# Steel bracings and shear panels as hysteretic dissipative systems for passive control of MR steel frames

# Controllo passivo di telai di acciaio mediante dissipazione isteretica: sistemi a controventi e pannelli a taglio

**The energy dissipation approach by means of passive structural control devices can be considered today as the most efficient way to protect steel framed buildings from earthquake damage, according to the so-called Damage Tolerant Structures approach.**

**In this paper an overview on the hysteretic dissipative systems, with specific reference to metal-based devices, is given.**

**In particular, the types of dissipative device considered are diagonal bracing and shear panel systems.**

**Their classification is made with respect to the arrangement, the adopted damping device, the relevant dissipative mechanism type and the utilized material.**

**A number of applications based on these systems are shown and the main experimental studies, analytical models and practical designs carried out worldwide in the last years are presented. Besides, the usually applied design methods are discussed, aiming at the definition of a proper design methodology, which could allow the optimization of the seismic performance of the structures at the light of a performance-based design method.**

*Nel campo dell'ingegneria sismica, l'approccio basato sulla dissipazione dell'energia attraverso l'impiego di dispositivi di controllo strutturale passivo può essere considerato attualmente il modo più efficiente per proteggere gli edifici intelaiati in acciaio dai danni sismici. Nella presente memoria è fornita una panoramica sui sistemi dissipativi di tipo isteretico, con specifico riferimento ai dispositivi che fanno uso della tecnologia dello snervamento metallico. In particolare, quali sistemi dissipativi vengono considerati quelli basati sull'impiego di controventi diagonali e dei pannelli a taglio. La classificazione di tali sistemi viene presentata rispetto alla configurazione geometrica, al dispositivo di smorzamento adottato, al relativo tipo di meccanismo dissipativo ed al tipo di materiale utilizzato. Vengono quindi illustrate numerose applicazioni basate su tali sistemi e presentati i principali studi sperimentali e numerici attualmente in corso a livello internazionale. Inoltre, vengono esaminati i metodi di progettazione di tali sistemi allo scopo di chiarire e definire un'appropriata metodologia di progetto, che permetterebbe l'ottimizzazione delle prestazioni sismiche delle strutture nelle quali si faccia uso di dispositivi dissipativi di tipo isteretico.*

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## INTRODUCTION

Steel framed structures in seismic areas are usually designed according to traditional methods, in which the structural performance is assessed in relation to the ductility resources of members and connections. A new seismic design trend is now based on controlling and limiting as much as possible the dynamic effects on the structural elements, not only the ones produced by earthquakes but also the ones related to other sources as wind and machinery (Figure 1).

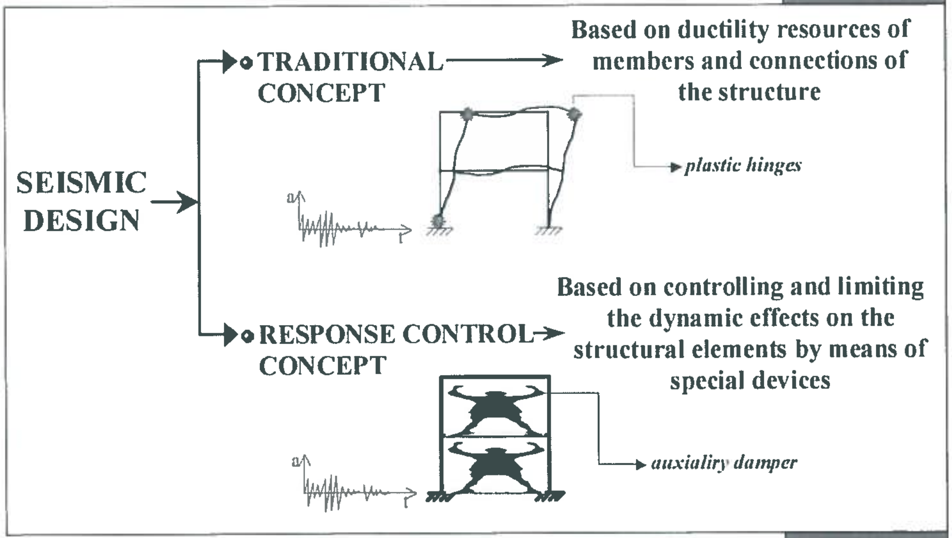


*Figure 1 Seismic design concepts for moment resisting frames*

This objective is obtained by means of special systems called response control systems that can be substantially based on two strategies:

- the modification of the dynamic characteristics, in which the structural period is shifted away from the predominant periods of the seismic input, so to reduce the dynamic effects produced by resonance phenomena;
- to increase the energy dissipation capacity of the structure by means of appropriate devices that reduce structural damage of the bearing structure.

*Figure 2 Diagram of the structural response control strategy*

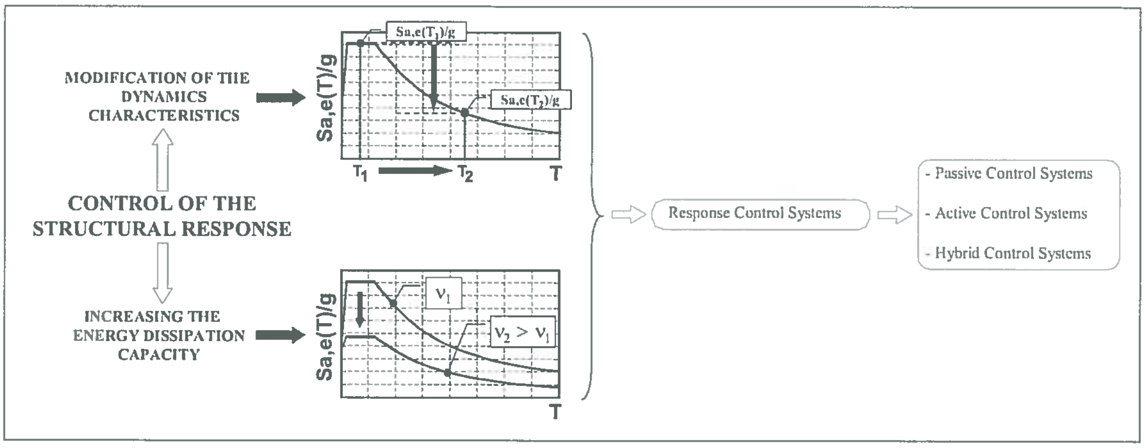
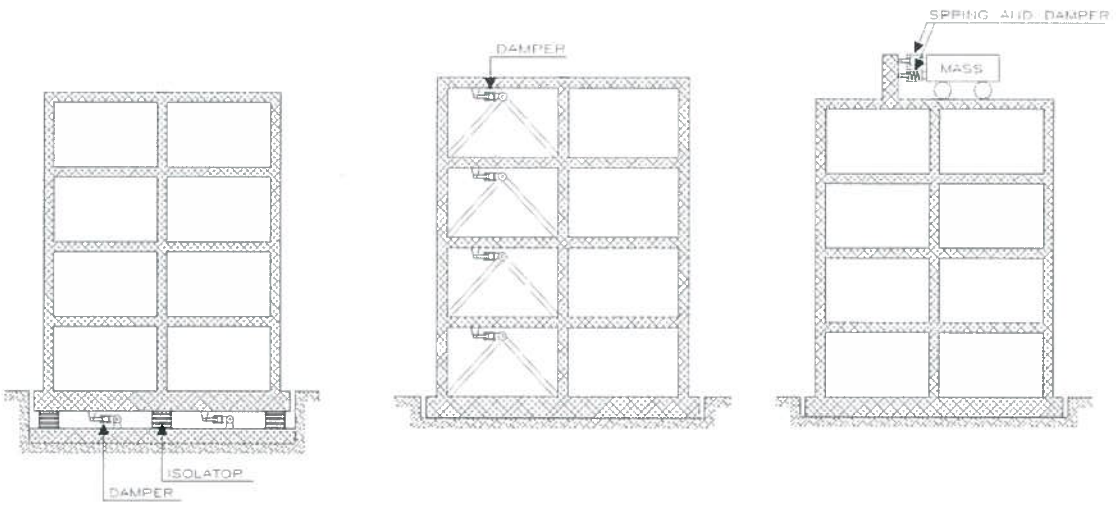


*Figure 3 Classification of passive control systems*



**a. Seismic isolation**
*Sliding or Rolling Mechanism:*
- Balla bearing
- Slide plate bearing
- Sliding layer

*Flexible elements:*
- Multi-rubber bearing
- Double column
- Flexible piles

**b. Energy dissipation**
*Hysteretic type:*
- Metallic-yielding type
- Friction type

*Viscous type:*
- Viscous type
- Viscoelastic type

**c. Mass effect**
- Mass spring type
- Pendulum type
- Sloshing of liquid

Both these strategies can be implemented in passive, active or hybrid systems (Figure 2).

