac{Z_m(t)}{\sum_j Z_j(t)} \tag{3}$$

The most significant mode is the one that leads to the largest MSF. It has to be noticed that for non-classically damped modal analysis, this modal decomposition needs to be done using complex modes [154].

5.2 Iso-performance curves

Iso-performance curves (IPCs) allow us to determine the global stiffness and damping that needs to be added to the structure to achieve an optimal KDPI (Fig. 5). Iso-performance curves state geometrically that there is an infinite number of pairs of supplemental stiffness and damping that lead to the same reduction of the KDPI. IPCs are derived from the response of a model of the

structure that could be an accurate 3D model, or a lower order SDOF model. For each combination of supplemental damping ratio ξ_d and frequency shift Ω^2 , the modal response is determined using this model and its response reduction recorded. The locus of parameters (Ω^2, ξ_d) defining the iso-performance surface corresponding to a response reduction factor R_m defines the IPC. The relationship between these parameters and the frequency and damping shift can be stated as:

$$\omega_f = \omega_0 \sqrt{1 + \Omega^2} \quad \text{and} \quad \xi_f = \frac{\xi_0 + \xi_d}{\sqrt{1 + \Omega^2}} \quad (4)$$

where the sub index 0 corresponds to the structure without dampers. Then, by knowing (Ω^2, ξ_d) it is possible to obtain ξ_f and ω_f , which are the $m - th$ new modal parameters used next to compute the required equivalent stiffness and damping in the structure.

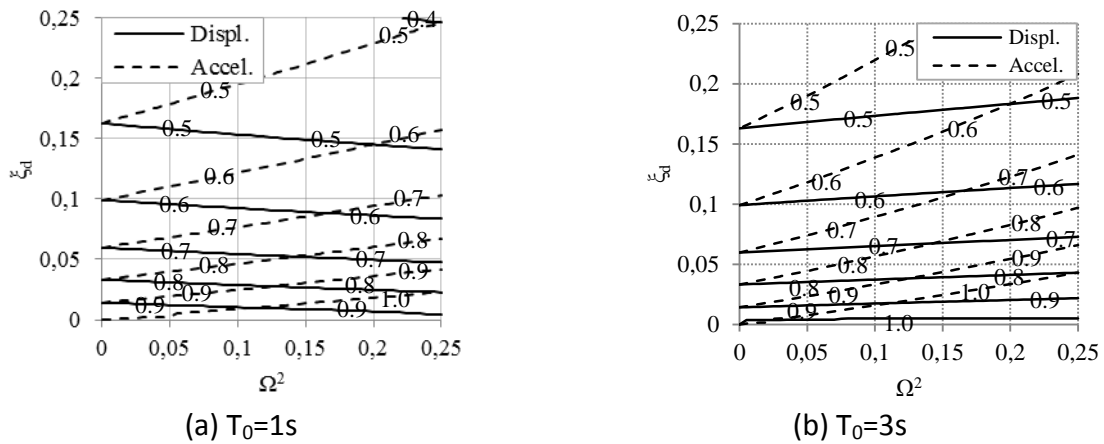


Fig. 5 – IPCs for displacement and acceleration corresponding to the NCh2745 spectrum, soil type I (rock), and Seismic Zone 1.

5.3 The Perturbation Based Optimal Distribution Algorithm (PBODA)

The optimal localization of damping is assessed according to the Perturbation Based Optimal Distribution Algorithm (PBODA) introduced elsewhere [154], which may be summarized as follows: (i) define an initial distribution of dampers α^0 that is consistent with the target frequency and damping shift and select a desired tolerance for the iteration—please note that α^0 is a distribution and that its components add to one, and that this initial guess is critical for the success of the iteration [154]; (ii) using, say, this distribution after k iteration steps, α^k , obtain the overall supplemental linear equivalent parameters k_d^k and c_d^k by the solution of the eigenvalue problem presented in reference [154]; (iii) update the distribution α^{k+1} by solving the following optimization problem that maximizes the modal damping of the controlling mode (m):

$$\alpha^{(k+1)} = \max_{\alpha} \xi_m \left(\alpha, c_d(\alpha^{(k)}), k_d(\alpha^{(k)}) \right), \text{ s. t. } \quad \sum_l \alpha_l = 1, \quad 0 \leq \alpha_l \leq 1 \quad (5)$$

(iv) if the tolerance is not reached, set $k = k + 1$ and iterate back to step (i); otherwise, set $\alpha = \alpha_k$ and exit. Upon exit, compute again the two-parameter eigenvalue problem to get the global stiffness and damping k_d^{k+1} and c_d^{k+1} . These parameters are then introduced into the new stiffness and damping system matrices, and the overall system response can be computed. With the response evaluate the response reduction factor and check if the algorithm ends when the target global response reduction factor R_z is achieved.

5.4 Case studies

The first example used to validate the proposed design procedure is a free-plan building with two interconnected symmetric towers (Fig. 6), and in which the conventional design method assuming classical damping does not work well. The second example is a group of eight shear-wall buildings damaged during the 2010 Chile earthquake. Further details of these structures and results can be found in [155].

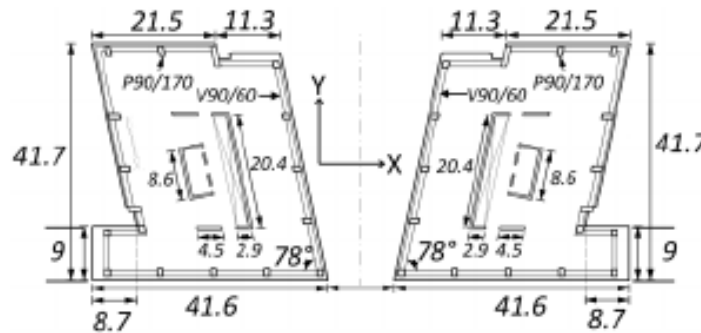


Fig. 6 – Structural plan of the free-plan building

The KDPI chosen for the free-plan building is the maximum lateral displacement of the roof. The target for the global response reduction factor R_z is 0.6. Modal analysis shows that building responses in the X- and Y-directions are spread in several modes. The final optimal linear equivalent supplemental damping and stiffness (c_d, k_d) resulting from the design procedure are obtained in the X-direction after 2 iterations and in the Y-direction after 5 iterations. The final optimal height-wise distribution of damping is presented in Fig. 7 and tends to agree with theory that says that the optimal damper location to control a given mode is to place damping in a single story. Also, a numerical comparison with other NCH2745 compatible ground motions recorded during the March 5, 1985, Chile Earthquake and for the same building design is presented in [154]. Results show the importance of selecting several compatible records for a robust design that ensures a minimum reduction level for the structure.

