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EXISTING STRUCTURES CONNECTED WITH DAMPERS: STATE OF THE ART AND FUTURE DEVELOPMENTS

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ABSTRACT

The effectiveness of coupling buildings through dampers to enhance their seismic performance and reduce damage was proved in past years with many numerical and experimental studies by several authors.

Initially conceived for the pounding control only, this method was extended to the seismic response mitigation of adjacent buildings through their mutual connection and, more recently, connecting parts of the same structure. The analytical model used to represent this interaction problem consists of two SDOF or MDOF systems connected with dampers with different mechanical characteristics and layouts. Dampers are acknowledged as being very effective in mitigating the seismic response of existing structures. The cost effectiveness of the solution, its reliability, the chance of lowering repair costs and shortening the building downtime after an earthquake foster an opportunity for a more widespread application of this technique.

Starting from an overview of the analytical problem and a critical discussion of the different studies and their main findings, the paper provides a state of the art of this seismic response control method aiming at extending the available results to the application of a novel retrofitting strategy in which the building will be connected through energy dissipation devices to specific earthquake resistant elements along the perimeter.

INTRODUCTION

The effect of added energy dissipation devices in reducing the seismic response of buildings was extensively investigated in past years, experimental investigations and real-scale applications were carried out, and the technology effectiveness was widely proven. The traditional way to implement dampers in the building frames consists in creating damped bracing systems between two adjacent storeys (Fig.1a) (Ciampi et al., 1995). The application of the devices in this classical configuration, however, could present some disadvantages, particularly when they are applied in building retrofits. In fact, even if in new structures the main frame is designed to bear the forces induced by the dampers, in existent buildings these forces can create an untimely failure of the elements. In this case, the design of the damped bracing system needs to take into account some issues as the bracing-frame connection points, the effects of the added mass on the existent frame, the new configuration of the loads and the need for extensive new foundations (Benavent-Climen, 2011). In addition to these matters, the application of this type of retrofit to the perimeter of an existing building can lead to a severe

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impairment of the building façade, without considering the aesthetic value of the building and of the urban contest.

Another way to improve the seismic performances of a building consists in connecting two adjacent buildings, or different subsystems of the same structure, with dampers (Fig.1b). This solution, firstly studied in the early 70s to reduce the wind response of high-rise buildings, was applied 20 years later to prevent the problem of mutual pounding between adjacent structures, which has been observed in the strong earthquakes of the 80s (Luco and De Barros, 1998). The excellent results in terms of seismic response reduction of the coupled buildings, lead the researchers to study this model in more detail: many parametric studies were carried out to find the optimal values of the connection parameters, which mostly reduce the response of the system.

The aim of this study is to give an insight into the solution of connecting two structures with different properties to reduce the seismic response, with the purpose of extending the analytical models available to the design of a new retrofit strategy. In fact, connecting an existing building to specific external earthquake resistant elements through energy dissipation devices (Fig.1c), could solve the problems related to the classical configuration (Fig.1a) stated before, providing, at the same time, an equal or greater response mitigation (Trombetti and Silvestri, 2007; Roh et al., 2011). The idea of connecting the building to a resistant wall was already proposed by Trombetti and Silvestri (2007), but they needed a very stiff lateral-resisting element to obtain an effective damping system, which was proportional to the mass component of the Rayleigh damping matrix; based on this assumption, the effectiveness of such method diminishes with the reduction of the stiffness of the added wall.

This paper presents a state of the art of the most significant researches carried out in the coupled building control field (Fig 1b,c). After a brief analytical description of the problem, the theoretical analyses and the parametric studies are presented, distinguishing between different types of dampers (viscoelastic, fluid viscous, friction or hysteretic), and overall system models (SDOF, MDOF or continuous beam models). Applications and future developments of this retrofit technique are finally presented.

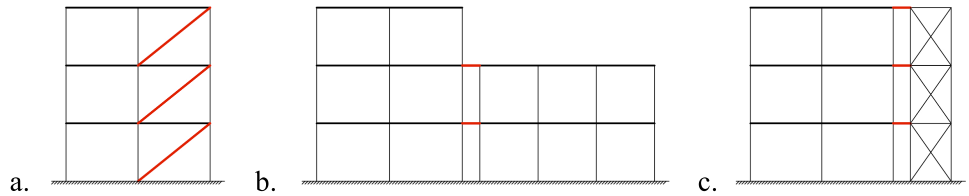


Figure 1. Ways to implement dissipative devices in the retrofit of existing buildings: a. between two adjacent storeys, b. connecting adjacent buildings, c. connecting building with lateral resistant walls

CHOICE OF THE CONNECTIONS

The problem of coupled building control has been widely studied and, in particular, the effectiveness of the method was demonstrated under various types of connection. The choice of the link is very important, because each type of connection influences the dynamic response of the final system in different ways.

