CONCEPTUAL SEISMIC DESIGN AND STATE-OF-THE-ART PROTECTION SYSTEMS

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ABSTRACT

New seismic design methods should address the system ability to dissipate energy and the effects of lateral deformation to improve the safety of buildings. These considerations, involving the architectural as well as the structural configurations of buildings, however, have not significantly influenced the fundamental concepts of architectural design so far. Analyzing the relations among architectural configuration, structural solution and seismic response of buildings equipped with innovative protection systems, leads to the outlining of new basic criteria in architectural conception. Isolation, damping and energy dissipation enhance the building performance and certain essential characteristics, usually considered to be inappropriate, become subordinate. At the same time, new design principles, such as flexibility, discontinuity, motion, device insertion, shape, comfort must be taken in consideration. With reference to new buildings, the criteria illustrated are those guiding the conceptual design of a class of configurations that is characterized by the suspension of portions or elements. With regard to existing buildings, the possibility of preserving the typical class of critical configurations with soft first story is demonstrated through a real case study.

Introduction

New relations among architectural configuration, structural arrangement and the seismic behavior of buildings arise when innovative protection systems, such as base isolation or energy dissipation, are used. The criteria through which architectural conception can guarantee suitable seismic behaviors and the selection of complex forms, or new architectural configurations, must be outlined. Some essential characteristics, usually considered inappropriate, can be used to enhance damping effects and energy dissipation.

This study is included in a more comprehensive research aiming at: organically listing structural solutions for the optimum articulation of architectural configurations for seismic protection, suitably outlining architectural configurations with their significant seismic performances, optimally classifying the innovative protection systems for the configuration classes defined. Applications on case studies and real buildings are illustrated.

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Traditional Rules for Optimum Configuration

The concept of building configuration must be regarded as broad since it includes shape, technology, structural solution and aesthetics. These aspects, although they may be separated from a logical point of view, are interconnected and sometimes interdependent.

Shape

The conventional shape parameters included in the classic principles of earthquake engineering are absolute dimensions, compactness and symmetry, regularity.

The basic configuration parameter, linked to the seismic behavior of structures, consists of buildings dimensions. It was the first parameter included in codes and it is still cited by certain guidelines. The dimension that is really controlled is generally the height of the building, but, in fact, the parameter relates to seismic resistance in connection to structural material. Prescriptions on dimensions have worked, and work out well for masonry buildings, but their effectiveness decreases when it comes to modern and innovative materials. In this case, the principle can be effective in controlling some building performances (overturning, tension in columns).

The principles of symmetry and compactness come to the forth since one objective is avoiding the irregular distribution of forces induced by the earthquake; the optimum goal of a correct seismic design being that all the structural members contribute to the resistance and energy dissipation (Arnold 1982). Avoiding spreading in the distribution of masses, resistances and stiffness eliminates large eccentricities and limits the torsion effect. Symmetry and compactness requirements not only concern the structural configuration but also strongly involve architectural configuration and may impose significant constraints on the building shape.

The principles of uniformity and regularity too aim at eliminating the occurrence of critical zones where concentrations of stress or large ductility demands might cause premature collapse. Actually, these principles, imposing significant limits to the variation of shape, mass, stiffness and resistance in plan and along the height of the building, actually introduce other severe constraints on the configuration and consequently guide the architectural design. They can often be in contrast with some visions of the modern architecture: a typical case is represented by the soft-first-story, which has been, and still is, widely used by architects because it corresponds to one of the leading principle of the modern architecture: the "pilotis-story". This configuration, represented by the absence of claddings at the ground level in framed buildings, was one of the five basic points explained by Le Corbusier in its "Vers une architecture" on 1923.

Technology

The technological aspect of configuration is fundamentally related to structural material. The physical and mechanical characteristics of the material can determine or strongly influence the building configuration. In fact, the optimum use of the material, from an economic and mechanic point of view, requires specific shapes for the structural elements and their assemblage: for example, bracing is required in steel frames characterized by slender elements to resist to lateral forces. In some historical cases - Egiptian pyramids or Babylonian zigurats - material and shape seem to coincide and can be confused. The same happens in the ordinary applications of masonry or stone buildings, where the global configuration depends on the configuration of the structural elements, the walls, depending on the materials.