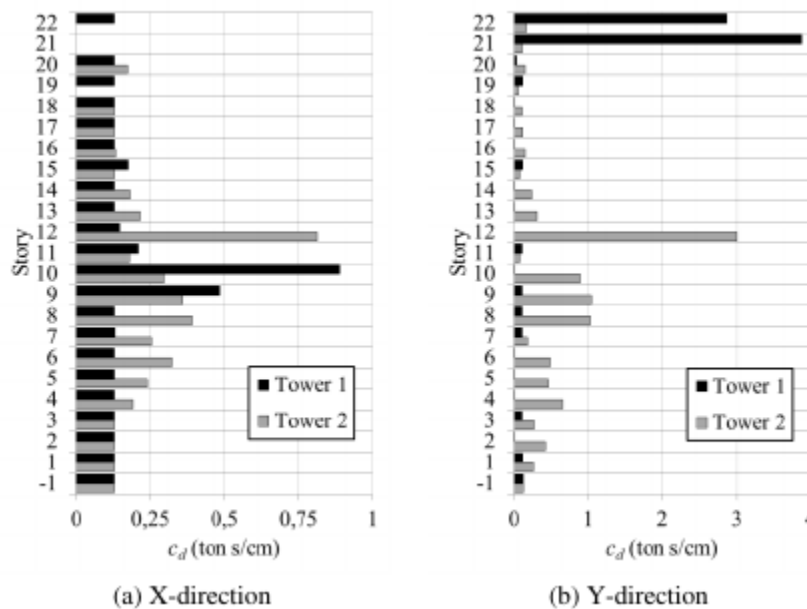


Fig. 7 – Optimal heightwise distribution of damping capacity for the free-plan building

The second example deals with eight shear-wall buildings damaged during the 2010 earthquake [106]. Again, the target for the global response reduction factor R_z is 0.6. As the structural configurations of the buildings are quite simple [106], one or two iterations were needed for convergence of the design procedure and find the required total linear equivalent supplemental damping and stiffness (Table 2). Similarly to the first building case, the results on these eight buildings prove that the applicability of the design procedure is general and that the linear equivalent method used leads to consistent results when compared to the inelastic building responses.

Table 2 – Summary of the total linear equivalent supplemental damping and stiffness required to achieve a response reduction factor $R_z \leq 0.6$

Building	Period T (s)	Equivalent Damping c_d (ton s/cm)			Equivalent stiffness k_d (ton/cm)			Design Iterations X ; Y
		X	Y	R_z	X	Y	R_z	
AA-1	0.71	4.06	3.67	0.59	18.61	21.91	0.60	1 ; 1
AH-2	0.70	6.31	10.39	0.59	43.18	125.88	0.42	1 ; 2
CM-3	0.80	6.99	3.01	0.62	44.25	22.48	0.58	1 ; 1
TL-4	0.77	2.95	1.43	0.58	15.06	7.94	0.58	1 ; 1
PR-6	0.50	1.73	2.03	0.56	11.20	21.22	0.56	1 ; 1
PP-7a, RT-8a	0.36	3.85	1.49	0.59	40.38	22.17	0.59	1 ; 1
PP-7b, RT-8b	0.34	2.98	1.52	0.54	55.42	16.93	0.58	1 ; 1
TO-9	0.93	1.70	6.50	0.58	8.04	39.40	0.55	1 ; 1

6 Chilean implementation case

This section describes the Chilean case with seismic protection and includes buildings as well as industrial facilities—bridges were excluded from this enumeration. Table 3 presents what is to the best of our knowledge the list of building projects with SPS that currently exist in Chile, or which are very likely going to be implemented in 2015. To generate this Table, a request was made to several structural engineers that have designed these structures in the country. The information was received from them in most of the cases and has been directly compiled in this Table. The original Table includes several additional fields but the data could not be obtained in many cases and was left out. It is apparent that seismic isolation is by far the most common system in Chile, used in about 75% of all structures. TMDs are the second most used system with 18%, and the remaining 7% includes all dissipation systems. Only one case is a semi-active proof-of-concept implementation, and no active system has been implemented so far.

Table 3 – Building and industrial projects with SPS in Chile organized alphabetically

N	Project	Use	N° of stories	Location	Protection system
1	Centro Anacleto Angelini	Educational	11	Macul	43 isolators y 13 sliders
2	Centro de Distribución Sodimac Lo Espejo	Industrial	1	Lo Espejo	309 elastomeric dampers
3	Cerro Colorado, Torre A	Residential	16	Las Condes	2 isolated TMDs
4	Cerro Colorado, Torre B	Residential	14	Las Condes	2 isolated TMDs
5	Clínica Cruz Blanca	Hospital	7	Santiago	212 isolators, 86 sliders
6	Clínica UC San Carlos de Apoquindo	Hospital	5	Las Condes	52 isolators
7	Costa Laguna La Portada				
8	DUOC UC Santiago Centro	Educational	5	Santiago	60 isolators, 21 sliders
9	Edificio ACHS Viña del Mar	Office	7	Viña del Mar	25 isolators
10	Edificio Amura	Residential	21	Antofagasta	41 isolators
11	Edificio Andalucía	Residential	4		8 isolators
12	Edificio Angamos Oriente	Residential	21	Antofagasta	33 isolators, 8 sliders
13	Edificio Angamos Poniente	Residential	21	Antofagasta	35 isolators, 7 sliders
14	Edificio Camara Chilena de la Construcción	Office		Las Condes	