With only reference to passive control systems, where external power sources are not required, the properties of a structure, such as fundamental period and damping capacity, remain constant with seismic ground motion. Such systems, which are nowadays the most used to control the seismic structural response, can be classified in three types: base isolation systems, energy dissipation systems and mass effect systems (Figure 3).

In the base isolation systems, elongating the natural period through isolators reduces the acceleration response of the structure. The seismic isolation devices are usually installed between the foundation and the structure or between two relevant parts of the structure itself, as in the case of the suspension buildings. The isolation of a building can be done by means of sliding or rolling mechanisms (ball bearing, slide plate bearing, sliding layer) as well as flexible elements (multi-rubber bearing, double column, flexible piles).

The mass effect systems are based on supplementary masses connected to the structure by means of springs and dampers in order to reduce the dynamic response of the structure. These devices are tuned to the particular structural frequency so that when that frequency is excited, the devices will resonate out of phase with structural motion, dissipating energy by inertia forces applied on the structure by such masses. The structural response control technology by mass effect mechanism can be principally applied by tuned mass dampers as mass-spring systems and pendulum systems and by tuned liquid dampers systems based on sloshing of liquid.

Finally, the energy dissipation systems consist of special sacrificial devices that act as hysteretic and/or viscous damper, absorbing the seismic input energy and protecting the primary framed structure from damage. The hysteretic dampers include devices based on yielding of metal and friction, while viscous dampers include both devices operating by deformation of viscoelastic solid and fluid materials (viscoelastic dampers) and the ones operating by forcing fluid materials to pass through orifices (viscous dampers).

In this paper, diagonal bracing and panel systems, which are typical energy dissipation systems currently used in steel framed structures, are analyzed and discussed. Both systems are based on metallic-yielding approach and are activated by the relative interstorey drift occurring during the loading process of the structure. They are here examined in relation to the different adopted arrangements, the shape of damping devices, the dissipative mechanisms and used materials, showing shortly also the benefits related to their utilization. Besides, some applications based on such systems are shown, with particular reference to experimental studies, analytical models and design methods developed at the light of the performance-based design approach.

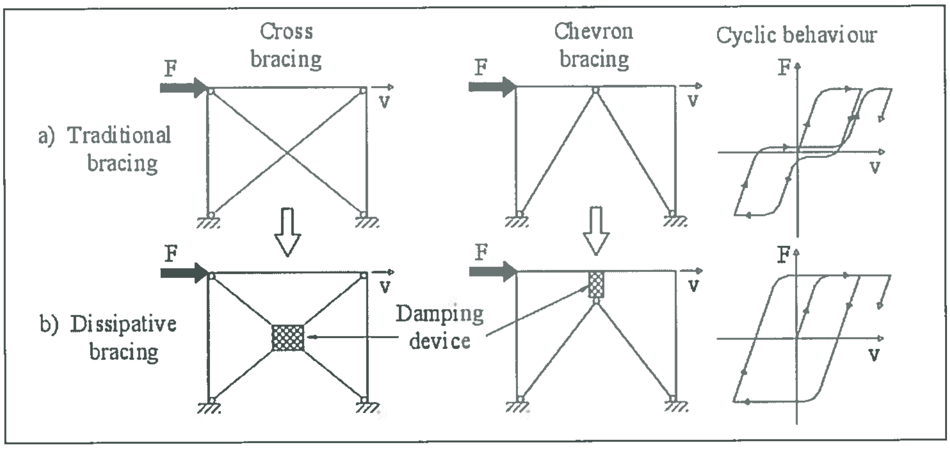


*Figure 4 Traditional and dissipative bracing*

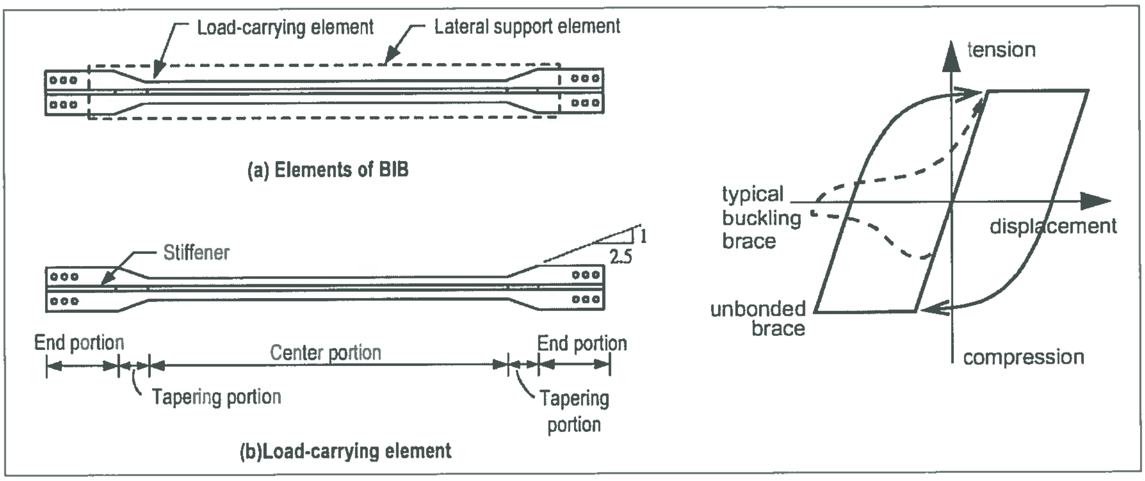


*Figure 5 Typical Buckling Inhibited Brace (BIB) system and relevant cyclic behaviour*

## DIAGONAL BRACING SYSTEMS

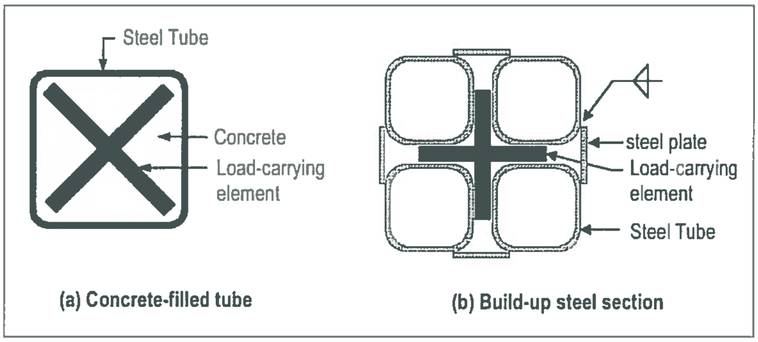
A common way for seismic protecting of both new and existing framed structures is traditionally based on the use of concentric steel members arranged into a frame mesh (Concentrically Braced Frame – CBF), according to single bracing, cross bracing, chevron bracing and any other concentric bracing scheme. Even if such systems posses high lateral stiffness and strength for wind loads and moderate intensity earthquakes, some drawback have to be taken into account, concerning the unfavorable hysteretic behaviour under severe earthquake, due to buckling of the relevant members, which generally causes a poor dissipation behaviour of the whole (Figure 4a).

In case of seismic retrofitting, in addition to the strengthening of the existing frame, it is necessary to improve the global seismic performance of the structure, also in terms of dissipative capacities. Therefore, it is necessary to avoid the mentioned drawback by preventing the buckling and the premature rupture of braces. This aim can be achieved by placing in the conventional bracing system some special devices that dissipate the input energy seismic before heavy damage of the primary structure occurs. In the Figure 4b, some solutions to modify an ordinary bracing system in a dissipative bracing system are schematically shown. In all the cases, the bracings are equipped with a damping device, which has to be easily accessible and replaceable.