Structural solution

Arch and vaults are the classic examples of structural solutions determining the configuration: the Roman aqueducts and the domes of the Italian Renaissance well express this principle. Usually the structural solution can slightly influence, and not necessarily determine, the final configuration. It can be considered a "second level" parameter which can be determinant only when linked to the architectural choice of making evident a structural aspect. On the contrary, in some architectural solutions structure is slave to shape, which is chosen on the base of aesthetical or expressive considerations (as, for example, in some projects of irregularly shaped buildings, like the Guggeneim Museum by Frank Gehry, in Bilbao).

New Configuration Rules from Innovative Solutions

New design concepts are required for making the performance of the enhanced system of seismic protection possible (Mezzi et al. 2004). They consist of deformation, motion, discontinuity, visibility of devices, shape and comfort.

One guiding principle is the ability to deform. This principle can be described as the capacity of the construction to perform large local displacements so as to permit the displacement of dissipative devices inserted in the structural grid. Vertical dissipative bracing can be inserted in the frame grid and dissipate energy in the relative displacement through adjacent floors. Horizontal bracing can be equipped with dampers dissipating energy through the horizontal shifts of braced floors. In both cases, large displacements via adjacent connections guarantee remarkable energy dissipation and response reduction.

Another performance guaranteeing for an easy energy dissipation is linked to the capacity of a construction to move, that is to change its spatial position in time. The concept contrasts one of the four classical Vitruvius' principles: the "firmitas", which represents the solidness of the construction, rigidly connected to a firm soil. The movement may affect the entire structure or only a section, it deforms devices that, mounted between the building and the firm soil or between building sections which have relative movement, dissipate energy and reduce lateral response.

The principle of discontinuity relates to that of movement and challenges the architect. Making the motion of the total construction or its parts possible requires forgetting about external continuity with the ground and internal continuity among members. Motion can be allowed only if a solution of continuity is present: (a) the whole building disconnected from the ground, as in base isolation; (b) mobile sections of building separated from the firm portions integral with the ground, as in suspended building with floating stories; (c) total portions of the building separated to benefit from relative displacements; (d) local structural elements separated from the main structure, as in suspended or floating floors.

The reduction of seismic response does not depend on deformations or displacements but on the movement of special dissipating or isolating devices in function during those deformations or displacements. The presence of devices introduces another theme in the architectural design of buildings equipped with these enhanced protection systems, consisting in the insertion of "devices" that look like and generally are mechanisms (viscous, friction or plastic dissipating elements), machines (active dampers) or are made of special materials, unusual in constructions, such as laminated rubber isolators. Sometimes these devices have been shown, exalting the characteristic of special earthquake protection, Figure 1 a and c, while, in other situations, their presence and signs are hidden and the building appears as an ordinary one, Figure 1 b.

Figure 1. (a) Union House,Auckland - (b) Umeda DT Tower, Osaka - (c) Emergency Management Center, Foligno (Italy)

More complex concepts regarding the shape must be applied when new seismic protection systems are inserted for enhancing seismic performances. The shape is not an absolute factor directly influencing the effectiveness of the seismic response anymore, but it must be related to the presence and position of the devices. Two principles can be referred to.

The first principle corresponds to the goal of a shape optimizing the performance of the seismic protection system. Specific criteria must be found for each system. In base isolation, for instance, the stiffness centrifugation of the isolator system and the perimeter concentration of vertical load have been proven to optimize the device behavior and the building response (Mezzi 2003). The application of new criteria can even lead to innovative global shapes as shown in Figure 1c (Parducci 2001).

The second principle concerns the possibility to overcome the traditional shape constraints related to symmetry, compactness and regularity, considering the whole effect of global building shape, discontinuities and devices position. These factors interact and determine the real behavior of buildings: for example, buildings with complex irregular in-plan shapes can have a "regular" response, strongly mitigating torsion effects, if an isolation system, characterized by the absence of eccentricity between mass and stiffness centers and by good stiffness centrifugation, is provided.