15	Edificio Chacay	Office	6	Temuco	10 isolators
16	Edificio CIO Chuquicamata de Codelco	Office	2	Calama	10 isolators, 13 sliders
17	Edificio Corporativo Komatsu Cummis	Office	6	Quilicura	16 isolators
18	Edificio Corporativo Sodimac	Office	6	Santiago	76 isolators
19	Edificio Data Center Claro			Colina	110 isolators
20	Edificio Geocentro Agustinas	Residential	35	Santiago	2 isolated TMDs
21	Edificio Idahue	Residential	10	Concepción	40 isolators
22	Edificio Jardines de Infante	Residential	17	Nuñoa	2 isolated TMDs
23	Edificio José Joaquín Vallejos	Residential	16	Copiapó	2 isolated TMDs
24	Edificio Magnus II	Office	5	Huechuraba	31 isolators, 12 sliders
25	Edificio Manchester	Residential	9	Temuco	37 isolators, 10 sliders
26	Edificio Marina Pai Hue	Residential	10	Pucón	13 isolators
27	Edificio Minvu Serviu de Antofagasta	Office	7	Antofagasta	37 isolators, 2 sliders
28	Edificio Mistral	Office			
29	Edificio Nueva Las Condes - Habitacional	Residential	16	Las Condes	2 isolated TMDs
30	Edificio Nueva Las Condes - Oficinas	Office	20	Las Condes	46 viscous dampers
31	Edificio Nuevo Poniente	Residential	22	Viña del Mar	2 isolated TMDs
32	Edificio ONEMI	Office	3	Santiago	16 isolators
33	Edificio Parque Araucano	Office	22	Las Condes	2 pendulum TMDs
34	Edificio Parque Manuel Rodríguez	Residential		Calama	
35	Edificio San Agustín	Educational	4	Macul	53 isolators, 16 sliders
36	Edificio Titanium	Office	52	Vitacura	45 metallic dampers
37	Edificio Tucapel	Residential	33	Santiago	2 isolated TMDs
38	Edificio VULCO	Office	2	San Bernardo	12 isolators, 6 sliders
39	Edificios Condominio Parque	Residential	11	Vitacura	16 metallic dampers
40	Estanque de gas natural licuado	Industrial	-	Mejillones	501 isolators
41	Facultad de Química, U. de Concepción	Educational	3	Concepción	18 isolators, 18 sliders
42	Horno de fundición, planta Llay Llay	Industrial	-	Llay-Llay	80 isolators, 18 sliders
43	Hospital Clínico U. de Los Andes	Hospital	7	Las Condes	118 isolators
44	Hospital de Antofagasta	Hospital	9	Antofagasta	280 isolators, 139 sliders
45	Hospital del Trabajador ACHS	Hospital	7	Providencia	32 isolators
46	Hospital Dr. Gustavo Fricke	Hospital	9	Viña del Mar	352 isolators
47	Hospital Exequiel González Cortés	Hospital	6	San Miguel	162 isolators y 38 sliders
48	Hospital HUAP	Hospital	3	Santiago	33 isolators y 19 sliders
49	Hospital La Florida	Hospital	5	La Florida	224 isolators
50	Hospital Las Higueras	Hospital	7	Talcahuano	169 isolators
51	Hospital Maipú	Hospital	5	Maipú	347 isolators
52	Hospital Militar	Hospital	5	La Reina	164 isolators
53	Intendencia de Talca	Office	11	Talca	18 isolators, 15 sliders
54	Mirador del Santuario	Residential	8	Valdivia	
55	Muelle Coronel	Industrial	1	Coronel	96 isolators
56	Nuñoa Capital	Residential		Nuñoa	TMDs
57	Parque San Damián				
58	Planta DTP de SQM	Industrial	9	María Elena	21 isolators
59	Proyecto Marconi 10 pisos (2)	Residential	10	Los Angeles	12 isolators each
60	Proyecto Marconi 8 pisos (4)	Residential	8	Los Angeles	12 isolators each
61	Security Vida				
62	Silos Termoeléctrica Andina	Industrial	-	Mejillones	24 isolators
63	Torre Uno	Office	11	Temuco	20 isolators, 10 sliders
64	Viviendas Sociales de Paniahue	Residential	4	Santa Cruz	7 isolators, 21 sliders

7 Conclusions

This article described some of the trends observed in global research and design of structures equipped with seismic protection systems (SPS), but concentrated exclusively on the last 10 years of development in the field. It also summarizes some results of the SPS research done in Chile by the principal author and the graduate students, presents an overview of a new widely applicable design

procedure that has been calibrated for the past 15 years, and shows the current state of building and industrial implementations with SPS in the country. From a very detailed literature review, it is concluded that there is no clear evidence of neither particular changes in emphasis in research work, nor a definite boom of SPS technology research relative to other fields in earthquake engineering despite the great success observed in the seismic performance of structures with SPS during large recent earthquakes. Some promising trends that could become increasingly relevant in the near future are seismic isolation of tall buildings, the more frequent use of semi-active (and smart) SPS, a better alignment of industrialized (and precast) construction techniques and SPS, the use of self-centering SPS and the minimization of damage, and the expansion of SPS toward the protection of low-cost and lightweight structures. It is also concluded that the proposed design procedure for structures equipped with SPS worked very well in all 9 building cases considered as test beds, and due to its simplicity relative to other static and dynamic inelastic models, it could be useful for the engineering profession and future energy dissipation seismic codes. Finally, the request done to several Chilean structural engineers enabled to compile a list of 64 seismically protected buildings and industrial facilities, which to the best of our understanding is an accurate reflection of the situation as of 2015.

