DISTRIBUTED DISSIPATION MECHANISM FOR PRECAST STRUCTURES

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ABSTRACT

In this paper an innovative solution for seismic protection of precast structures is introduced. The design strategy is simple and basic. It uses already available and common components to take advantage of economic benefit and to be suitable to be adopted rapidly by Industry and Constructors.

The main concept is to insert at each node of a precast structure a suitable dissipation pad. If it is true that the single pad has a small and very limited dissipation capacity, it is also true that in a generic structure there are several hundreds of this pads. In this way, a distributed dissipation mechanism is developed, taking also the advantage to realize a sort of tuned mass dampers by the isolation of whole floors.

The peculiarities of the prefabricated structures, the need to seismically resistant design of buildings and the substantial and growing number of prefabricated buildings in Italy and elsewhere arouse a particularly interesting to the study of a this passive control devices.

The effectiveness of this dissipation strategy is evaluated with reference to a three dimensional structure under several earthquake accelerograms.

Keywords: Precast Structures, Connections, Seismic Protection, Dissipation Devices, Seismic Isolation

INTRODUCTION

Precast concrete construction results in cost-effective structures that provide high quality production and rapid erection. The connections between precast concrete elements, in particular beam-to-column connections, play an important role in determining the successful of precast concrete framed structures. Typical precast beam-to column connection details are recommended by the Prestressed Concrete Institute (PCI), but some of them have showed poor performance during earthquakes.

In fact, for many years the use and development of precast structures in seismic areas has been worldwide limited by the lack of confidence and knowledge about their performance in seismic regions as well as by the absence of rational seismic design provisions in major model building codes.

Furthermore, the poor performance of precast structures in past earthquakes (Priestley et al., 1995) has increased a common but unjustified lack of confidence on such structural systems. In fact, it is important to underline that the aforementioned observed problems in the seismic response of existing precast structures, were in general due to substantial deficiencies during either the design or the construction phases, as incorrect design details, inadequate structural schemes, or absence of a correct seismic design philosophy, rather than to intrinsic limits of “precast”.

Significant advances have been accomplished in the last decade in the seismic design of structures, based on the introduction and refinement of innovative approaches.

The traditional approach consists of designing ductile constructions and dissipating the earthquake energy through big strains; but this causes damage and might lead to over-conservative and impractical designs (De la Cruz & López-Almansa, 2007).

However, there are more modern approaches, protection-oriented, using special devices (Fig.1). The first major classification identifies the active protection system and the passive protection. As for the passive protection there are two main techniques: seismic isolation and energy dissipation.

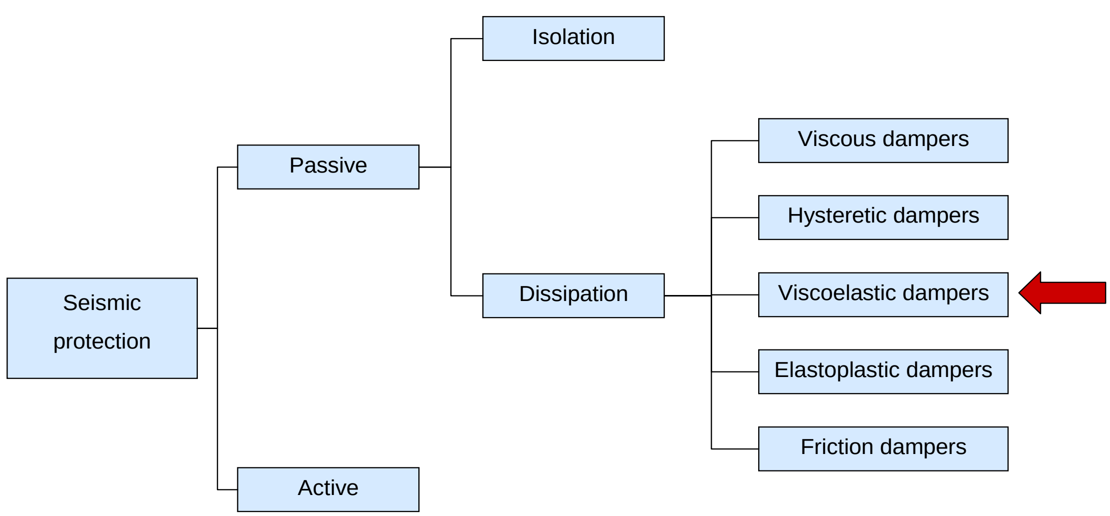


Fig.1: Seismic Protection.