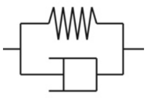
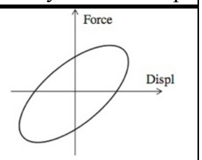
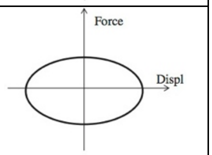
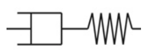
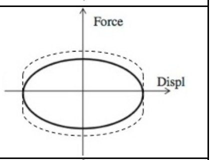
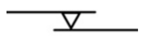
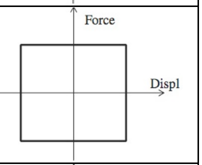
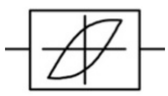
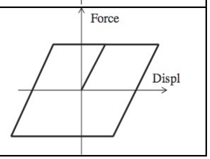
Structures can be coupled with two main types of connection: rigid links or damped links. Although the first studies considered rigid links, their not so good performances, as discussed in the following, and the development of new damping technologies have lead to privilege a passive damped connection.

The most widespread classification of the passive energy dissipating systems divides the dampers into three main categories: displacement-activated, velocity-activated and motion-activated (Christopoulos and Filiatrault, 2006). Velocity-activated devices include hydraulic linear and nonlinear fluid-viscous (FV) dampers; displacement-activated devices include friction (Fr) and hysteretic or elastoplastic (EP) dampers; finally the viscoelastic (VE) dampers belong to both categories. The dissipating mechanisms of these devices, their model, and their hysteresis loop are summarized in Table 1.

These kinds of dampers have very different characteristics, from which the final behaviour of the coupled system depends. Friction and elastoplastic dampers are simple and relatively inexpensive mechanisms; they can deliver large displacements, and can be fairly small. Compared with viscous dampers they have excellent capability to resist forces in lateral direction, but are not self-centering and are not as stable as hydraulic devices. On the other hand, viscous dampers are effective in reducing vibration, may have self-centring capability after the earthquake and high durability. They usually have a higher cost, but it should be considered that most hydraulic dampers are reusable after strong earthquakes, whereas elastoplastic dampers must be replaced (Liang et al., 2012). In addition, viscous dampers are insensitive to shrinkage deformation and thermal expansion, because these phenomena happen at nearly zero velocity (Xu et al., 1999).

In reference to the application of the coupled building control, the main difference between these types of dampers is that friction and EP dampers apply additional lateral stiffness to the structure (total stiffness matrix and periods will be altered), whereas fluid viscous dampers do not contribute extra stiffness (typically the contribution of the spring is not significant) (Liang et al., 2012).

Table 1. Types of dampers

Damper	Classification	Dissipating Mechanism	Rheological Model and Hysteresis Loop	
Visco-elastic VE	Displacement- and Velocity-activated	shear deformation of the visco-elastic material	 Kelvin-Voigt	
Linear Fluid viscous FV	Velocity-activated	passage of a silicone oil through shaped orifices	 Maxwell	
Nonlinear Fluid viscous FV	Velocity-activated	passage of a silicone oil through shaped orifices	 Maxwell	
Friction Fr	Displacement-activated	sliding of two solid bodies	 sliding force	
Elasto-plastic EP	Displacement-activated	hysteretic behaviour of metals after yielding	 Bouc-Wen	

ANALYTICAL COUPLING MODELS

The effectiveness of the coupled building method (Fig 1b,c) was demonstrated through different types of analyses, and under various configurations of the system. The definition of the analytical model underlying the coupled system is presented herein. Being the system constituted by two buildings and their connection, some assumptions about their characteristics must be taken, in order to define the equation of motion of the overall system.

Connection model

As previously described, with reference to the dissipating mechanism, four different types of dampers may be classified, each one with a different rheological model and, consequently, a different expression of the damping force. The type of damper affects the dynamic of the system, and the governing equations of motion.

Visco-elastic dampers are the simplest connections, they are modelled as a spring and a damper in parallel, and their parameters (respectively k_d and c_d) are directly included in the damping and stiffness matrices of the whole system, being the damping force expressed by Eq.(1):

$$f_d = k_d x + c_d \dot{x} \tag{1}$$

Fluid-viscous dampers are considered in the equation of motion as an additional force defined by Eq.(2):

$$f_d + \Lambda \dot{f}_d = C_0 \dot{x} \tag{2}$$

where C_0 is the damping coefficient at zero frequency matrix, and Λ is the relaxation time matrix (it was shown that these dampers exhibit purely viscous behaviour for frequencies below a certain cut-off frequency, thus typically Λ is considered equal to the null matrix (Constantinou and Symans, 1993)).

Usually the analyses consider linear damper models, but very often in the practical structural engineering applications nonlinear viscous dampers are applied, in order to maximize the energy dissipation. In this case, nonlinear force-velocity relationships must be used, introducing a fractional exponent α of the velocity, typically included within 0.1÷0.2 (Gattulli et al., 2011).