Beneficial dissipative and damping devices have been proposed and used worldwide. In the case of the traditional cross bracing, a simple damping system can be obtained by designing the braces in such a way plastic mechanisms due to material yielding are exploited before the buckling of the braces occurs. This result can be obtained by using Low Yield Strength Point (LYSP) steel [1, 2], which allows having very stiff braces also for lesser cross section, thanks to greater $E/f_y$ ratio than the ordinary steel, where E is the Young's modulus and $f_y$ is the steel yield stress. The lower yield strength of a LYS allows the bracing system to dissipate energy at a rather small interstorey drift angle, reducing the seismic response of the structure also for moderate earthquakes. In addition, its higher ductility respect to common carbon steel increases the energy dissipation capacity of a CBF.

Another way to improve the cyclic performance of traditional cross bracing system is based on the use of a special types of bracing members, which are notoriously called Buckling Inhibited Brace (BIB) [3] or also Unbonded Brace (UB) [4] (Figure 5).

The design technology of these dissipative systems consists in the use of special trusses composed by a steel



(a) Concrete-filled tube (b) Build-up steel section

*Figure 6 Common type of lateral support element for BIB members*

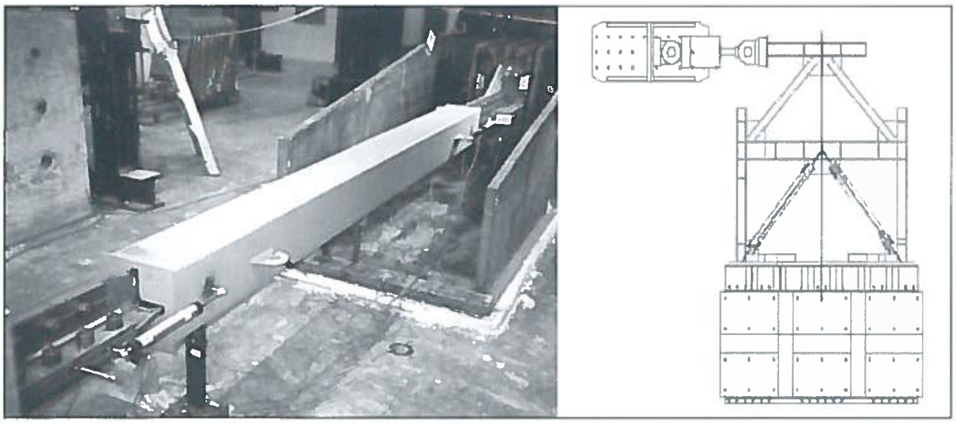


*Figure 7 Test set-up for unbonded bracing at the University of Berkeley (California)*

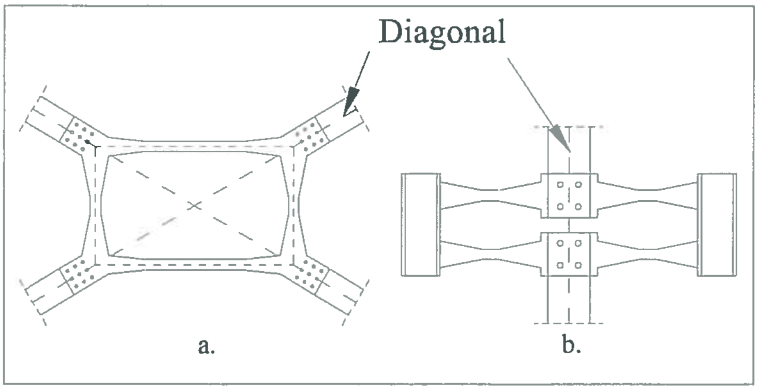


*Figure 8 Typical dissipative systems for braced frames*

core, as load-carrying element, placed inside a lateral support element, in order to obtain a buckling restrained bracing. While the load-carrying element takes the tensile and compressive axial forces, the lateral support prevents buckling of the central core when the member is compressed, owing to appropriate lateral restraining mechanisms. The flexural strength and stiffness of the lateral support prevent global and local buckling of the brace, obtaining axial yielding under both tension and compression force. Therefore a stable hysteretic behaviour is provided, without any pinching and/or degradation of strength and stiffness up to the failure, which is generally caused by the tensile rupture after significant necking of steel core. Due to the high energy dissipation capacity, a CBF made of BIB members is also called DCBF (Ductility Concentrically Braced Frame).

Several types of these systems, characterized by various materials and geometry, have been proposed in the last years, namely concrete-filled tubes (Figure 6a) and built-up steel sections (Figure 6b). In the first case, the lateral support element is composed by steel tube filled with concrete or mortar, while in the second case it is composed by steel tubes connected together through steel plates.

When designing BIB members, it is necessary to make cure in the construction details related to the separating surface which has to allow the relative movement between the steel core and the lateral support, avoiding the occurrence of shearing and Poisson's effects. For this reason, a slip surface or unbonding layer should be created, so that the internal axial force is concentrated on the load-carrying element only.

Another important aspect of the BIB members is the possibility to independently control strength, stiffness and ductility by varying the yield strength of the steel and by changing both the cross section area and the yield length of the steel core.

Actually, few buildings have been constructed with these dissipative bracing types. An example is represented by the Plant & Environmental Sciences Replacement Facility in the University of California Davis campus that can be considered the first structural application based on BIB members in the United States. It is about a steel laboratory building whose lateral system includes the unbonded braces as an alternate scheme to the traditional EBF base system.

At the Structural Engineering Research Laboratory of the University of California, in Berkeley, some full-scale tests on sub-assemblage of the braced frame with buckling restrained diagonals were carried out in order to enable the new Stanley Hall replacement building to resist the effects produced by earthquakes on the nearby Hayward fault (Figure 7). The BIB members were manufactured by Nippon Steel in Japan and were made by encasing a core steel within a concrete matrix confined by a steel tube. The tests showed a good hysteretic behaviour, without any degradation or fracture effect after several inelastic excursions.

While the above bracing member dissipate the input energy by the occurring axial plastic deformations, there are systems whose dissipative mechanism is based on shear and/or flexural yielding of some particular devices, which are placed along the diagonals according to several arrangements. Many of these devices have been proposed and tested in Italy in 90's years at the University of Rome and Padua [5, 6, 7].

Some of the first proposed devices were based on a rectangular frame inserted into a frame mesh and connected to its joints by tension-only braces. It is made of thick steel plate shaped in order to have a uniform flexural resistance for a linearly variable asymmetrical flexural moment, which occurs when the external frame is laterally deformed (Figure 8a).

Similar devices can be obtained by assembling a number of thick elements arranged as a sandwich and pin-connected at the ends of the two parts of a diagonal member (Figure 8b).

As far as the chevron bracing scheme is concerned, the transformation from traditional bracing to a dissipative scheme takes place by inserting special dissipative devices between the joint of the diagonal members and the beam (Figure 9a). The simplest scheme is based on the transformation of a conventional concentric bracing into an eccentric bracing system by means of a steel link, which is fixed to the beam and pin-joined to the diagonals (Figure 8b). In this way the typical Y-shaped eccentric bracing behaves as a passive control device, since the inelastic cyclic behaviour of the link element allows a large amount of the input energy to be dissipated without any damage of the external framed structure. In fact, the basic design principle of the system is that, while plastic deformations occur in the dissipative device, the diagonals have to remain elastic both in tension and in compression.

The recent technological evolution of the link is represented by so-called Added Damping And Stiffness (ADAS) elements [8]. It is an energy dissipation device mounted atop chevron bracing and differentiated for shape, dissipative mechanism and utilized material. From the shape point of view, several types of devices have been proposed, namely X-shaped (fig. 9c), E-shaped (fig. 9d), U-shaped (fig. 9e), W-shaped (fig. 9f), honeycomb-shaped (fig. 9g) and so on. As far as the dissipative mechanism is concerned, devices that can dissipate energy for flexural, shear, axial (fig. 9a,b,c,d,e,f,g) and torsion (fig. 9h) deformations, or also by their combination, have been proposed.