In the first case the buildings are placed on the devices, seismic isolators, consisting of alternating layers of rubber and steel, which give an high vertical stiffness at the support system (that allows to support the weight of the structure) and give a low horizontal stiffness, (which absorbs and reduces the acceleration due to the earthquake significantly).

The energy dissipation helps to metabolize the energy introduced by the earthquake, trough special devices called energy dissipators, installed between two points of the structure subject to relative movements.

As shown in Fig.2, the energy dissipation can occur in different ways, depending on the device type (viscous, elastic-plastic, viscous-elastic) and material (oil, steel, elastomer). Each device features a set of parameters and its behavior is studied on the basis of a specific rheological model.

Among the existing energy dissipation devices, three major types are currently used: metallic yield dampers, friction dampers and viscous and viscoelastic dampers (Soong & Dargush, 1997).

In this study a preliminary analysis to evaluate their applicability in the design of prefabricated structures subjected to seismic actions has been made.

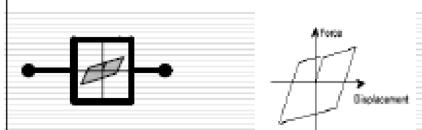
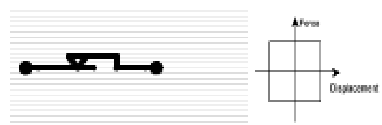
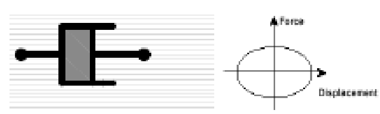
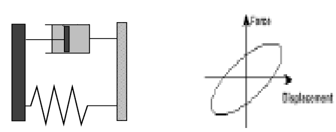
	Dampers	Parameters	Rheological models
Displacement-dependent devices	Elastoplastic	k elastic stiffness α hardening factor μ ductility	
	Friction	F_1 sliding force	
Velocity-dependent devices	Viscous linear	c_d viscous coefficient	
	Viscoelastic	k elastic stiffness η loss factor	

Fig.2: Summary table showing the possible dissipation devices, the characteristic parameters and their rheological models.

USE OF DISSIPATION DEVICES IN PRECAST STRUCTURES

As seen in the previous section, the hybrid frame makes use of mild steel, in addition to the post-tensioning steel, to reduce the lateral displacements during a seismic event.

As an alternative, the seismic behavior of post-tensioned non emulative precast concrete frame structures can be improved by using supplemental passive energy dissipation.

In the last few decades, a substantial amount of research has been conducted on the use of supplemental passive energy dissipation from various types of damping assemblies (e.g. friction metallic yielding, and viscous fluid dampers) in steel and reinforced concrete structures as summarized in a number of overview publications (Soong and Dargush, 1997; Soong and Spencer, 2002; Martinez-Rueda, 2002).

In comparison, there has been little research on the application of supplemental energy dissipation in precast concrete construction (Pall and Pall, 1993; Cherry and Filiatrault, 1993).

Morgen and Kurama (2004), for example, investigated a new type of friction damper that can be used externally at selected beam-to-column joints in a precast concrete frame system to dissipate energy during an earthquake.

In this paper the applicability of viscoelastic dampers is investigated and some preliminary results are presented.

BASIC PRINCIPLES

Energy Dissipation Devices (EDDs) absorb seismic energy thereby reducing the demand on primary structural members. In this way, structural and nonstructural damage is significantly reduced. The energy dissipation is effective because it provides a damping added to the original system.

An increase in damping produces a lowering of the dynamic actions and response. The dampers absorb a good part of the energy making the displacements tolerable (Fig.3).

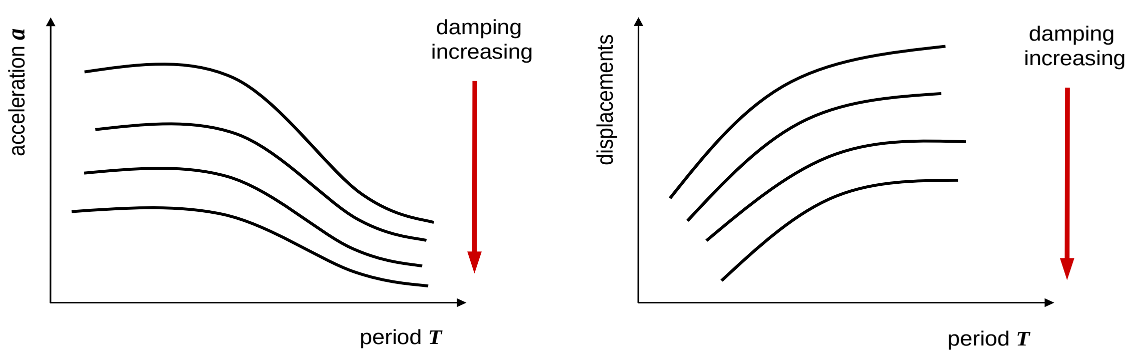


Fig.3: Performance of dynamic actions and response to increasing damping.