Friction dampers are quite cumbersome to model, as the number of equations of motion varies depending upon the non-slip and slip modes; moreover the 2-MDOF system connected with friction dampers is even more complicated because some dampers may be in a non-sliding phase and some may be in a sliding-phase at a particular instant of time, so at each time step the state of each damper has to be checked and the forces recalculated (Bashkararao and Jangid, 2006). The presence of the friction dampers in the system is modelled with the slip forces of the devices; the resulting force matrix is simply added to the right side of the equation of motion.

Finally elasto-plastic dampers are usually modelled with the nonlinear hysteretic Bouc-Wen model and appear in the equation of motion as an hysteretic damping force vector, defined in Eq.(3):

$$f_d(x) = \Lambda_1 x + \Lambda_2 z \qquad\qquad \dot{z}(x) = G(z, \dot{x})\dot{x} \tag{3-4}$$

where Λ_1 and Λ_2 are diagonal matrices which represent the coefficients of elastic and inelastic components of the hysteretic damping force and z is a non-dimensional auxiliary argument vector related to x through the differential Eq.(4). The complete treatment of this method was first described in Ni et al. (2001).

Building model

Once selected the type of connection, the connected buildings can be modelled in different ways. The cumbersomeness of the coupling problem requires many simplifications to the system, and the most restrictive assumptions are often made on building models. The choice of the model relies on the desired level of accuracy and affordability of the analysis.

2-SDOF System

The easiest way to represent the coupled building problem is to model the buildings with two single-degree-of-freedom (SDOF) structures, connected by a passive link (Fig.2).

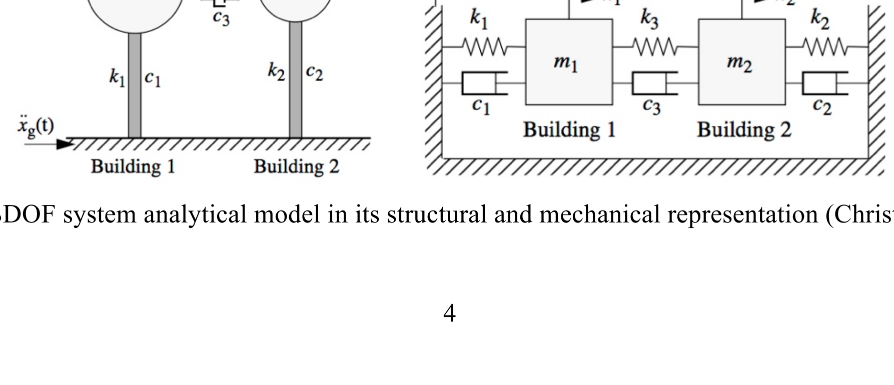


Figure 2. 2-SDOF system analytical model in its structural and mechanical representation (Christenson, 2001)

This is a very simple model which allows to study the effects of coupling on the dynamic response of the system (Christenson, 2001), to obtain closed-form equations for optimum parameters of the damper (Zhu et al., 2011; Basili and De Angelis, 2007) or to validate the efficiency of the coupling method in some practical applications (Kim et al., 2006; Hwang et al., 2007; Gattulli et al., 2011).

For brevity, in the following the only case of the VE dampers is illustrated, the one used in Christenson (2001), and Kim et al. (2006); for the other cases refer to: Hwang et al. (2007) for simple linear viscous dampers (modelled with only a dashpot – k_3=0 in Fig.2), Zhang and Xu (2000) for fluid viscous dampers, and Basili and De Angelis (2007) for hysteretic dampers.

The equations of motion of the 2-SDOF system connected with viscoelastic dampers are expressed in Eq.(5).

$$M\ddot{x} + C\dot{x} + Kx = -MI\ddot{x}_g \tag{5}$$

where $M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$, $C = \begin{bmatrix} c_1 + c_3 & -c_3 \\ -c_3 & c_2 + c_3 \end{bmatrix}$, $K = \begin{bmatrix} k_1 + k_3 & -k_3 \\ -k_3 & k_2 + k_3 \end{bmatrix}$,

and $x = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T$

The solution of the equation of motion can be found considering directly the second order differential equation, or transforming it into a first order time-invariant system.

The 2-SDOF system is the simplest model of the real system; it gives an idea of the coupled behaviour but could lead to very approximate solutions. Moreover this model could not be used when the objective of the research is to optimize the position and the properties of the dampers along the structure height.

<u>2-MDOF System</u>

The 2-MDOF system (Fig.3) allows more detailed analyses. Here different characteristics of the buildings (floor mass or stiffness, number of floors, etc.) and of the connective link (damper parameters, number and location) can be varied along the height.