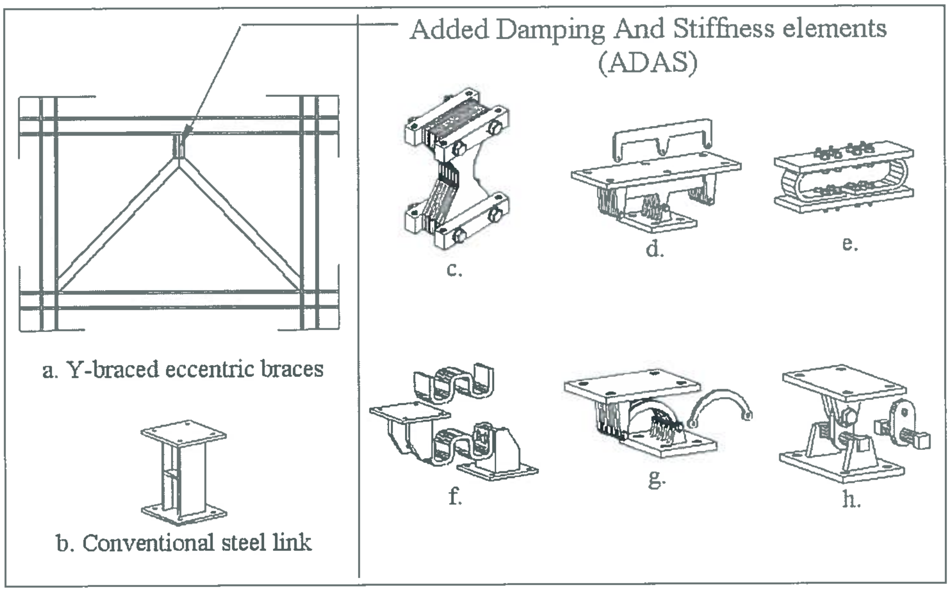


*Figure 9 Typical dissipative chevron bracing systems*

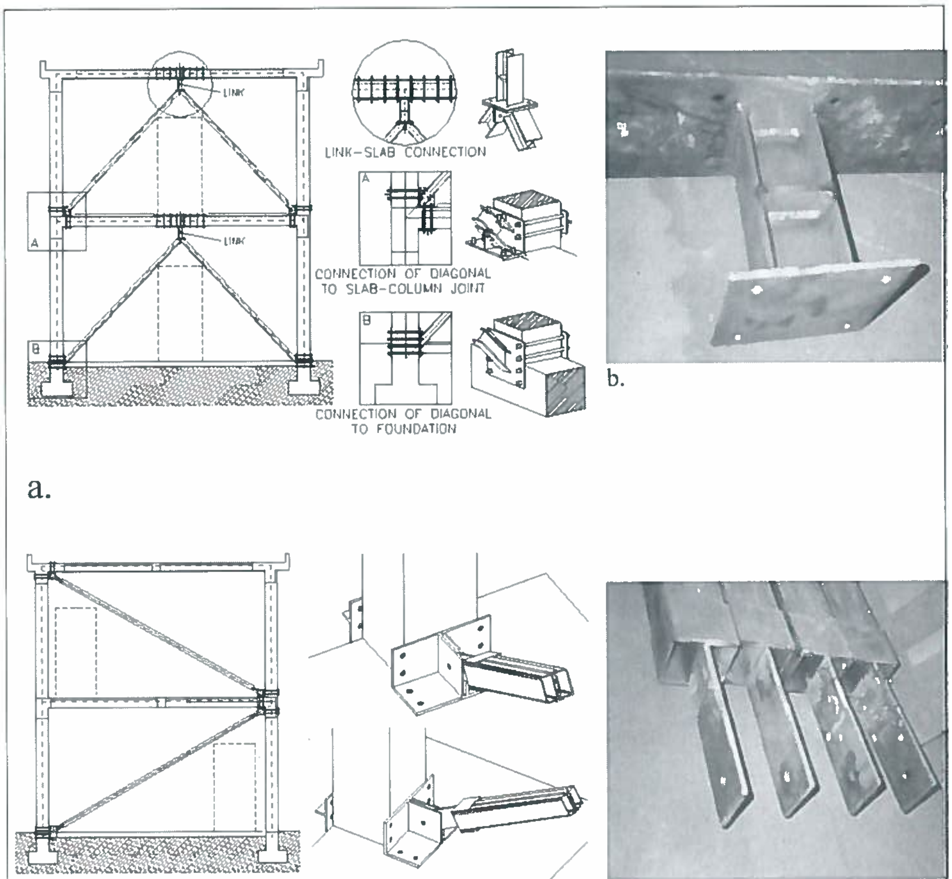


*Figure 10 Some metal-based seismic upgrading techniques of existing r.c. frame: a,b Y-shaped eccentric bracing system with detail of the link; c,d Buckling inhibited braces with detail of the braces*

Finally, ADAS elements can be differentiated in relation to the basic material, the common adopted materials being mild steel, low-yield strength steel, lead, shape-memory alloys and aluminium. Their use can be particularly advantageous also in case of seismic retrofitting of existing r.c. and steel frames, since they increase both damping and stiffness of the whole structure, avoiding to enhance the ductility characteristics of beam-column joints. Besides, respect to the use of conventional steel bracing as retrofit system, it is possible to reduce or to avoid completely the costs related to the strengthening of the existing foundations, since the limited yielding strength of the dissipative device does not allow a considerable increase of column axial force.

With regard to this type of application, a wide experimental investigation has been recently undertaken at the University of Naples Federico II [9]. The experimental activity, which is developed in cooperation with many other Institution and industrial partners, concerns the investigation of different metal-based upgrading technologies applied to an existing full-scale r.c. building, designed in the Seventies according to the gravity loads only.

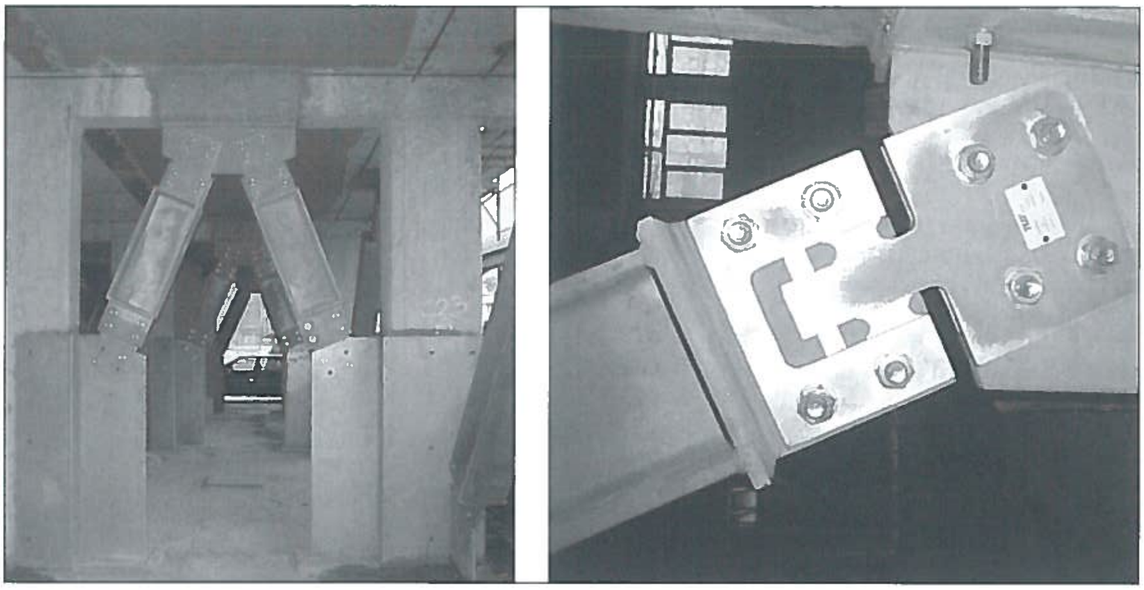


*Figure 11 A seismic retrofitting system based on dissipative cover plates*

The building under investigation is located in Naples, in the area called Bagnoli, in the ex-industrial plant of the Italian steel producer "ILVA" ("Italsider"). Among different metal-based seismic upgrading techniques, the Y-shaped eccentrics bracing system (Figure 10a,b) and the dissipative concentric bracing system (Figure 10c,d) have been considered. In the former case, the link has been vertically placed and directly attached to the slab of the existing structure, while in the latter case buckling inhibited braces made of common mild carbon steel have been applied. The feasibility of such systems will be proved by full-scale tests under both monotonic and cyclic loading, also in relation to other typical intervention strategies based on the use of FRP.