8 References

- [1] Guha-Sapir D, Below R, Hoyois P (2015): EM-DAT: International Disaster Database. <http://www.emdat.be>. Accessed 17 Feb 2015
- [2] Superintendencia de Valores y Seguros de Chile (2012): Terremoto 2010: Análisis e Impacto del 27-F en el Mercado Asegurador. Santiago de Chile.
- [3] Housner GW, Bergman LA, Caughey TK, et al (1997): Structural Control: Past, Present, and Future. *Journal of Engineering Mechanics*, **123** (9), 897–971.
- [4] Soong TT, Spencer BF (2002): Supplemental energy dissipation : state-of-the-art and state-of-the- practice. *Engineering Structures*, **24**, 243–259.
- [5] Symans MD, Charney FA, Whittaker AS, Constantinou MC, Kircher CA, Johnson MW, McNamara RJ (2008): Energy Dissipation Systems for Seismic Applications: Current Practice and Recent Developments. *Journal of Structural Engineering*, **134** (1), 3–21.
- [6] Spencer BF, Nagarajaiah S (2003): State of the Art of Structural Control. *Journal of Structural Engineering*, **129** (7), 845–856.
- [7] Warn GP, Ryan KL (2012): A Review of Seismic Isolation for Buildings: Historical Development and Research Needs. *Buildings*, **2**, 300–325.
- [8] Wilson JC, Wesolowsky MJ (2005): Shape memory alloys for seismic response modification: A state-of-the-art review. *Earthquake Spectra*, **21** (2), 569–601.
- [9] Song G, Sethi V, Li HN (2006): Vibration control of civil structures using piezoceramic smart materials: A review. *Engineering Structures*, **28**, 1513–1524.
- [10] Cheng FY, Jiang H, Lou K (2008): *Smart Structures: Innovative Systems for Seismic Response Control*. CRC Press.
- [11] Naeim F, Kelly JM (1999): *Design of Seismic Isolated Structures: From Theory to Practice*. John Wiley & Sons.
- [12] Robinson WH, Tucker AG (1977): A lead-rubber shear damper. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **10** (3), 151–153.
- [13] Robinson WH (2011): Lead-rubber hysteretic bearings suitable for protecting structures during earthquakes. *Seismic Isolation and Protective Systems*, **2** (1), 5–19.
- [14] Derham CJ, Kelly JM, Thomas AG (1985): Nonlinear natural rubber bearings for seismic isolation. *Nuclear Engineering and Design*, **84**, 417–428.

- [15] Tarics AG, Way D, Kelly JM (1984): The Implementation of Base Isolation for the Foothill Communities Law and Justice Center. Report to the National Science Foundation and the County of San Bernardino
- [16] Frahm H (1909): Device for Damping Vibrations of Bodies. US patent #989958.
- [17] Den Hartog JP (1947): *Mechanical vibrations*. McGraw-Hill.
- [18] Clark AJ (1988): Multiple passive tuned mass damper for reducing earthquake induced building motion. *Proceeding 9th World Conf. Earthq. Eng.*, Tokyo/Kyoto, Japan.
- [19] Palazzo B, Petti L (1994): *Seismic response control in base isolated systems using tuned mass dampers*. Seismic engineering -- 1994: Volume 2. PVP-Volume 275-2.
- [20] Bauer HF (1984): Oscillations of immiscible liquids in a rectangular container: A new damper for excited structures. *Journal of Sound and Vibration*, **93** (1), 117–133.
- [21] Pall AS, Marsh C (1979): Energy Dissipation in Large Panel Structures Using Limited Slip Bolted Joints. *AICAP/CEB Seism. Conf.*, Rome, Italy.
- [22] Pall AS, Marsh C (1981): Friction-devices to control seismic response. *ASCE/EMD Speciality Conference on Dynamic Response of Structures*, Atlanta, USA.
- [23] Pall AS, Marsh C, Fazio P (1980): Friction joints for seismic control of large panel structures. *Journal of the Prestressed Concrete Institute*, **25** (6), 38–61.
- [24] Pall AS, Marsh C (1981): Friction-damped concrete shear walls. *Journal of the American Concrete Institute* **78**:
- [25] Pall AS, Marsh C (1982): Response of friction damped braced frames. *Journal of Structural Engineering*, **108** (9), 1313–1323.
- [26] Aiken ID, Kelly JM (1990): Earthquake simulator testing and analytical studies of two energy-absorbing systems for multistory structures.
- [27] FitzGerald TF, Anagnos T, Goodson M, Zsutty T (1989): Slotted Bolted Connections in Aseismic Design for Concentrically Braced Connections. *Earthquake Spectra*, **5** (2), 383–391.
- [28] Nims DK, Richter PJ, Bachman RE (1993): The Use of the Energy Dissipating Restraint for Seismic Hazard Mitigation. *Earthquake Spectra*, **9** (3), 467–489.
- [29] Kelly JM, Skinner RI, Heine AJ (1972): Mechanisms of energy absorption in special devices for use in earthquake resistant structures. *Bulletin of the New Zealand National Society for Earthquake Engineering*, **5** (3), 63–88.
- [30] Skinner RI, Kelly JM, Heine AJ (1974): Hysteretic Dampers for Earthquake-Resistant Structures. *Earthquake Engineering & Structural Dynamics*, **3** (3), 287–296.
- [31] Whittaker AS, Bertero V V, Thompson CL, Alonso LJ (1991): Seismic Testing of Steel Plate Energy Dissipation Devices. *Earthquake Spectra*, **7** (4), 563–604.
- [32] Iwata M, Kato T, Wada A (2000): buckling-restrained braces as hysteretic dampers. *Behaviour of steel structures in Seismic Areas, STESSA*, **2000**, 33–38.
- [33] Nielsen EJ, Lai ML, Soong TT, Kelly JM (1996): Viscoelastic damper overview for seismic and wind applications. *Proc SPIE*, **2720**, 138–144.
- [34] Soong TT, Dargush GF (1997): *Passive energy dissipation systems in structural engineering*. John Wiley & Sons, Chichester, England.
- [35] Hüffmann GK (1985): Full base isolation for earthquake protection by helical springs and viscodampers. *Nuclear Engineering and Design*, **84** (3), 331–338.
- [36] Arima F, Miyasaki M, Tanaka H, Yamasaki Y (1988): A study on building with large damping using viscous damping walls. *Proceedings of the 9th World Conference on Earthquake Engineering*, , 821–826.
- [37] Karnopp D, Crosby MJ, Harwood RA (1974): Vibration Control Using Semi-Active Force Generators. *Journal of Engineering for Industry*, **96** (2), 619.
- [38] Hrovat D, Barak P, Rabins M (1983): Semi-Active versus Passive or Active Tuned Mass Dampers for Structural Control. *Journal of Engineering Mechanics*, **109** (3), 691–705.