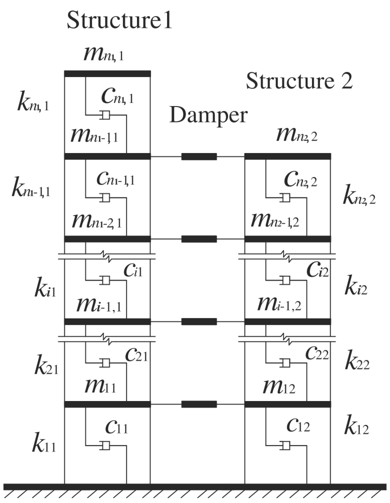


Figure 3. 2-MDOF system analytical model (Zhu et al., 2011)

In this system the buildings are mainly modelled as elastic shear buildings. Typically, in order to simplify the problem, the buildings are assumed to be symmetric with their symmetric planes in alignment, and the ground motion is assumed to occur in one direction in this symmetric plane. It is further assumed that floor elevations are the same for both buildings, and that both buildings are subjected to the same base acceleration, neglecting the spatial variation of the ground motion and the soil-structure interaction (Xu et al, 1999). It must be noted that the use of the shear-building models can lead to a system which is very different from the real case, especially in the case of existent buildings, which often have very flexible beams and floor systems (Chopra, 2012).

This system was first adopted in Xu et al. (1999), considering the simplified building model previously described, with buildings connected at each floor. Initially used to study the effectiveness of the method (Xu at al., 1999; Zhang and Xu, 2000; Ni et al., 2001), this model was then applied for the optimization of the damping system. In these analyses the number and the parameters of the dampers were varied in order to obtain the better performances with minimum cost through parametric analyses (Huang and Zhu, 2013; Patel and Jangid, 2010; Bashkararao and Jangid, 2006; Bakeri, 2012) or multi-objective optimization approaches (Ok et al., 2008). Finally the 2-MDOF system model was used to validate some practical applications (Li et al., 2004).

Also for this system, only the equation of motion of the simplest case of VE connection is here presented (for the complete theory refer to Xu et al., 1999); for the fluid-viscous refer to Zhang and Xu (2000), for the friction to Bhaskararao and Jangid (2006) and for the hysteretic ones to Ni et al. (2001).

The equations of motion of the 2-MDOF system connected with viscoelastic dampers are expressed in Eq.(6).

$$M\ddot{x} + \left(C + C_d\right)\dot{x} + (K + K_d)x = -MI\ddot{x}_g \qquad (6)$$

where $M = \begin{bmatrix} m_{n+m,n+m} & 0_{n+m,n} \\ 0_{n,n+m} & m_{n,n} \end{bmatrix}$, $C = \begin{bmatrix} c_{n+m,n+m} & 0_{n+m,n} \\ 0_{n,n+m} & c_{n,n} \end{bmatrix}$, $K = \begin{bmatrix} k_{n+m,n+m} & 0_{n+m,n} \\ 0_{n,n+m} & k_{n,n} \end{bmatrix}$,

$$C_d = \begin{bmatrix} c_{d(n,n)} & 0_{(n,m)} & -c_{d(n,n)} \\ 0_{(m,n)} & 0_{(m,m)} & 0_{(m,n)} \\ -c_{d(n,n)} & 0_{(n,m)} & c_{d(n,n)} \end{bmatrix}, \text{ and } K_d = \begin{bmatrix} k_{d(n,n)} & 0_{(n,m)} & -k_{d(n,n)} \\ 0_{(m,n)} & 0_{(m,m)} & 0_{(m,n)} \\ -k_{d(n,n)} & 0_{(n,m)} & k_{d(n,n)} \end{bmatrix}$$

2-shear or flexible beams

Finally the buildings can be modelled as two uniform, elastic, continuous and damped shear beams of different heights, as proposed by Luco and De Barros (1998). The same model was adopted by Aida et al. (2001), in the numerical validation of their tuning method, and by Christenson (2001), which yet considered two cantilever beams modelled with the Galerkin and the finite elements methods, in order to represent two flexible high-rise buildings.

Type of damping

The last feature for the definition of the system model is the type of damping of the overall system, namely proportional or nonproportional damping. When a building is provided with dissipative devices, the system becomes non-proportionally damped (Liang et al., 2012). This evidence was experimentally proven also for the coupled building problem by Xu et al. (1999). Despite of it, the nonproportional damping is not always considered.

Taking into account the non-classical damping in the analytical model is cumbersome, and it was demonstrated that it could be ignored when very strict simplifications are applied to the system (Hwang et al., 2007) or when the total damping after the installation of the dampers is still not very large (Liang et al., 2012). In all the other cases, it was proven that if not considered, the analyses of real structures could lead to unrealistic results (Liang et al., 2012).

In order to handle the non-proportional damping, the equation of motion must be reformulated; typically the dynamic characteristics of the system are found through the eigenvalue problem, and the total response is determined using the complex mode superposition method. The response of each mode can be determined in different ways, some examples can be found in Chopra (2012) and in Liang et al. (2012), who solve the equation of motion in the time domain, or in Zhang and Xu (1999), who apply a simplified procedure in the frequency domain to study the coupling problem.