A practical application of dissipative devices in the seismic retrofitting of existing r.c. frames is represented by Domiziano Viola and La Vista school buildings located in Potenza (Italy). This retrofit system was built in 1999 by using traditional steel bracings connected to the structure by means of cover plates that behave as dissipative elements by shear plastic deformation of mild steel (Figure 11). These devices were patented by Dolce and Marnetto and tested at the Department of Structures of the University of Basilicata [10].

Many research projects have been started both at national and international level to identify new possible developments in the field of metal-based dissipative devices. The projects aiming at improving the knowledge about advanced materials, like shape memory alloys (SMA), seem to be the most promising ones. For example, the MANSIDE (Memory Alloys for New Seismic Isolation DEvices) is a research project aimed at exploiting the Shape Memory Alloys properties by experimental and theoretical studies. The devices based on SMA allow eliminating some limitations of the current passive protection technologies, such as problems due to ageing and durability, maintenance, installation complexity or replacement and geometry restoration after strong earthquakes, as well as variable performances depending on temperature [11]. These capabilities can be exploited by bracing systems in the seismic retrofitting of both reinforced concrete structures and old masonry buildings. In the latter case, some experimental studies carried out on the seismic protection of cultural heritage (ISTECH project) [12] have shown that the SMA devices can be better used as reinforcing devices besides than as energy dissipators, thanks to their capability to provide constant forces. The above research projects have been especially focused on the possibility to join the two main capabilities of the SMAs, namely re-centring and energy dissipation, in the same element, since these requirements are often conflicting.

The problem has been overcome by joining two separate groups of SMA in the same device, the re-centring SMA group based on the superelasticity of pre-tensioned austenitic wires and the energy dissipating SMA group realized with martensite bars, steel hysteretic bars or with the same pre-tensioned austenitic wires [13]. The resulting device is shown in Figure 12 and it can be used to build both the bracing and the isolating devices. The bell tower of St. George Church in Trignano (Reggio Emilia) and Church of St. Francesco of Assisi (Perugia) are the main examples of application of SMA in structural restoration of monumental building in Italy.

## SHEAR PANEL SYSTEMS

Shear panels represent an alternative solution to diagonal bracings for resisting lateral forces and to control the dynamic response of framed buildings. Firstly, they can be used as basic seismic resistance system under earthquake loading, due to their considerable lateral stiffness and strength. In addition, due to the large energy dissipation capacity related to the large portion where plastic deformations take place, they are very effective for the seismic protection of structures under strong loading conditions, serving as dissipative elements.

Steel shear walls were firstly used in the late 1920s as cladding panels without any structural purpose [14]. Afterwards some studies proved their significant influence on the global behaviour of structure, since the measured displacements were significantly smaller than the computed ones [15]. In order to take profit of their presence, it was proposed to include explicitly the stiffness and strength of cladding panels into structural models, so to improve the performance of the low- and medium-rise moment resisting frames under wind and seismic loads. Generally, cladding panels are made of lightweight steel sheeting (mainly corrugated sheeting or sandwich panels), simply connected to the supporting frame by means of steel bolts, rivets or spot welds [16]. However, recent experimental and numerical studies carried out at the University of Naples Federico II [17] have shown that they can considerably contribute to increase the seismic performance of steel framed structure, especially under moderate-intensity earthquakes, while their contribution at ultimate limit state is quite limited owing to poor hysteretic behaviour (Figure 13).

Since the thin metal plates usually adopted as cladding elements are not able to significantly contribute to the energy dissipation [18], in order to increase the damping of the whole structure, dissipative requirements of the panels used as enclosure of the building were obtained by adopting special cladding-to-frame connections (Figure 14).

Then, shear panels made of steel plates continuously and rigidly connected to the external frame were proposed, in order to be used as primary system in absorbing external lateral actions, while beams and columns had only the role of carrying out stationary loads [19]. In the Seventies shear walls have been used as primary lateral load resisting systems for both new constructions and seismic retrofitting of existing buildings in Japan and United States. As shown in Figure 15, the cyclic behaviour of un-stiffened shear panels is characterized by pronounced degradation of stiffness and strength. Therefore, initially, in order to avoid shear buckling of the plate, they were supplied with appropriate stiffeners. Then, due to economical reasons, unstiffened shear walls were proposed and largely used in Canada in the 80's and the 90's.

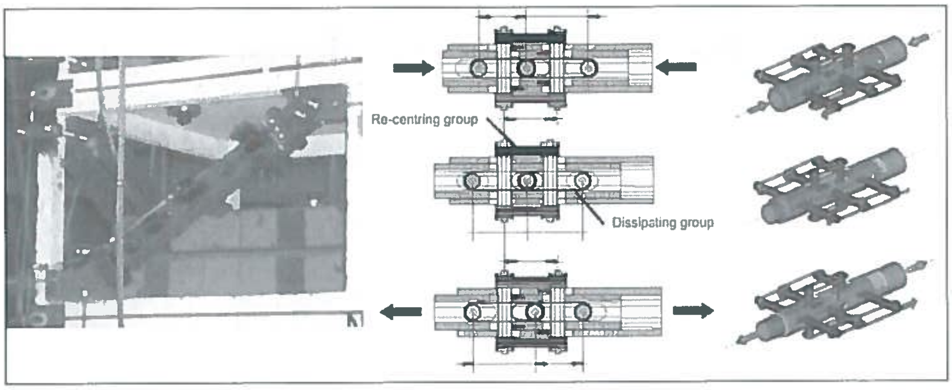


*Figure 12 Bracing device with SMA and functioning scheme of the functional groups*

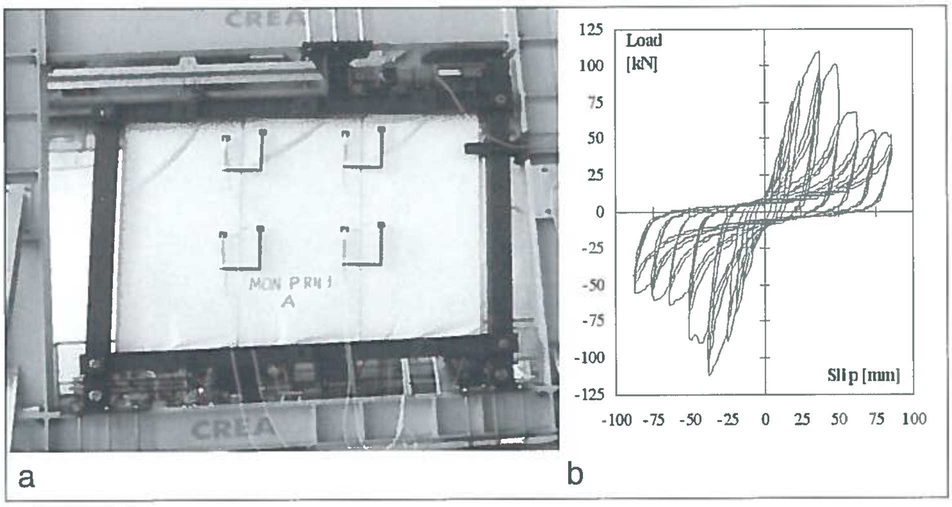


*Figure 13 Lightweight sandwich steel panels:*
*a. Tests performed at the Crea Laboratory under the coordination of the University of Naples*
*b. Cyclic behaviour*

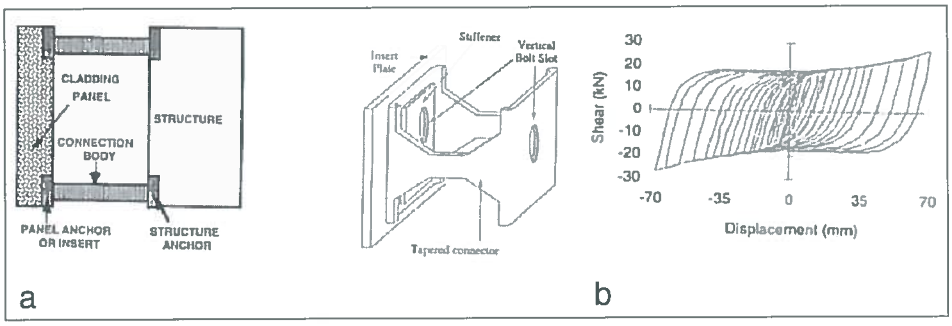


*Figure 14 Panel based on dissipative connections:*
*a. Advanced tapered connector tested at the University of Florida.*
*b. Cyclic behaviour*