A different class of problems derives from the special performances of buildings equipped with innovative protection systems and relates to their deformability. The motion capability of the buildings, to be developed under seismic attacks, remains a constant characteristic of the construction and could create troubles under ordinary service loads. Strong earthquakes that induce movement in buildings are rare events, characterized by short duration, therefore motion is admissible or large values of the acceptance limits can be assumed, but flexible and movable buildings must be checked, for the comfort of the occupants, under service lateral loads which are frequent and can have a long duration that could provoke the same movements, even though with reduced amplitude. Comfort and panic controls criteria, generally well established both in national and international codes and based on the examination of the cinematic parameter, can be applied.

Even though the effects must be checked, this cannot be considered a real problem creating difficulties on the application of the innovative systems, actually, the presence of isolating or dissipating devices and, even more so, of active or hybrid systems for the control of vibrations, usually has a positive effect on the construction dynamic, reducing the impact that vibrations may have on occupants.

Application of New Concepts of Seismic Protection

Two aspects of design are involved in the application of innovative seismic protection systems and their relation with building configuration. The first concerns the possibility, or need, to develop new configurations made possible, or required, by the new performances. The second consists in the possibility, prompted by the new systems, to sustain the seismic performance of configurations that would otherwise be incompatible with earthquake resistance, and then enable the enhancement of existing unsuited configurations. These two options, the use of state of the art in aseismic technologies, are described and discussed in the next two chapters, by referring to two classes of configurations: the suspended schemes for new buildings, and the soft story for existing buildings.

Enhanced Configurations of New Buildings

A typical category of structural solutions, making configuration rules compatible with innovative solutions, particularly in discontinuity and motion, is that provided for the suspension of building parts or elements. Different structural schemes with these characteristics have been investigated. The first consists of seismically isolated suspended buildings in which energy dissipating devices are inserted between the oscillating floor block and the rigid core; the second is based on the suspension of the floor slabs connected to the main structure by means of dissipative devices; last but not least, the third centers on "bridge buildings" where floors are suspended and laterally connected with dissipating devices.

Suspended buildings

Some years ago, the authors of this study carried out a research (Mezzi et al. 1994) on the configuration of suspended buildings aimed at analyzing seismic behavior, pointing out design criteria, designing special dissipating devices and a prefabricated structural system and planning its industrialized production. Different global configurations, shown in Figure 2, were compared. They differ in the internal connecting system between the structural parts: in scheme A the top connection is rigid, in scheme B the connection is pinned, in scheme C a balancing beam is provided as suspension deck. Six schemes were compared considering - apart from the basic schemes A, B and C in Figure 2 - a reference configuration (B0) with rigid lateral connections and two variants: in variant B1 the upper lateral connection was omitted, in variant C1 a rigid head connection was considered.

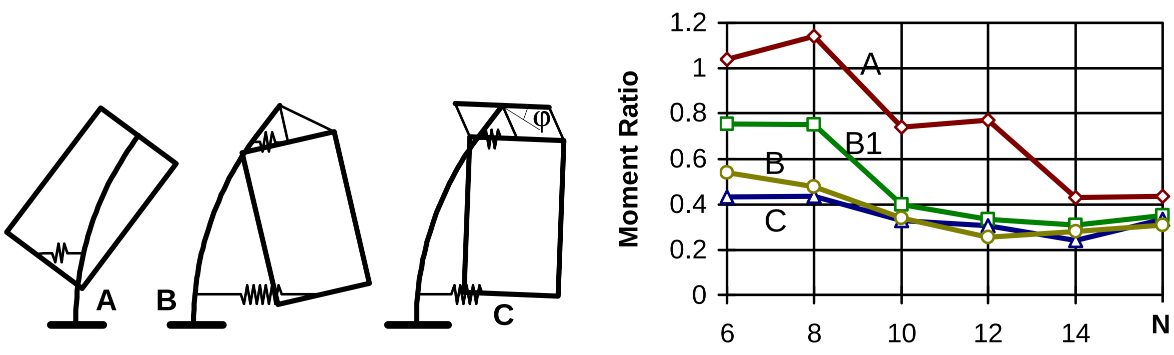


Figure 2. Schemes and performances of suspended buildings (Mezzi et al. 1994)

On the right of Figure 2 the graph shows the bending moment ratio (against the reference configuration rigidly connected) at the bottom section of the core wall versus the building height (in terms of number of floors of the suspended block), of the different configurations. Schemes B and C have rather similar response reductions, but the latter was preferred because it permits reducing the rotations of the suspended story-block and the additional tension in the suspension ties associated to lateral oscillations.