- [39] Lou J, Lutes L, Li J (1994): Active tuned liquid damper for structural control. *Proc 1st World Conf on Struct Control*, Los Angeles, CA.
- [40] Banerji P, Murudi M, Shah AH, Popplewell N (2000): Tuned liquid dampers for controlling earthquake response of structures. *Earthquake Engineering and Structural Dynamics*, **29** (5), 587–602.
- [41] Akbay A, Aktan HM (1991): Actively regulated friction slip braces. *Proc. 6th Can. Conf. Earthq. Eng.*, Toronto, Canada.
- [42] Chen G, Chen C (2000): Behavior of piezoelectric friction dampers under dynamic loading. *Proc SPIE*, **3988**, 54–63.
- [43] Makris N (1997): Rigidity-plasticity-viscosity: Can electrorheological dampers protect base-isolated structures from near-source earthquakes? *Earthquake Engineering & Structural Dynamics*, **26** (5), 571–591.
- [44] Kemmetmüller W, Holzmann K, Kugi A, Stork M (2013): Electrorheological semiactive shock isolation platform for naval applications. *IEEE/ASME Transactions on Mechatronics*, **18** (5), 1437–1447.
- [45] Dyke SJ, Spencer BF, Sain MK, Carlson JD (1999): Modeling and control of magnetorheological dampers for seismic response reduction. *Smart Materials and Structures*, **5** (5), 565–575.
- [46] Dyke SJ, Spencer BF, Sain MK, Carlson JD (1996): Experimental verification of semi-active structural control strategies using acceleration feedback. *Proc of the 3rd Intl Conf on Motion and Vibr Control*.
- [47] Dyke SJ, Spencer BF, Sain MK, Carlson JD (1996): Seismic response reduction using magnetorheological dampers. *Proceedings of the IFAC world congress*, San Francisco, CA.
- [48] Spencer BF, Carlson JD, Sain MK, Yang G (1997): On the current status of magnetorheological dampers: seismic protection of full-scale structures. *Proceedings of the American Control Conference*.
- [49] Spencer B, Dyke S, Sain M (1996): Magnetorheological dampers: a new approach to seismic protection of structures. *Proceedings of the 35th IEEE Conference on Decision and Control*, 1996, Kobe, Japan.
- [50] Liao WH, Wang DH (2003): Semiactive Vibration Control of Train Suspension Systems via Magnetorheological Dampers. *Journal of Intelligent Material Systems and Structures*, **14**, 161–172.
- [51] Wang X, Gordaninejad F (2002): Lyapunov-Based Control of a Bridge Using Magneto-Rheological Fluid Dampers. *Journal of Intelligent Material Systems and Structures*, **13**, 415–419.
- [52] Sahasrabudhe SS, Nagarajaiah S (2005): Semi-active control of sliding isolated bridges using MR dampers: An experimental and numerical study. *Earthquake Engineering and Structural Dynamics*, **34** (January), 965–983.
- [53] Gordaninejad F, Saiidi M, Hansen BC, Ericksen EO, Chang F-K (2002): Magneto-Rheological Fluid Dampers for Control of Bridges. *Journal of Intelligent Materials Systems and Structures*, **13**, 167–180.
- [54] Wang JY, Ni YQ, Ko JM, Spencer BF (2005): Magneto-rheological tuned liquid column dampers (MR-TLCDs) for vibration mitigation of tall buildings: Modelling and analysis of open-loop control. *Computers and Structures*, **83**, 2023–2034.
- [55] Feng Q, Shinozuka M (1990): Use of a variable damper for hybrid control of bridge response under earthquake. *Proc. U.S. Natl. Work. Struct. Control Res.*
- [56] Kawashima K, Unjoh S, Iida H, Mukai H (1992): Effectiveness of the variable damper for reducing seismic response of highway bridges. *Proceedings of Second US–Japan Workshop on Earthquake Protective Systems for Bridges*.
- [57] Uang C-M, Bertero V V. (1990): Evaluation of seismic energy in structures. *Earthquake Engineering & Structural Dynamics*, **19** (1), 77–90.
- [58] Kumar M, Whittaker AS, Constantinou MC (2014): An advanced numerical model of elastomeric seismic isolation bearings. *Earthquake Engineering & Structural Dynamics*, **43** (13), 1955–1974.
- [59] De la Llera JC, Lüders C, Leigh P, Sady H (2004): Analysis, testing, and implementation of seismic isolation of buildings in Chile. *Earthquake Engineering and Structural Dynamics*, **33** (August 2003), 543–574.
- [60] Calugaru V, Panagiotou M (2014): Seismic response of 20-story base-isolated and fixed-base reinforced concrete structural wall buildings at a near-fault site. *Earthquake Engineering & Structural Dynamics*, **43** (6), 927–948.