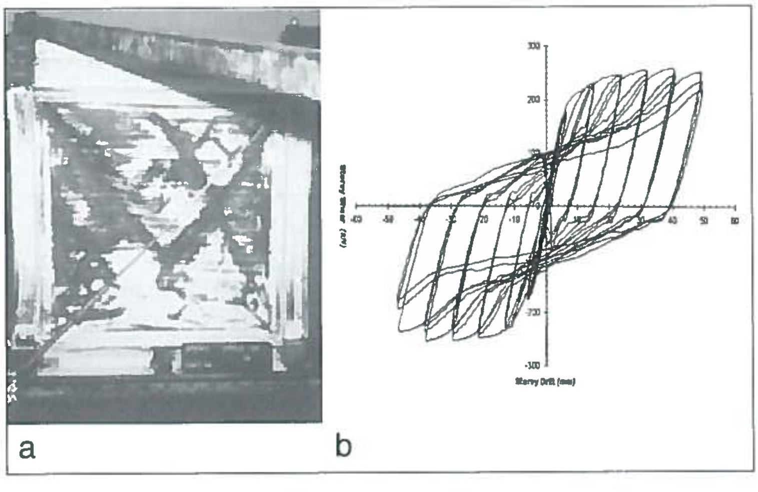


*Figure 15*
*Un-stiffened steel plate shear walls:*
*a. Experimental tests at the University of British Columbia.*
*b. Cyclic behaviour*

*Figure 16 Applications of steel shear walls: a. A 30-story hotel in Dallas, Texas; b. The 6-story Sylmar hospital in Los Angeles, California; c. The 52-story "Century building" in San Francisco, Texas; d. A 22-story office building in Seattle, Washington*

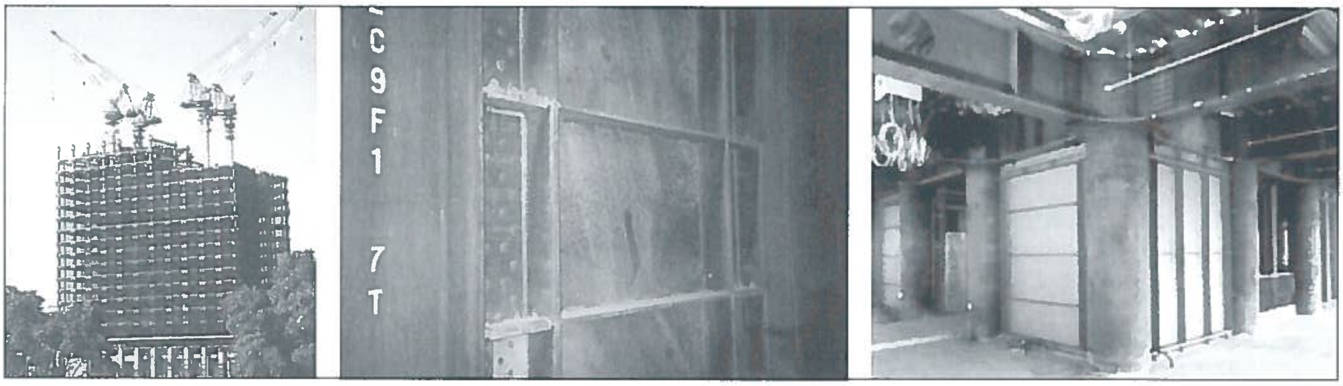


*Figure 17 Example of application of LYS shear panels with panel detail (design by Kitamura et al., Nikken Sekkei, Tokyo)*

For the sake of example, in Figure 16 some recent important applications in USA of both stiffened and unstiffened steel plate shear walls, are shown [20].

Over the last few years, following the introduction of LYS steel, stiffened shear steel plates have been proposed in Japan [21], where many high-rise buildings based on the application of low-yield shear panels have been already erected and some others are under construction (Figure 17) [22].

As far as the structural systems provided with steel shear walls are concerned, there are basically two types of structural schemes that are normally adopted for steel buildings: (1) standard scheme, where beam-to-column joints are simply pinned, while shear walls are assumed to be the only lateral-force-resisting element in the system (Figure 18a); (2) dual scheme, where steel shear walls and moment frames behave as a combined system to resist lateral forces. The moment resisting frames act as a back up system to the steel shear walls, which represent the primary lateral force resisting structure (Figure 18b).

Steel shear wall systems can be built according to several configurations. The most common ones are: single wall (Figure 19a), coupled walls (Figure 19b), out-rigger walls (Figure 19c) and mega-truss wall configuration (Figure 19d).

Steel plate shear walls can be applied in the steel frame buildings with the following arrangements: (1) as large panels rigidly and continuously connected along columns and beams of frame mesh, serving also as cladding panels (Figure 20a); (2) as smaller elements installed in the frameworks of a building at nearly middle height of the storey and connected to rigid support members to transfer shear forces to the main frames [23], according to bracing scheme, partial bay scheme or pillar scheme (Figure 20b,c,d).

The energy dissipation takes place due to shear mechanism, by means of either pure shear stress action (Figure 21a) or tension field action (Figure 21b), in which the lateral shear forces are carried by developing of diagonal tension in the web plates parallel to the directions of the principal tensile stresses. Steel shear walls behaving with a pure shear dissipative mechanism are also identified as "compact shear panels" because they yield in shear without the occurrence of buckling phenomena. Whereas the steel shear panels dissipating energy by means of the tension field action are also denoted as "slender shear panels" because they are expected to buckle in elastic field. An intermediate category of shear walls is instead identified as "non-compact shear panels", where shear yielding has been already reached when buckling occurs [24].

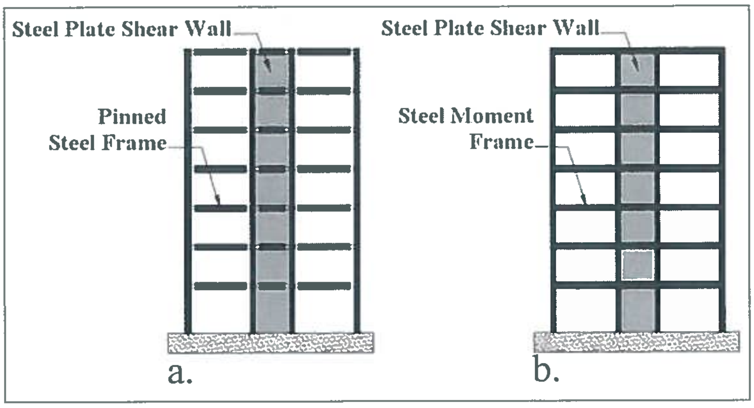


*Figure 18 Typical steel structural system with shear walls:*
*a. Standard structural system*
*b. Dual structural system*

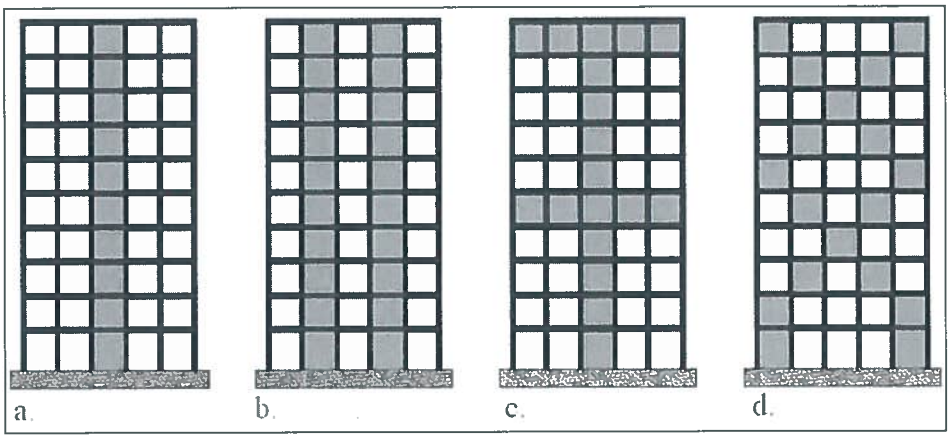


*Figure 19 Structural configurations of shear walls:*
*a. Single wall*
*b. Coupled walls*
*c. Out-rigger walls*
*d. Mega-truss walls*

Obviously, the premature shear buckling in the elastic field occurring in slender shear panels produces a poor dissipative behaviour owing to a pronounced slip-type hysteretic response. The pure shear dissipative mechanism is preferable because it allows stable inelastic cyclic behaviour and uniform material yielding spread over the entire panel. The main problem related to this type of mechanism is due to the relatively small thickness of the basic metal plates, which then have to be stiffened to delay shear buckling in the plastic field. This objective can be more easily achieved by using metals with greater $E/f_y$ ratio than the ordinary steel. The low yield stress allows a larger width-to-thickness ratio in relation to shear buckling. It is also to be considered that the low yield point ensures the energy dissipation yet for smaller deformation levels, as in the case of wind and moderate earthquakes, working as dampers also for the serviceability limit state. Finally, the high elongation of the material allows the energy dissipation in a wide range of deformation demand.