There are many types of dampers used to mitigate seismic effects, including:
- Viscous dampers compress a fluid in a piston-like device: it depends on the velocity;
- Hysteric dampers utilize the deformation of metal parts;
- Viscoelastic dampers stretch an elastomer in combination with metal parts;
- Frictional dampers use metal or other surfaces in friction;
- Hybrid dampers utilize the combination of elastomeric and metal or other parts.

In Equation (1) the energy balance is showed:

$$E = E_\varepsilon + E_k + \underbrace{E_H + E_V}_{E_D} \qquad (1)$$

where:

E = input power (work done by the force of inertia acting on the structure)

E_ε = elastic strain energy

E_H = energy dissipated by hysteresis

E_V = energy dissipated by viscous phenomena

E_D = total energy dissipated

EQUIVALENT VISCOUS DAMPING

Damping in actual structures is usually represented by equivalent viscous damping. It is the simplest form of damping to use since the governing differential equation of motion is linear and hence amenable to analytical solution.

The simplest definition of equivalent viscous damping is based on the measured response of a system to harmonic force at exciting frequency ω equal to the natural frequency ω_n of the system.

Another definition of equivalent viscous damping is that it is the amount of damping that provides the same bandwidth in the frequency-response curve as obtained experimentally for an actual system.

The most common method for defining equivalent viscous damping is that it is to equate the energy dissipated in a vibration cycle of the actual structure and an equivalent viscous system. The energy dissipated in the actual structure is given by the area E_D enclosed by the hysteresis loop (Fig. 4).

Equating this to the energy dissipated in viscous damping leads to:

$$4\pi \xi_{eq} \frac{\omega}{\omega_n} E_H = E_V \qquad (2)$$

where ξ_{eq} is the equivalent viscous damping ratio. From the (2) can be obtained ξ_{eq}:

$$\xi_{eq} = \frac{1}{4\pi} \frac{1}{\omega / \omega_n} \frac{E_V}{E_H} \tag{3}$$

The experiment leading to the force-deformation curve should be conducted at $\omega = \omega_n$ where the response of the system is most sensitive to damping. Thus, Equation N specializes to

$$\xi_{eq} = \frac{1}{4\pi} \frac{E_V}{E_H} \tag{4}$$

It is widely accepted that this procedure can be extended to model the damping is systems with many degrees of freedom (Chopra, 1995).

Thus, equivalent viscous damping value is derived by equating the energy dissipated in one cycle by a SDOF oscillator to the viscous energy dissipated viscously in the linear model in a cycle to that dissipated by the yielding structure when subjected to the same maximum displacement (Fig.4).

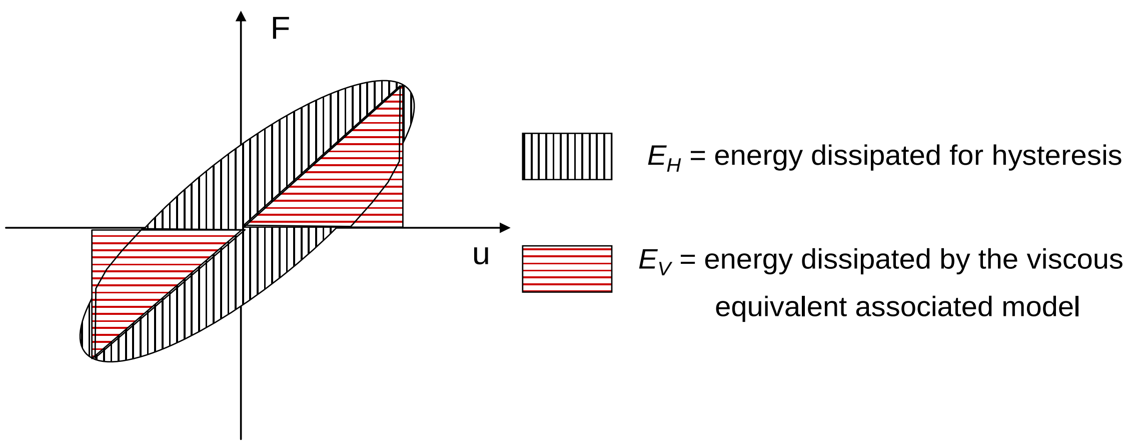


Fig.4: Equivalent viscous damping.