- [61] Masaeli H, Khoshnoudian F, Hadikhan Tehrani M (2014): Rocking isolation of nonductile moderately tall buildings subjected to bidirectional near-fault ground motions. *Engineering Structures*, **80**, 298–315.
- [62] Panchal VR, Jangid RS (2008): Variable friction pendulum system for near-fault ground motions. *Structural Control and Health Monitoring*, **15** (4), 568–584.
- [63] Nishitani A, Nitta Y, Wakahara C (2009): Artificial nonlinearity in structural control: Its original concept survey and significance in semiactive control scheme. *Structural Control and Health Monitoring*, **16** (1), 17–31.
- [64] Suresh S, Narasimhan S, Sundararajan N (2008): Adaptive control of nonlinear smart base-isolated buildings using Gaussian kernel functions. *Structural Control and Health Monitoring*, **15** (4), 585–603.
- [65] Loh C-H, Weng J-H, Chen C-H, Lu K-C (2013): System identification of mid-story isolation building using both ambient and earthquake response data. *Structural Control and Health Monitoring*, **20** (2), 139–155.
- [66] Wang S-J, Chang K-C, Hwang J-S, Hsiao J-Y, Lee B-H, Hung Y-C (2012): Dynamic behavior of a building structure tested with base and mid-story isolation systems. *Engineering Structures*, **42**, 420–433.
- [67] Wang S-J, Hwang J-S, Chang K-C, Lin M-H, Lee B-H (2013): Analytical and experimental studies on midstory isolated buildings with modal coupling effect. *Earthquake Engineering & Structural Dynamics*, **42** (2), 201–219.
- [68] Wang S-J, Chang K-C, Hwang J-S, Lee B-H (2011): Simplified analysis of mid-story seismically isolated buildings. *Earthquake Engineering & Structural Dynamics*, **40** (2), 119–133.
- [69] Charmpis DC, Komodromos P, Phocas MC (2012): Optimized earthquake response of multi-storey buildings with seismic isolation at various elevations. *Earthquake Engineering & Structural Dynamics*, **41**, 2289–2310.
- [70] Araki Y, Kawabata S, Asai T, Masui T (2011): Response of vibration-isolated object to ground motions with intense vertical accelerations. *Engineering Structures*, **33** (12), 3610–3619.
- [71] Furukawa S, Sato E, Shi Y, Becker T, Nakashima M (2013): Full-scale shaking table test of a base-isolated medical facility subjected to vertical motions. *Earthquake Engineering & Structural Dynamics*, **42** (13), 1931–1949.
- [72] Unal M, Warn GP (2014): Optimal cost-effective topology of column bearings for reducing vertical acceleration demands in multistory base-isolated buildings. *Earthquake Engineering & Structural Dynamics*, **43** (8), 1107–1127.
- [73] Araki Y, Asai T, Masui T (2009): Vertical vibration isolator having piecewise-constant restoring force. *Earthquake Engineering & Structural Dynamics*, **38** (13), 1505–1523.
- [74] Lee S-H, Lee K-K, Woo S-S, Cho S-H (2013): Global vertical mode vibrations due to human group rhythmic movement in a 39 story building structure. *Engineering Structures*, **57**, 296–305.
- [75] Caetano E, Cunha Á, Moutinho C, Magalhães F (2010): Studies for controlling human-induced vibration of the Pedro e Inês footbridge, Portugal. Part 2: Implementation of tuned mass dampers. *Engineering Structures*, **32** (4), 1082–1091.
- [76] Chang M-L, Lin C-C, Ueng J-M, Hsieh K-H, Wang J-F (2010): Experimental study on adjustable tuned mass damper to reduce floor vibration due to machinery. *Structural Control and Health Monitoring*, **17** (5), 532–548.
- [77] Pinkaew T, Fujino Y (2001): Effectiveness of semi-active tuned mass dampers under harmonic excitation. *Engineering Structures*, **23** (7), 850–856.
- [78] Lin C-C, Lin G-L, Wang J-F (2010): Protection of seismic structures using semi-active friction TMD. *Earthquake Engineering & Structural Dynamics*, **39** (6), 635–659.
- [79] Valente M (2013): Innovative Systems for Seismic Protection of Precast Industrial Buildings. *Applied Mechanics and Materials*, **274**, 117–120.
- [80] Braconi A, Morelli F, Salvatore W (2012): Development, design and experimental validation of a steel self-centering device (SSCD) for seismic protection of buildings. *Bulletin of Earthquake Engineering*, **10** (6), 1915–1941.
- [81] Pinochet J, de la Llera JC, Lüders C (2006): Analysis of a kinematic self-centring seismic isolator. *Earthquake Engineering & Structural Dynamics*, **35** (12), 1533–1561.
- [82] Song G, Ma N, Li H-N (2006): Applications of shape memory alloys in civil structures. *Engineering Structures*, **28** (9), 1266–1274.

- [83] Ozbulut, O.E. and Hurlbaeus S (2012): A Comparative Study on the Seismic Performance of Superelastic-Friction Base Isolators against Near-Field Earthquakes. *Earthquake Spectra*, **28** (3), 1147–1163.
- [84] Gur S, Mishra SK, Chakraborty S (2014): Stochastic optimization of shape-memory-alloy rubber bearing (SMARB) for isolating buildings against random earthquake. *Structural Control and Health Monitoring*, **21** (9), 1222–1239.
- [85] Sharabash AM, Andrawes BO (2009): Application of shape memory alloy dampers in the seismic control of cable-stayed bridges. *Engineering Structures*, **31** (2), 607–616.
- [86] Zuo X-B, Li A-Q, Chen Q-F (2007): Design and Analysis of a Superelastic SMA Damper. *Journal of Intelligent Material Systems and Structures*, **19** (6), 631–639.
- [87] Andrawes B, DesRoches R (2007): Effect of hysteretic properties of superelastic shape memory alloys on the seismic performance of structures. *Structural Control and Health Monitoring*, **14** (2), 301–320.
- [88] Roh H, Reinhorn AM (2010): Hysteretic behavior of precast segmental bridge piers with superelastic shape memory alloy bars. *Engineering Structures*, **32** (10), 3394–3403.
- [89] Shook DA, Roschke PN, Ozbulut OE (2008): Superelastic semi-active damping of a base-isolated structure. *Structural Control and Health Monitoring*, **15** (5), 746–768.
- [90] Parulekar YM, Reddy GR, Vaze KK, Guha S, Gupta C, Muthumani K, Sreekala R (2012): Seismic response attenuation of structures using shape memory alloy dampers. *Structural Control and Health Monitoring*, **19** (1), 102–119.
- [91] Ozbulut OE, Hurlbaeus S (2012): Application of an SMA-based hybrid control device to 20-story nonlinear benchmark building. *Earthquake Engineering & Structural Dynamics*, **41** (13), 1831–1843.
- [92] Walter Yang C-S, DesRoches R, Leon RT (2010): Design and analysis of braced frames with shape memory alloy and energy-absorbing hybrid devices. *Engineering Structures*, **32** (2), 498–507.
- [93] Li L, Li Q, Zhang F (2007): Behavior of Smart Concrete Beams with Embedded Shape Memory Alloy Bundles. *Journal of Intelligent Material Systems and Structures*, **18** (10), 1003–1014.
- [94] Gur S, Mishra SK, Chakraborty S (2014): Performance assessment of buildings isolated by shape-memory-alloy rubber bearing: Comparison with elastomeric bearing under near-fault earthquakes. *Structural Control and Health Monitoring*, **21** (4), 449–465.
- [95] Tsang HH (2011): Geotechnical seismic isolation. *Earthquake Engineering: New Research*, 55–87, Nova Science Publishers, Inc.
- [96] Kelly JM (2002): Seismic Isolation Systems for Developing Countries. *Earthquake Spectra*, **18** (3), 385–406.
- [97] Jünemann R, de la Llera JC, Besa J, Almazán JL (2009): Three-dimensional behavior of a spherical self-centering precast prestressed pile isolator. *Earthquake Engineering & Structural Dynamics*, **38** (5), 541–564.
- [98] Tsang H-H (2008): Seismic isolation by rubber–soil mixtures for developing countries. *Earthquake Engineering & Structural Dynamics*, **37** (2), 283–303.
- [99] Calabrese A, Spizzuoco M, Serino G, Della Corte G, Maddaloni G (2015): Shaking table investigation of a novel, low-cost, base isolation technology using recycled rubber. *Structural Control and Health Monitoring*, **22** (1), 107–122.
- [100] Spizzuoco M, Calabrese A, Serino G (2014): Innovative low-cost recycled rubber–fiber reinforced isolator: Experimental tests and Finite Element Analyses. *Engineering Structures*, **76**, 99–111.
- [101] Besa J, de la Llera JC, Jünemann R (2010): Experimental behavior and design of a new kinematic isolator. *Engineering Structures*, **32** (2), 508–522.
- [102] Alarcon C, Hube MA, de la Llera JC (2014): Effect of axial loads in the seismic behavior of reinforced concrete walls with unconfined wall boundaries. *Engineering Structures*, **73**, 13–23.
- [103] Westenenk B, de la Llera JC, Besa JJ, Jünemann R, Moehle J, Lüders C, Inaudi JA, Elwood KJ, Hwang S-J (2012): Response of Reinforced Concrete Buildings in Concepción during the Maule Earthquake. *Earthquake Spectra*, **28** (S1), S257–S280.
- [104] Encina J, De la Llera JC (2013): A simplified model for the analysis of free plan buildings using a wide-column model. *Engineering Structures*, **56**, 738–748.