OVERVIEW OF SOME REPRESENTATIVE RESEARCHES

In the presented researches, many parametric analyses were carried out, aimed at validating the coupling building method and at optimizing the performances of the damped links.

The adopted optimum parameter criteria were: maximum response reduction (reducing first and second mode responses, minimum mean square displacement or acceleration response), maximum damping ratio, minimum energy in the system (minimum dissipation energy in the devices, minimum vibration energy and minimum energy stored in one or both structures), or both minimum response and minimum cost using a multi-objective genetic algorithm.

To evaluate the response of the systems, various types of analyses can be carried out. The most used were the transfer function analysis and the root mean square analysis. For the case of simple oscillators, another type of analysis is the root locus analysis, which observes the coupled system poles as a function of the coupling stiffness and damping (Christenson, 2001; Gattulli et al., 2013).

The transfer function analysis is very useful to study how the natural frequencies of the two systems vary after coupling. Indeed in a seismic retrofit the change of the initial dynamic properties of a building can also be very detrimental to the structures.

The root mean square analysis is useful in determining the influence of various parameters on the response of the system. Since the ground excitation is a stochastic process (filtered zero-mean stationary Gaussian white noise), the system responses will also be a stochastic process, and is fully defined by the mean vector and the covariance matrix. Thus, the RMS response, which is the square root of the diagonal terms of the covariance matrix, is a good measure of the system performance since it directly defines the multimode response of the system (Christenson, 2001).

Typically for these analyses the ground excitation is modelled as the filtered white noise corresponding to the Kanai-Tajimi spectrum. This transfer function in the Fourier domain is Eq.(7):

$$H_{\ddot{x}_g v}(\omega) = \frac{2\zeta_g \omega_g j\omega + \omega_g^2}{-\omega^2 + 2\zeta_g \omega_g j\omega + \omega_g^2} \tag{7}$$

This filter is privileged because it was conceived to capture the pertinent frequency content of four major seismic events: El Centro, Hachinohe, Northridge, and Kobe. In the case of low frequencies, another filter is applied, in order to better represent the lower energy content.

Main results

All the researches carried out on the coupled buildings had the objective of demonstrating the efficiency of the method on the reduction of the seismic response for various buildings and dampers configurations, and to provide guidance on how to choose the optimal parameters and the location of the dissipative links. The main results of these analyses are briefly summarized and critically commented in the following.

<u>Method efficiency</u>

As explained in the previous sections, the final behaviour of the system will differ depending on the type of connection (either rigid links or dampers).

The first studies of the coupling building method had as an objective the pounding mitigation and used rigid link connections. Westermo (1989), in order to prevent mutual pounding between adjacent buildings, suggested to connect two neighbouring floors using hinged links. He showed that in all the studied cases the complementing system can reduce the pounding, but it also increases the base shear on the stiffer structures and enhances undesirable torsional response if the buildings have asymmetric geometry. The same evidences are noted in Kim et al. (2006), Basili and De Angelis (2007), and Roh et al. (2011), whom compare the behaviour of two structures connected with dampers and with rigid links. Finally a very significant experience is reported in Gattulli et al. (2011), which report the failures occurred after the strong 2009 L'Aquila earthquake in some portions of a building, whose façade was connected with rigid links to the frame. With reference to rigid links, the observed bad performances were due to the high stiffness of the links, which altered the dynamic characteristics of the final coupled structure with respect to the unconnected structures. In fact, the connected structures form a new stiffer system, which is subjected to higher seismic forces (Fig.4). In the case of building retrofit, the frames were not designed to support horizontal forces; the post intervention situation was therefore worse than the original one and the stronger excitations induced by the rigid connections could induce the structural failure.

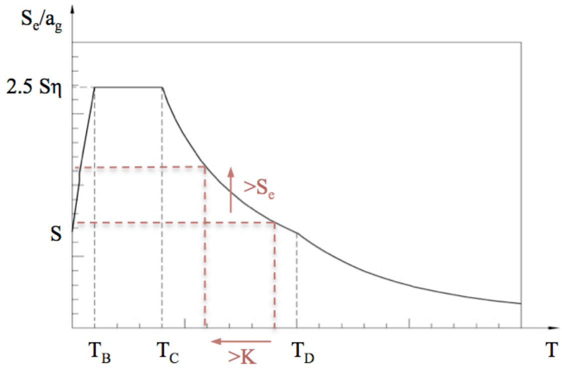


Figure 4. Increase of the seismic excitation due to the increase of the stiffness of the system (rigid connection)

On the basis of these results, in the following researches the rigid links were replaced with dissipative connections. The behaviour of the various types of dampers is very different, thus the effectiveness of the method is studied for each device type.