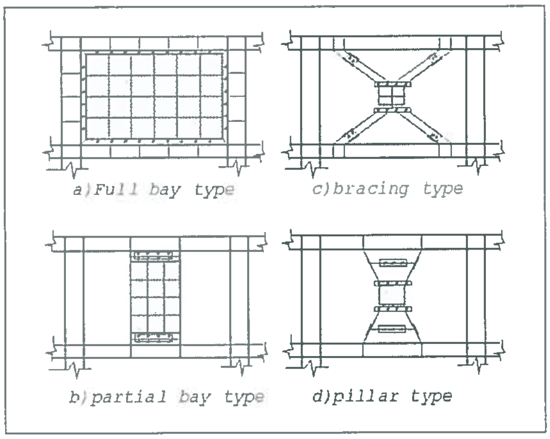


*Figure 20 Type of arrangements of the steel shear panels*

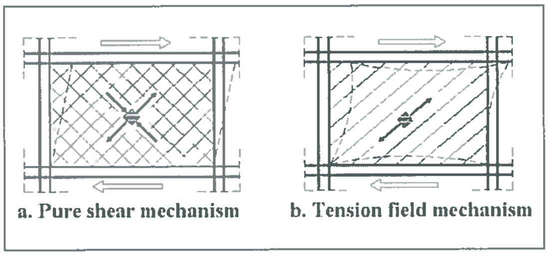


*Figure 21 Shear energy dissipation mechanism*

A number of experimental tests have shown that the hysteretic behaviour of LYS steel panels is excellent, provided that suitable stiffeners are arranged, in order to prevent shear buckling, and a rigid panel-to-frame connecting system is adopted, so to avoid any slipping phenomenon in the recovery characteristic of the system (Figure 22) [25].

In order to assess the effect of the main mechanical features of LYS shear panels on the seismic response of the whole structure, wide numerical study has been also carried out at the University of Naples "Federico II", where several types of frame-to-shear panels combinations have been investigated [26]. In particular, it has been shown that the application of low-yield shear panels appears to be particularly effective in case of primary structures characterized by limited late-

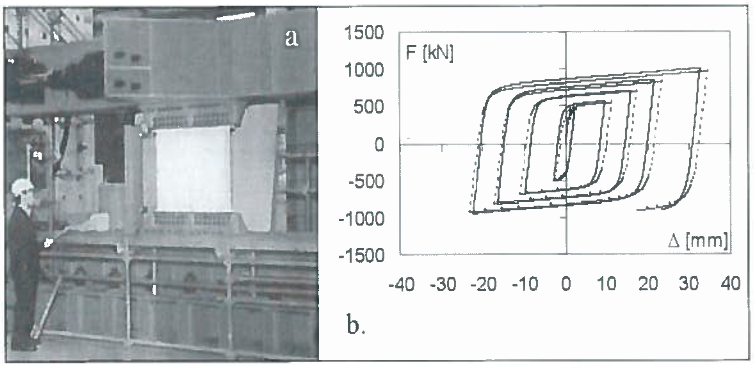


*Figure 22 Low-yield steel shear walls:*
*a. Experimental tests made in Japan*
*b. Cyclic behaviour*

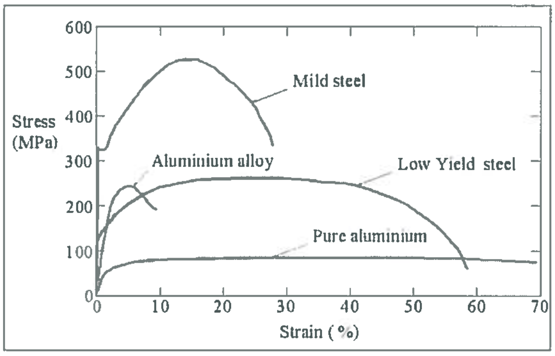


*Figure 23*
*Comparison of $\sigma$–$\varepsilon$ relationship for typical steel and aluminium alloys*

ral rigidity and reduced overstrength. In fact, in such a case, shear panels may behave as stiffening devices also, rather than as hysteretic dampers only. Therefore, the contribution provided by shear panels could be profitably taken into account when performing the serviceability limit state check of the primary structure, which usually has a strong impact on the design of steel frames.

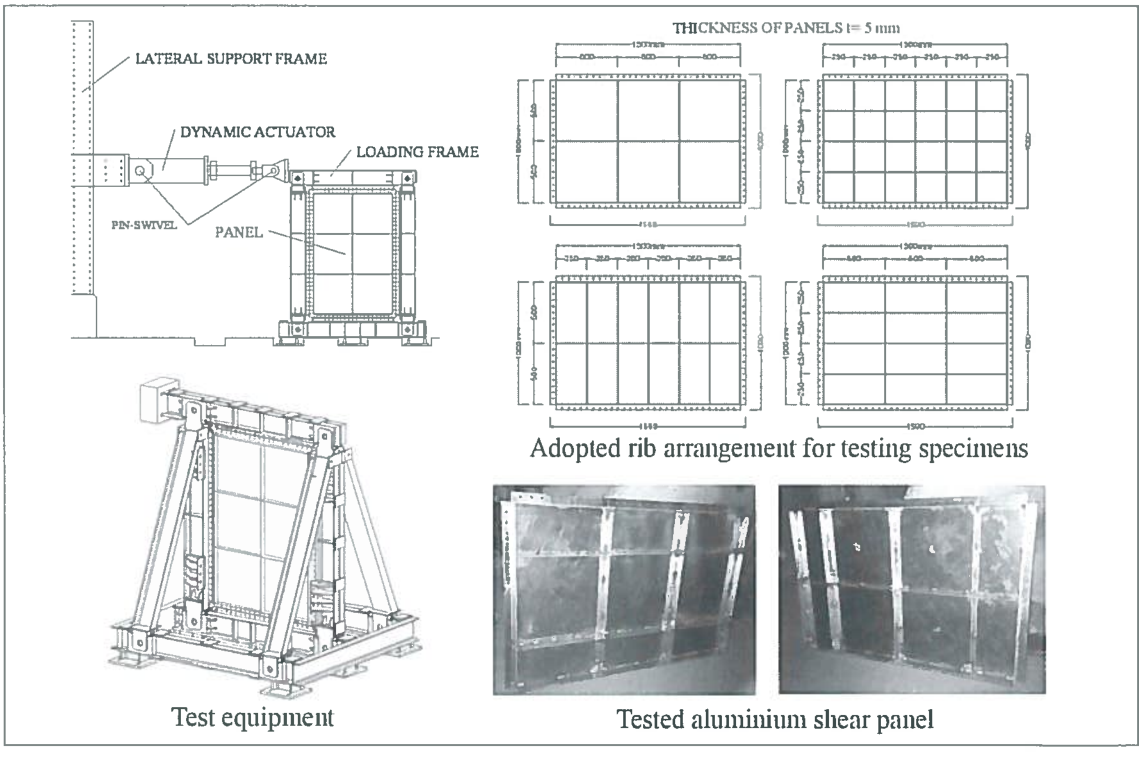
In order to optimize the protection of the primary structure against damage due to low-intensity earthquakes, it would be favourable to have dissipative devices which start to dissipate input energy even for small lateral displacements. This aim can be achieved by using devices made of aluminium alloys with low percentage of alloying elements (Figure 23), so to have a yield stress even lower than LYS steel and simultaneously to reduce the overloading on structural elements. Besides, with respect to LYS steel, pure aluminium is easily available on the world market. Recently, at the Department of Structural Analysis and Design of the University of Naples “Federico II” a new device has been proposed as an innovative solution for passive control of steel framed buildings. It consists on the use of pure aluminium shear panels, suitably reinforced by ribs to prevent shear buckling both in the elastic and plastic field, so to provide an excellent ductile performance (Figure 24) [27]. For a further reduction of the yield strength, the utilized aluminium for shear panels can be thermically treated also to eliminate the residual stresses produced by welding during the fabrication phases. To examine the seismic performance of shear panels, an experimental program comprising monotonic and cyclic tests has been undertaken. It will be developed in combination with analytical and numerical studies, aiming at assessing the actual beneficial effect of the above design methodology on the structural performance of MR steel frames.