Suspended floors

Another class of suspended configurations can be discussed by referring to floors suspension when the main vertical structures remain rigidly connected. This class of configurations can be used for the structural solution of those architectural themes which implies a regular framed structure as support and container of a free distribution of floors occupying only part of the building plan and having irregular shapes differing at different levels so that a complex distribution of spaces with different heights can be obtained within the container-structure. The Future University of Hakodate in Japan, designed by Riken Yamamoto, represents a good example of this distribution, Figure 3 shows an internal view of the building where the space articulation can be appreciated.

This class of solutions was investigated in depth in a thesis (Ottaviano 2002) addressing various solutions that differed in the dissipating system adopted to limit the horizontal forces transmitted to the main structure. Figure 3 shows the three solutions that were studied: suspended floors laterally connected with plastic devices (SP); suspended floors braced with viscous devices (SV); isolated floors (IF). The schemes have a span length of 12 m and a story height of 5 m, the story mass is 1.066 t/m2. Two solutions were adopted for the main structure, the first including ground-roof free columns, the second framing beams at floor level.

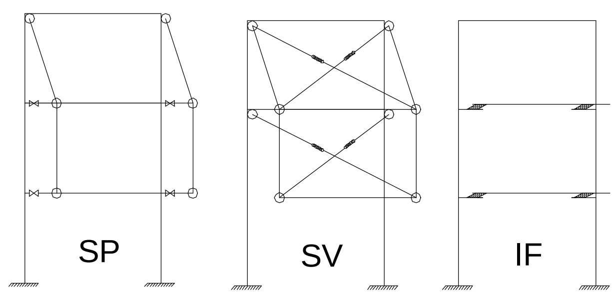


Figure 3. Left: internal view of the Future University of Hakodate in Japan (designer Riken Yamamoto). Right: elementary schemes of floor suspension.

Dynamic analyses carried out on simple schemes, using four artificial accelerograms having PGA equal to 0.35 g and fitting the spectrum B of (Eurocode 2001), show the effectiveness of the isolated or dissipated solutions. Table 1 shows the ratio of shear force, V, and bending moment, M, (average of the four responses) at the column base for the different enhanced solutions to the reference solution (REF) of the conventional continuous frame. The base shear and bending moment can be reduced to about one third of their nominal value, with reduction effectiveness practically independent of the type of enhancing solution used.

Table 1. Forces at the column base

FREE COLUMNS			FRAMED COLUMNS		
Scheme	V/V_{REF}	M/M_{REF}	Scheme	V/V_{REF}	M/M_{REF}
IF	0.33	0.35	IF	0.31	0.32
SP	0.37	0.36	SP	0.37	0.38
SV	0.32	0.35	SV	0.30	0.33

The study has been extended by taking in consideration simplified three-dimensional schemes as well as complex arrangements as those shown in Figure 4. The last model simulates a real structure with floors irregular shapes and free columns on the total height.