For the case of VE and FV connections, Takewaki (2007) proved that the total input energy of the overall system is approximately constant regardless of the number and location of the connecting links, thus if the dissipated energy in the viscous dampers increases, the input energy in the buildings can be reduced drastically. Moreover several frequency analyses demonstrated that by connecting buildings with VE dampers, only slight changes of the modal frequency of the individual buildings can be induced, even though the response peaks are significantly reduced after the installation of the dampers (Luco and De Barros, 1998; Xu et al., 1999; Zhang and Xu, 1999; Christenson, 2001) (Fig.5). These results show that a viscous connection does not change the dynamic characteristics of the unlinked buildings, which preserve their natural frequencies.

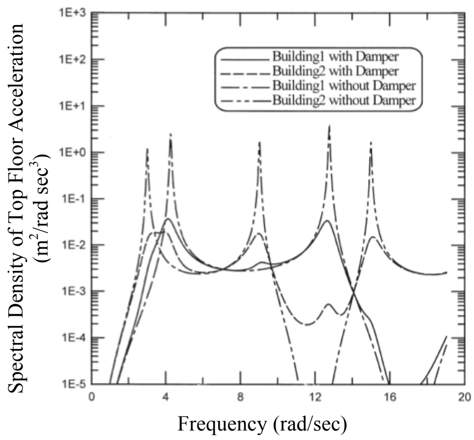


Figure 5. Damping of the spectral density functions of top floor displacements after coupling (Xu et al., 1999)

On the other hand, it could be supposed that hysteretic and friction dampers have behaviour similar to rigid links. In fact, in the initial phase they act as a rigid link, then, beyond a certain value of the seismic force, they yield (or slide) localizing the energy dissipation in the device.

Despite these differences, the efficiency of the connecting method in terms of response reduction (floor displacement, shear and acceleration) is proved for all the types of dampers (with a reduction of the responses even up to 70-80%).

Some authors showed also the efficiency of the coupled building method (Fig.1b,c) compared with the classical damping method (Fig.1a): Trombetti and Silvestri (2007) highlighted the best performance of the former configuration rather than the latter, but with the very strong assumption of connecting the building to a infinitely stiff wall (Fig.1c); instead Roh et al. (2011) showed that coupling buildings (Fig.1b) leads to performance similar to that of the classic damped bracing solution, but at lower costs (requiring smaller values of the damping coefficient).

Method optimization

Once showed the efficiency of the coupled building method, various parametric analyses were carried out by many authors in order to optimize the coupling system. The main characteristics investigated are the building configuration, the damper parameters and location, and the seismic excitation.

The study of different building configurations is very important in order to define the application field of the method, both for the connection of two existing buildings or for the design of new complementing resistant elements. The considered parameters are the relative mass, stiffness and building height ratios. Typical values of stiffness and mass ratios vary respectively between 1 and 10 and between 0.1 and 1 (Bakeri, 2012). When two existent buildings are coupled, ratios are similar and tend to unity; when a building is coupled with a resistant lateral element, higher stiffness ratios and lower mass ratios are considered. In order to study this second case, Trombetti and Silvestri (2007) consider stiffness ratios as high as 20 and 50, and mass ratios equal to 0.02 and 0.05; although the mass ratio could be plausible, it is very difficult to obtain such high stiffness ratio values either with additional RC staircase/elevator shells or steel bracing systems. The main results of these studies show that when two adjacent buildings are similar, i.e. the mass, stiffness and height ratios tend to unity, the dampers have no effect because the buildings have the same displacements and velocity in the same direction and the damping force becomes zero; for different ratios the dampers are activated, the building response diminishes, and optimum damper parameters can be found (Xu et al., 1999; Bakeri, 2012). The variation of the building height ratio has the same effect of the variation of the stiffness ratio, because both of them affect the natural period of the buildings.

Some other investigations were carried out for varying characteristics of the connection in order to study the changes in the system behaviour and to define the optimal damper parameters. In the case of VE dampers, the damper parameters are the damping coefficient and the stiffness. The stiffness has no effects on the seismic mitigation only for low values, but when it increases, the natural frequencies of both buildings increase and the performance of dampers reduces significantly (Xu et al, 1999). The damping coefficient has a defined optimal value for each couple of buildings: smaller c_d causes a gradual deterioration of the damper performances until the uncoupled situation is restored for very low values of the coefficient; c_d larger than the optimal value cause a variation of the natural frequencies: as the buildings become more coupled, a resonant peak dampens out and only a peak is observed (rigidly connected system) (Xu et al, 1999; Christenson, 2001) (Fig.6).