- [105] Sepúlveda C, De la Llera JC, Jacobsen A (2012): An empirical model for preliminary seismic response estimation of free-plan nominally symmetric buildings using ANFIS. *Engineering Structures*, **37**, 36–49.
- [106] Westenenk B, de la Llera JC, Jünemann R, Hube MA, Besa JJ, Lüders C, Inaudi JA, Riddell R, Jordán R (2013): Analysis and interpretation of the seismic response of RC buildings in Concepción during the February 27, 2010, Chile earthquake. *Bulletin of Earthquake Engineering*, **11** (1), 69–91.
- [107] Jünemann R, de la Llera JC, Hube M a., Cifuentes L a., Kausel E (2015): A statistical analysis of reinforced concrete wall buildings damaged during the 2010, Chile earthquake. *Engineering Structures*, **82**, 168–185.
- [108] Quiral F (2014): Comportamiento inelástico-frágil de edificios de muros durante el terremoto de Chile, 2010. Master's Thesis, Pontificia Universidad Católica de Chile.
- [109] Vásquez J (2015): Nonlinear modeling of reinforced concrete shear walls using an improved fiber element. Master's Thesis, Pontificia Universidad Católica de Chile.
- [110] De la Llera JC, Esguerra C, Almazán JL (2004): Earthquake behavior of structures with copper energy dissipators. *Earthquake Engineering & Structural Dynamics*, **33** (3), 329–358.
- [111] Briones B, de la Llera JC (2014): Analysis, design and testing of an hourglass-shaped copper energy dissipation device. *Engineering Structures*, **79**, 309–321.
- [112] De la Llera JC, Lüders C, Rodríguez JT (2013): Partition wall dissipator. WO Patent 2013/059952.
- [113] Rodríguez JT (2011): Energy Dissipation Partition Walls. Master's Thesis, Pontificia Universidad Católica de Chile.
- [114] Frings C, de la Llera JC (2011): Multiphysics Modeling and Experimental Behavior of Viscous Dampers. *8th Int. Conf. Struct. Dyn. Eurodyn 2011*.
- [115] Sternberg A, Zemp R, de la Llera JC (2014): Multiphysics behavior of a magneto-rheological damper and experimental validation. *Engineering Structures*, **69**, 194–205.
- [116] Zemp R, de la Llera JC, Roschke P (2011): Tall building vibration control using a TM-MR damper assembly: Experimental results and implementation. *Earthquake Engineering and Structural Dynamics*, **40** (3), 257–271.
- [117] Zemp R, de la Llera JC, Almazán JL (2011): Tall building vibration control using a TM-MR damper assembly. *Earthquake Engineering and Structural Dynamics*, **40** (3), 339–354.
- [118] Zemp R, de la Llera JC, Weber F (2014): Experimental analysis of large capacity MR dampers with short- and long-stroke. *Smart Materials and Structures*, **23** (12), 125028.
- [119] Pardo-Varela J, de la Llera JC (2015): A semi-active piezoelectric friction damper. *Earthquake Engineering & Structural Dynamics*, **44** (3), 333–354.
- [120] Herreros R (2014): Caracterización del Comportamiento Axial de Elastómeros Magnetoreológicos. Master's Thesis, Pontificia Universidad Católica de Chile.
- [121] Beltran JF, Cruz C, Herrera R, Moroni O (2011): Shape memory alloy CuAlBe strands subjected to cyclic axial loads. *Engineering Structures*, **33** (10), 2910–2918.
- [122] Heresi P, Herrera RA, Moroni MO (2014): Testing and modelling of shape memory alloy plates for energy dissipators. *Smart Structures and Systems*, **14** (5), 883–900.
- [123] Sepúlveda J, Boroschek R, Herrera R, Moroni O, Sarrazin M (2008): Steel beam–column connection using copper-based shape memory alloy dampers. *Journal of Constructional Steel Research*, **64** (4), 429–435.
- [124] Moroni MO, Saldivia R, Sarrazin M, Sepúlveda A (2002): Damping characteristics of a CuZnAlNi shape memory alloy. *Materials Science and Engineering A*, **335** (1), 313–319.
- [125] Boroschek RL, Farias G, Moroni O, Sarrazin M (2007): Effect of SMA Braces in a Steel Frame Building. *Journal of Earthquake Engineering*, **11** (3), 326–342.
- [126] Lafontaine M, Moroni O, Sarrazin M, Roschke P (2009): Optimal Control of Accelerations in a Base-Isolated Building using Magneto-Rheological Dampers and Genetic Algorithms. *Journal of Earthquake Engineering*, **13** (8), 1153–1171.