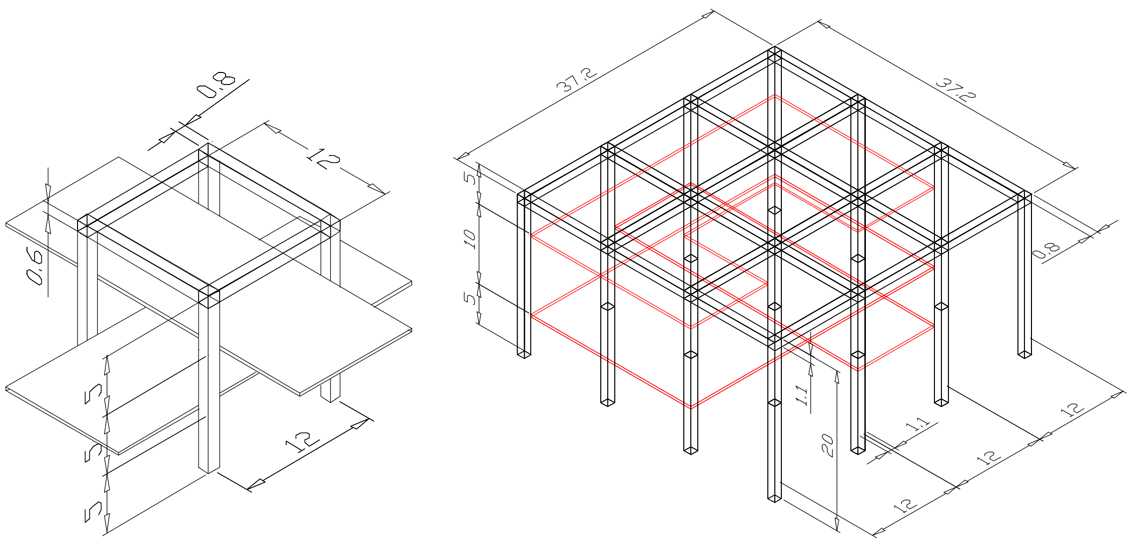


Figure 4. General scheme of simplified 3D models (left) and complex 3D model (right).

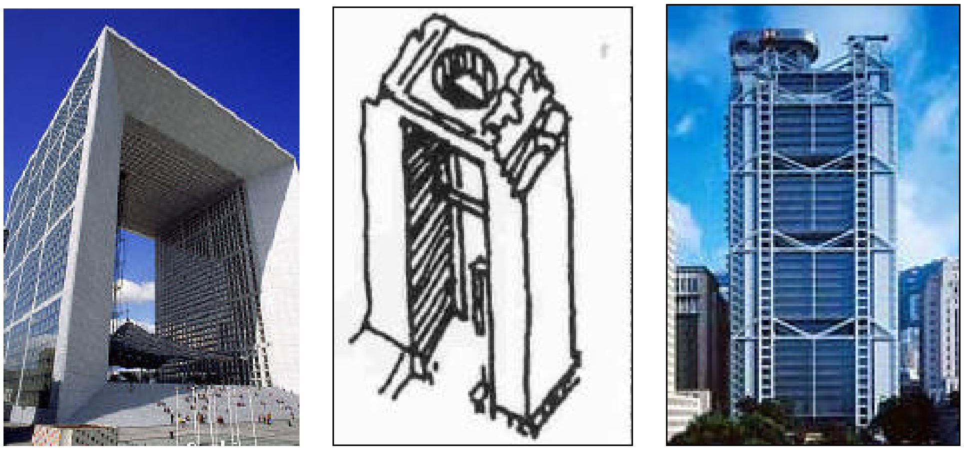
Table 2 features the results obtained on the last complex scheme. The ratios of the maximum forces at column base (shear forces, VX and VY, and bending moment, MX and MY) and roof beam (shear, VB, and moment, MB) are shown in comparison to the reference scheme. The reduction factors range from 0.231 to 0.419 for the columns, doubling the seismic capacity of the enhanced structure when compared to the conventional configuration.

Table 2. Ratio of the forces at column base and roof beam with respect to the reference scheme

	COLUMN				BEAM	
Scheme	VX	VY	MY	MX	VB	MB
IF	0,345	0,321	0,321	0,415	0,514	0,441
SP	0,392	0,230	0,290	0,419	0,509	0,434
SV	0,307	0,240	0,290	0,379	0,562	0,430

"Bridge buildings"

One of the themes of contemporary architecture is represented by the so called "bridge buildings" where the entire shape of the structure reproduces the opening typical of bridges. Well known, impressive examples of this kind of buildings are shown in Figure 5 (a) and (b). The void of the bridge building can be "filled" with a suspended block of stories thus obtaining the structural scheme of suspended "bridge buildings", consisting of a main bridge structure were the floors are suspended, like in Figure 5 (c). The lateral connections between floors and the main structure consist of dissipative devices that limit the force transmitted and dissipating energy.



(a) (b) (c)

Figure 5. (a) Grand Arche de la Défense, Paris (design Johan Otto von Spreckelsen), (b) Umeda Sky Building, Osaka (design Hiroschi Hara), (c) Hong Kong and Shanghai Bank Building, Hong Kong (design Norman Foster).