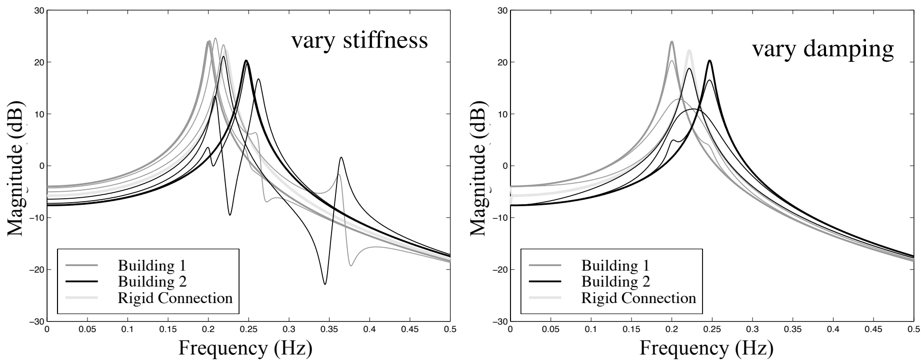


Figure 6. Transfer function from the ground acceleration to displacement as damper stiffness and damping is varied (Christenson, 2001)

The FV dampers have two parameters: the relaxation time and the damping coefficient at zero frequency. In this case the performances of the connection are not influenced by the relaxation time in each time interval, whereas the damping coefficient to zero frequency has the same behaviour of the damping coefficient of VE dampers. For this reason the two types of dampers have similar efficiency in practical applications (Zhu et al., 2011; Zhang and Xu, 2000).

Finally, hysteretic (or friction) dampers have only a parameter: the yielding (or friction) force. This parameter can influence the system differently depending on the state of the damper. In particular, depending upon the system parameters and excitation level, at a first stage the connected structures vibrate together without any slip in the damper (the connection behaves like a rigid link); if hysteretic or frictional force in the damper exceeds the limiting value, the structures vibrate independently (Bhaskararao and Jangid, 2006).

The last issue studied for the optimization of the coupling method is the variation of the number and location of the connections, aiming at reducing the cost of the intervention. Recently, many researches dealt with this problem and the main results show that it is possible to use a reduced number of dampers placed in proper location. In particular, Huang and Zhu (2013) show that the use of only one damper should be avoided, because the resulting force is too big and centralized and can cause damage to the structure; when more than one damper is used, they should be distributed and placed in accordance to the displacement and velocity distribution (for a shear building, at the top and the lower floors). The most important rule for the damper location is not to place the coupling link at the node of a dominant vibratory node (Christenson, 2001); for example, one of the best locations is in the vicinity of a loop of the first mode of the system (Aida et al., 2001).

Finally the effectiveness of the coupling method depends also by the type of the excitation; for instance Roh et al. (2011) demonstrated that with FV dampers, the coupling control is more effective in structures with fundamental natural frequency closer to the main frequency of the excitation.

APPLICATIONS AND FUTURE DEVELOPMENTS

The widely proved efficiency of the coupling building method makes it attracting for the retrofit and seismic enhancement of existent buildings, particularly with viscous connections. The cost effectiveness of the solution, its reliability, the chance of lowering repair costs and shortening the building downtime after an earthquake foster an opportunity for a more widespread application of this technique.

Many retrofit solutions based on this method were already studied (Fig.7): Kim et al. (2006) investigated the effects of inserting dampers in places such as seismic joints or building-sky-bridge connections; Hwang et al. (2007) studied the seismic retrofit of microelectronic factories, installing viscous dampers at the separation gap between the interior and exterior structures of the fab; Li et al. (2004) proposed the reduction of seismic forces on existent buildings with newly constructed additional stories including friction layer and VE dampers; Trombetti and Silvestri (2007) applied viscous dampers to connect a structure to an infinitely-stiff support structure.

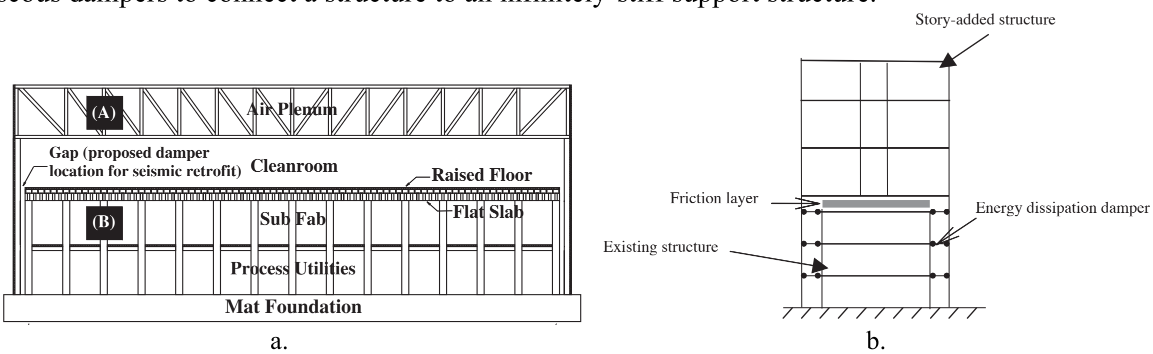


Figure 7. Examples of seismic retrofit solutions that apply the coupling method (a. Hwang et al., 2007; b. Li et al., 2004)

All these solutions connect either two adjacent existent buildings or an existent building to a new specifically designed resistant structure. The latter technique gives the possibility to design the complementing structure with desired geometry and dynamic properties, and this could lead to a more focused and efficient strategy. Moreover this new structure could fulfil also other architectural tasks: it could be used to create a new elevator core (Trombetti and Silvestri, 2007), or to add spaces to the building through lateral expansion or elevation (Li et al., 2004).