- [127] Instituto Nacional de Normalización (2009): *NCh 433 Of. 1996, Modified in 2009, Earthquake resistant design of buildings [in spanish]*. Santiago, Chile.
- [128] Ministerio de Vivienda y Urbanismo (2011): *DS N°61, Reglamento que fija el diseño sísmico de edificios y deroga Decreto N° 117, de 2010 [in spanish]*. Diario Oficial.
- [129] Instituto Nacional de Normalización (2013): *NCh 2745 Of. 2003, Modified in 2013, Earthquake-resistant design of base-isolated buildings [in spanish]*. Santiago, Chile.
- [130] Instituto Nacional de Normalización (2002): *NCh 2369 Of. 2002, Earthquake-resistant design of industrial structures and facilities [in spanish]*.
- [131] ASCE (2010): *Minimum design loads for buildings and other structures*, ASCE/SEI 7. ASCE/SEI 7, Reston, VA.
- [132] European Committee for Standardisation (2004): *EN 1998-1, Eurocode 8: Design of structures for earthquake resistance - Part 1*. Brussels.
- [133] Applied Technology Council (1996): *ATC-40, Seismic Evaluation and Retrofit of Concrete Buildings*. Redwood City, CA.
- [134] Takewaki I (1997): Optimal damper placement for minimum transfer functions. *Earthquake Engineering and Structural Dynamics*, **26** (11), 1113–1124.
- [135] Fujita K, Yamamoto K, Takewaki I (2010): An evolutionary algorithm for optimal damper placement to minimize interstorey-drift transfer function in shear building. *Earthquake and Structures*, **1** (3), 289–306.
- [136] Goel RK (1998): Effects of supplemental viscous damping on seismic response of asymmetric-plan systems. *Earthquake Engineering & Structural Dynamics*, **27** (2), 125–141.
- [137] Goel RK, Booker CA (2001): Effects of supplemental viscous damping on inelastic seismic response of asymmetric systems. *Earthquake Engineering & Structural Dynamics*, **30** (3), 411–430.
- [138] Almazán JL, de la Llera JC (2009): Torsional balance as new design criterion for asymmetric structures with energy dissipation devices. *Earthquake Engineering & Structural Dynamics*, **38** (12), 1421–1440.
- [139] Aguirre JJ, Almazán JL, Paul CJ (2013): Optimal control of linear and nonlinear asymmetric structures by means of passive energy dampers. *Earthquake Engineering & Structural Dynamics*, **42** (3), 377–395.
- [140] Yang JN, Lin S, Kim J-H, Agrawal AK (2002): Optimal design of passive energy dissipation systems based on H₂ and H_∞ performances. *Earthquake Engineering & Structural Dynamics*, **31** (4), 921–936.
- [141] Moreschi LM, Singh MP (2003): Design of yielding metallic and friction dampers for optimal seismic performance. *Earthquake Engineering and Structural Dynamics*, **32** (8), 1291–1311.
- [142] Dargush GF, Sant RS (2005): Evolutionary aseismic design and retrofit of structures with passive energy dissipation. *Earthquake Engineering and Structural Dynamics*, **34** (May), 1601–1626.
- [143] Uz ME, Hadi MNS (2014): Optimal design of semi active control for adjacent buildings connected by MR damper based on integrated fuzzy logic and multi-objective genetic algorithm. *Engineering Structures*, **69**, 135–148.
- [144] Cha Y-J, Agrawal AK, Phillips BM, Spencer BF (2014): Direct performance-based design with 200kN MR dampers using multi-objective cost effective optimization for steel MRFs. *Engineering Structures*, **71**, 60–72.
- [145] Gluck N, Reinhorn AM, Gluck J, Levy R (1996): Design of Supplemental Dampers for Control of Structures. *Journal of Structural Engineering*, **122** (12), 1394–1399.
- [146] Lavan O, Levy R (2005): Optimal design of supplemental viscous dampers for irregular shear-frames in the presence of yielding. *Earthquake Engineering & Structural Dynamics*, **34** (8), 889–907.
- [147] Lin YY, Tsai MH, Hwang JS, Chang KC (2003): Direct displacement-based design for building with passive energy dissipation systems. *Engineering Structures*, **25**, 25–37.
- [148] Chen Z, Ge H, Kasai A, Usami T (2007): Simplified seismic design approach for steel portal frame piers with hysteretic dampers. *Earthquake Engineering & Structural Dynamics*, **36** (4), 541–562.
- [149] Habibi A, Chan RWK, Albermani F (1996): Energy-based design method for seismic retrofitting with passive energy dissipation systems. *Engineering Structures*, **46**, 77–86.

- [150] Moehle J, Deierlein GG (2004): A framework methodology for performance-based earthquake engineering. *Proc. 13th World Conf. Earthq. Eng.*, Vancouver, Canada.
- [151] Tubaldi E, Barbato M, Dall'Asta A (2014): Performance-based seismic risk assessment for buildings equipped with linear and nonlinear viscous dampers. *Engineering Structures*, **78** (1), 90–99.
- [152] Huang Y-N, Whittaker AS, Luco N (2010): Seismic performance assessment of base-isolated safety-related nuclear structures. *Earthquake Engineering & Structural Dynamics*, **39** (13), 1421–1442.
- [153] Uliarte RJ (1998): Sistemas Pasivos de Disipación de Energía para la Reducción de Vibraciones en Estructuras: Análisis y Diseño. Master's Thesis, Pontificia Universidad Católica de Chile.
- [154] Besa JJ, de la Llera JC, Westenank B (2015): Design of Buildings Equipped with Energy Dissipation Devices. to be published
- [155] Besa JJ (2012): Effective Design Procedure of Buildings with Energy Dissipation Devices. Master's Thesis, Pontificia Universidad Católica de Chile.