Analytical evaluations have been carried out on simplified plane models like that shown in Figure 6, to check the efficiency of the enhanced dissipative scheme of the suspended "bridge buildings". The model reproduces the lateral behavior of a thin building or a unit depth of a thick one. Different plastic threshold values have been assigned to the laterally connecting devices. Optimized threshold distribution along the height have been found, generally using reduced values at lower levels. Figure 6 shows the shear along the pier height for different device characteristics. Evidently, optimized device distribution reduces the column base shear of about 40%. The scheme could become even more efficient by increasing height, with triple height the base moment remains virtually the same. In this case, a better structural response can be obtained if the piers are framed with horizontal beam at one third and two thirds of the height.

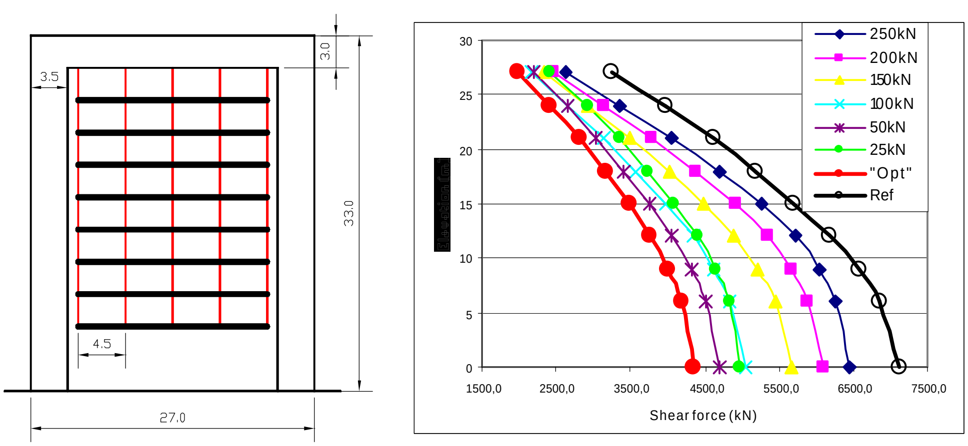


Figure 6. Left: model of suspended "bridge building". Right: shear force along the pier height.

Safeguard of Existing Critical Configurations

From an opposite point of view, the application of innovative principles of seismic protection makes configurations representative of modern architectural design possible, though they are critical or incompatible with seismic safety. In these cases, modern technologies enhance the seismic performances and allow the retrofitting without modifying the architectural vision.

A typical example is offered by the so called "pilotis" configurations where claddings, present on higher stories, are absent at ground floor. While architects like this configuration for aesthetics and distribution performances, it is very dangerous from a seismic point of view, because the large rotations imposed onto the columns of the soft-first-story. At present the solution is penalized by the code requirements, but the real problem is represented by the number of existing buildings already built and located in areas that only recently have been recognized to be under seismic risk. This is true of large areas of Italy that have been reclassified in 2003 according to the new seismic code (Ordinanza 2003).

The soft-first-story can be regarded as the equivalent of a base isolation configuration: the first story columns limit the base shear to the value corresponding to their flexural resistance, therefore the building elevation undergoes low seismic forces while the first story collapses.

An effective seismic retrofitting of the buildings can be obtained by enhaning this spontaneous behavior, through a special compound energy dissipating system consisting of dissipating devices (primary system) placed among the columns of the framed elements supporting the building and the ductility enhanced extreme critical zones of all the columns (secondary system). The enhancement of the ductile capacity can be obtained by replacing the concrete cover with high ductile concrete and by the confining columns ends with FRP.

The system is described in detail in (Parducci et al. 2005) and (Mezzi et al. 2005) where a case study is also illustrated, there, a particular configuration of buildings with first soft story is retrofitted using the compound energy dissipating system. The complex of buildings and the main works necessary are shown in Figure 7. These buildings are 6 stories and 14 stories high and were designed 30 years ago without taking seismic forces in consideration, while at present a design PGA of 0.25 g has been attributed to the site. The energy approach illustrated seems to be the most appealing way of achieving the enhancement goal. The displacement limit at base level, corresponding to the collapse of the first column, increases from 32 mm, for the existing structure, to 82 mm, favouring the existence of a performance point if a non linear static "pushover" analysis is performed.