Recently two additional research projects related to special types of steel plate shear walls are being carried out at the Department of Civil and Environmental Engineering of the University of California, Berkeley. The former concerns composite shear walls consisting of steel plate shear walls with reinforced concrete walls attached to one side or both sides of the steel plate by using mechanical connectors such as studs or bolts (Figure 25) [28]. The latter is related to steel plate shear walls used as primary lateral load resisting system into dual structural schemes. The structural system is composed by exterior concrete filled tubes, interior wide flange beams and columns and the bolted splices at mid-height of shear walls and interior columns (Figure 26) [29]. It has been developed and used by Skilling Ward Magnusson Barkshire of Seattle to build the 52-story “Century building” in San Francisco, Texas (Figure 16c).

## ANALYSIS METHODOLOGIES AND CONCLUDING REMARKS

Current seismic design method for ordinary structures is based on the conventional force-based design procedure, where the seismic forces are calculated by reducing the elastic design acceleration spectrum by a response modification factor R which takes into account the energy dissipation capacity of the structure. The adopted design philosophy, which is based on the well known concept of ‘strong column – weak

*Figure 24*
*Experimental tests on pure aluminium shear panels*



Adopted rib arrangement for testing specimens

Test equipment

Tested aluminium shear panel

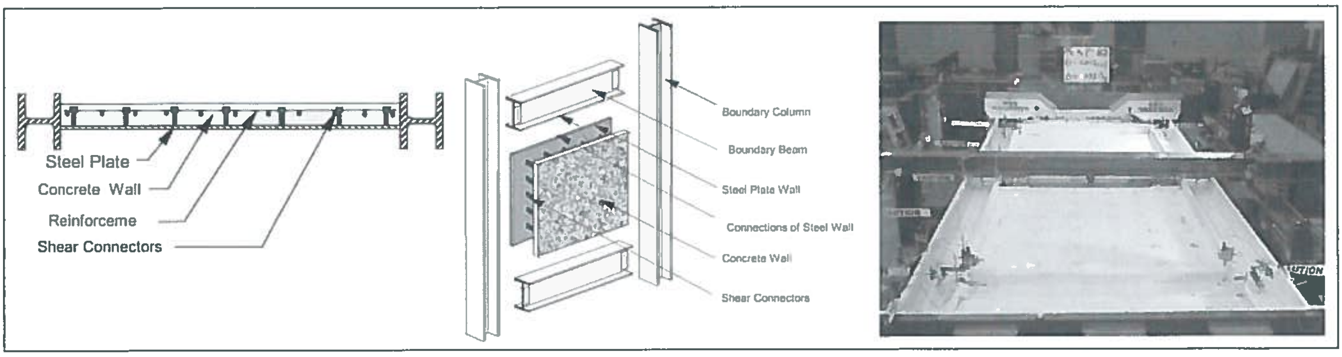


*Figure 25 Composite shear wall system studied at the University of California , Berkeley*

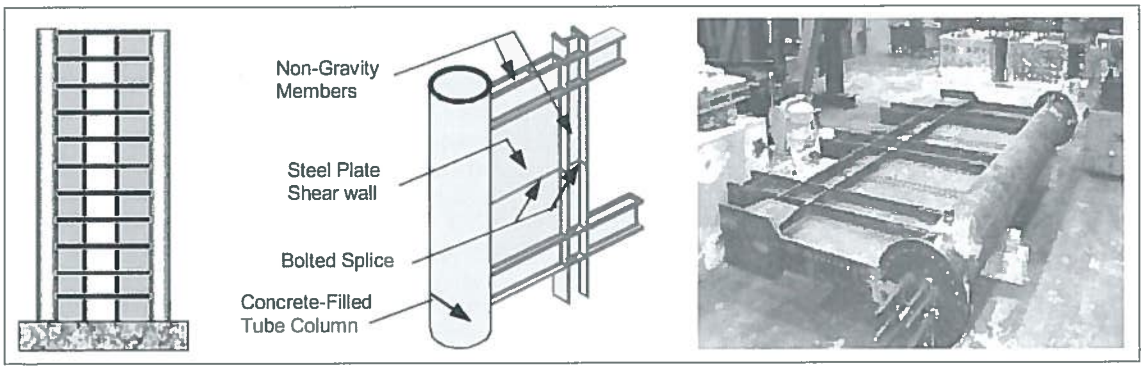


*Figure 26 Steel plate shear wall system studied at the University of California , Berkeley*

beam', aims at guaranteeing that the energy absorption capacity of steel buildings is greater than the energy demand of the earthquake by the development of global collapse mechanisms. Therefore, such a design procedure involves damaging of structural members under strong earthquakes. A moment resisting frame designed according to 'strong column – weak beam' criterion could be adequately modeled as a sort of 'series system', in which the plastic deformation phase of the structure follows the elastic one [30]. The aforementioned design procedure presents some difficulties, such as the uncertainty related to the evaluation of the force reduction factor and the fulfillment of serviceability limit state checking, since the evaluation of structural displacements is only done near the end of the design process without any link with the other design phases.

As far as the buildings equipped with energy dissipative devices are concerned, it has to be highlighted the difficulty related to preventive evaluation of the force reduction factor for a 'combined system', whose behaviour is strongly dependent on the stiffness and strength ratios between primary structure and the adopted device. Recently, new design approaches have been therefore set up. First of all, a structure supplied with energy dissipation devices could be represented as a 'parallel system', in which the whole structure can be modeled as two independent systems: "the primary structure" and "the energy dissipation system". The former denotes the system composed by beams and columns of the main frame, which can be assumed to remain elastic under moderate earthquakes and used as supplementary energy dissipation system when medium and large earthquakes occur. Instead, the latter system is the one composed by the dissipative devices, which are mainly designed to resist lateral seismic loads, but provide also a contribution to the stiffness, strength and damping of the whole structure. Therefore, a structure equipped with dissipative devices could be also denoted as 'Damage Tolerant Structure' (DTS). Possible relevant advantage is not only the protection of the main structure from damage but also the saving of constructional costs [31, 32].

Since the damage of structural and non structural elements during earthquakes is mainly due to lateral interstorey drift, it would be appropriate to replace the traditional force-based design approach with the displacement-based one, in accordance to the performance-based design method. The main concept of displacement-based design consists in designing the structure in such a way under an assigned design earthquake (ground motion level), corresponding to a predefined recurrence interval, the maximum interstorey drift does not exceed the target value (performance level). For inelastic behaviour of the structures, this method is applied according to the so-called 'substitute structure approach' [33], where the structure is substituted by an equivalent linear elastic scheme having both stiffness and damping equal to the actual ones [34], so to employ the elastic displacement spectra as design tool. In the case of DTS, the 'substitute structure approach' can be applied according to the iterative procedure given by Lin et al. [35].

The first guidelines and commentary for the seismic rehabilitation of buildings supplied with dissipative devices are presented in the FEMA 273 [36] and were developed by Whittaker et al. [37]. Non-linear static and dynamic analysis procedures for building with dissipative devices based on metallic yielding have been implemented in FEMA 273, in which the target displacement can be established by either the 'coefficient method' or the 'capacity spectrum method'. Such methods can be easily developed and applied, on yhe basis of push-over analyses and the assumption of some basic values related to both the damping features of the structure and to the target displacement. For instance, a simplified procedure for seismic retrofitting of framed buildings by means of low yield shear walls has been recently proposed by De Matteis and Mistakidis [38].

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