A new idea under development by the authors is to design this second structure as an external cladding, which would be able to improve the energy performance of the existent building and to remodel the aesthetic of the façade. This structure could be designed as a simple double skin, as a bidimensional system stiffening the façade at the roof level, or as a tridimensional system connected simultaneously in the two horizontal directions (Fig.8a,b,c). In these cases the exterior structure should be designed as thin as possible, but stiff enough to contribute to the seismic response mitigation.

A further intent is to overcome the traditional shear wall retrofit approach, by designing a shell structure which exploits the shape and the extension of the façade to reduce the cross section area of the single structural component and force the new involucre box-structural behaviour. In the shell structure the dissipating system can be either integral part of the exterior energy-saving cladding (Fig.8d) or the connection of the envelope to the existing building. In all cases an interesting solution might aim at activating dissipative devices only for ultimate limit state seismic actions, whereas for low intensity earthquake the structure might be conceived as non dissipative.

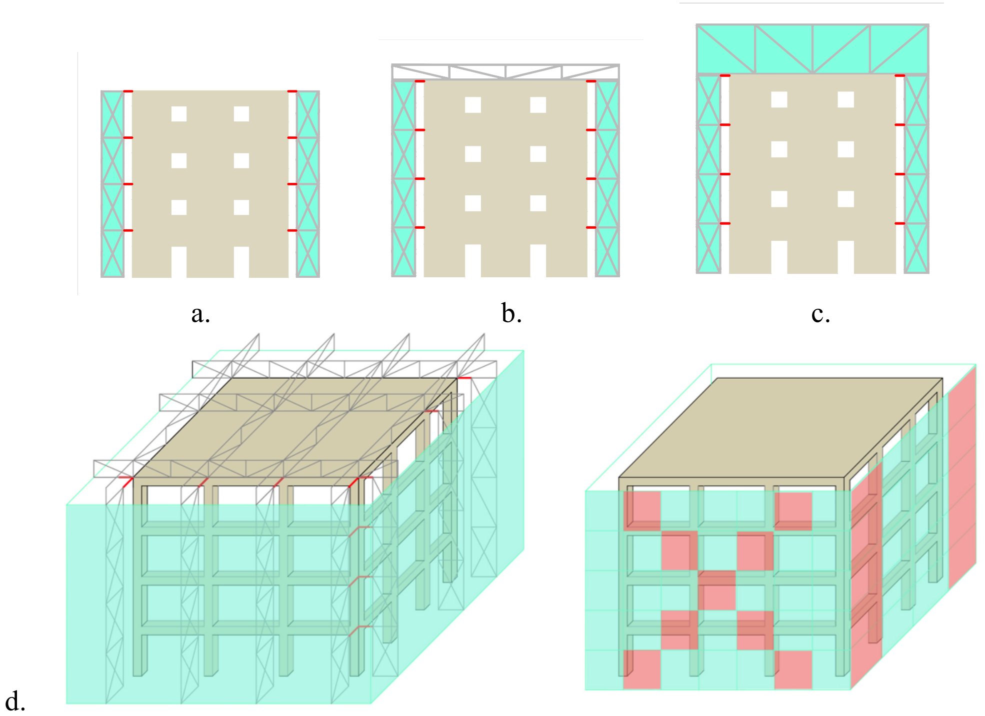


Figure 8. Structural double skin façade as new development, with dissipative elements in red (a. simple double skin; b. bidimensional system; c. tridimensional system; d. wall structure versus shell structure)

CONCLUSIONS

The coupling of buildings for the seismic performance improvement was presented through the analysis of previous studies. Firstly the main assumptions were explained; in particular the type of connection, the system configuration and the type of damping were discussed. Then an overview of the most relevant analytical studies was provided, presenting the various types of analyses and the main results. The system dependency from various parameters, such as the building configuration, the damper coefficients and the damper placement was discussed and commented for each type of damper.

Unlike the case of rigid links, coupling two structures with dissipative connections is a very efficient method for the improvement of their seismic behaviour in terms of energy dissipation and response reduction. The behaviour of the system depends on the type of dampers. Displacement- and velocity-activated dampers are both valid. As an added value, viscous connections maintain the dynamic characteristics of the unlinked buildings, which is particularly beneficial when acting on existent buildings.

Finally various applications of the coupling method for the seismic retrofitting of existent buildings were showed, and future applications of this technique for the design of new advanced and integrated retrofit solution under development were presented.

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