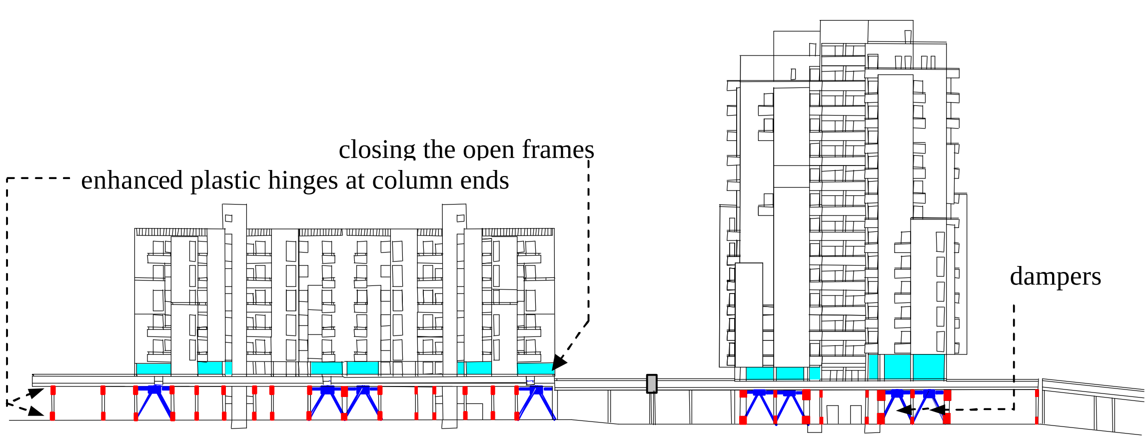


Figure 7. Retrofitting of buildings with soft first story.

Conclusions

A correct design using innovative seismic protection systems requires new basic criteria controlling the relation between architectural and structural configuration. Isolation, damping, energy dissipation, active control, greatly enhance buildings performances. The traditional rules become subordinate, while new design principles must be used. These are summarized by the concepts of flexibility, discontinuity, motion, device insertion, shape and comfort. The definition of tentative rules for the application of these principles to new and existing buildings has been accomplished by making reference to special sample configurations of new and existing buildings, consisting of suspended solutions for the former and soft-first-story for the latter.

References

Arnold C. and R. Reitherman, 1982. *Building Configuration and Seismic Design*, John Wiley, New York.

Eurocode no.8, 2001. *Design of Structures for Earthquake Resistance, prDraft No.3.*

Mezzi M., A. Parducci and A. Marioni , 1994. Aseismic Suspended Buildings Based on Energy Dissipation, *in Proc. 10th ECEE*, Balkema, Rotterdam.

Mezzi M., 2003. Optimum Structural Configurations of Seismic Isolated Buildings, *2nd Int.Spec.Conf on The Conceptual Approach to Structural Design*, Milan, Italy.

Mezzi M., A. Parducci and P. Verducci , 2004. Architectural and Structural Configurations of Buildings with Innovative Aseismic Systems, *13th WCEE*, Vancouver, Canada.

Mezzi M. and A. Parducci, 2005. Preservation of Existing Soft-First-Story Configurations by Improving the Seismic Performance, *3rd Int.Spec.Conf on The Conceptual Approach to Structural Design*, Singapore.

Ordinanza PCM 3274, 2003. *Primi Elementi in Materia di Criteri Generali per la Classificazione Sismica del Territorio Nazionale e di Normative Tecniche per le Costruzioni in Zona Sismica (in Italian)*, Roma, Italy.

Ottaviano L., 2002. *Configurazione architettonica e prestazione sismica: applicazione di sistemi innovative per la protezione degli edifici (in Italian)*, Graduation Thesis, University of Perugia, Italy.

Parducci A., 1999. Seismic Isolation: Why, Where, When - Design options for ordinary buildings: the Italian experience, *International Post-Smirt Conference Seminar Isolation, Energy Dissipation and Control of Vibration of Structures*, Cheju, Korea.

Parducci A., 2001. Seismic Isolation and Architectural Configuration, *Special Conference on the Conceptual Design of Structures*, Singapore.

Parducci A., F. Comodini and M. Lucarelli, 2005. A Synergic Dissipation Approach to Retrofit Framed Structures with a Soft First Storey, *9th World Seminar on Seismic Isolation, Energy Dissipation and Active Vibration Control of Structures*, Kobe, Japan.