ELASTOMERIC VISCOELASTIC DAMPERS: EXPERIMENTAL PROPERTIES AND NUMERICAL MODELING

In viscoelastic devices the dissipation is given by the shear deformation of a high damping rubber. These devices are characterized by hysteretic cycles with shear deformation and a highly nonlinear response; experimentally has been shown that stiffness values and damping depending mainly on the shear deformation (Cancellara and Pasquino, 2007).

Some experimental methods characterizing the dynamic properties and thermal properties of elastomeric compounds are shown in Cambiaghi et al. (2001).

Devices are characterized by low horizontal stiffness, high vertical stiffness and dissipative adequate capacity. These features allow to increase the period of the structure, to support vertical loads without appreciable sagging and to contain the horizontal displacement (Fig.5).

In determining the vertical and horizontal stiffness, the basic design parameters are the geometric characteristics of the devices and the mechanical properties of the elastomer. The dissipation capability is determined by the type of elastomeric compound.

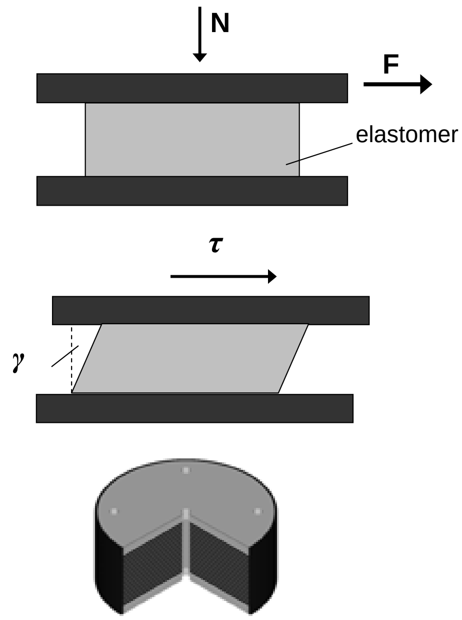


Fig.5: Elastomeric damper.

The most common elastomeric compounds are characterized by a dynamic shear modulus G_{din} between 0.4 MPa and 1.4 MPa and viscous damping ratio equal to 10% -15% (according to UNI Standards and / or OPCM No 3431 Italian Code).

The high damping elastomeric compounds are characterized by a shear modulus G_{din} varying with the shear deformation γ when γ <0.5. This prevents excessive movement in the face of low-intensity dynamic excitations, such as those due to wind.

For values of γ between 1 and 2, G_{din} is almost constant. The equivalent viscous damping ratio ξ depends on the shear deformation γ.

Considering a sinusoidal forcing type:

$$F_d = F_{d,\max} \cdot \sin(\omega t + \delta) = k_d u_d(t) + C_d \dot{u}(t) \tag{5}$$

- $F_{d,\,max}$ = amplitude (maximum value)
- ω = excitation frequency;
- δ= phase shift;
- k_d = stiffness of the Kelvin model;
- C_d = damping of the Kelvin model.

In a viscous-elastic material behavior, the relationship equation is:

$$\tau(t) = G\gamma(t) + B\dot{\gamma}(t) \tag{6}$$

where *G* and *B* are a deformation-dependent and a velocity dependent constant respectively. Imposing a harmonic law of angular deformation:

$$\gamma(t) = \gamma_0 \sin \omega t \tag{7}$$

By substituting the (7) in the (6) it results:

$$\tau(t) = \gamma_0 G \sin(\omega t) + \gamma_0 \omega B \cos(\omega t) = \tau_0 \sin(\omega t + \delta) \tag{8}$$

where

$$\tau_0 = \gamma_0 \sqrt{G^2 + B^2 \omega^2} \tag{9}$$

$$\tan \delta = \frac{B\omega}{G} \tag{10}$$

Experimentally these materials are characterized by two parameters G 'and G" depending of:

1) Displacement u;
2) Ambient temperature T;
3) Distortion γ;
4) Material temperature θ.

The shear storage modulus (*G '*= *G*) influences the stiffness of the system and expresses the energy stored in a cycle; while the loss shear modulus (*G''* proportional to *B*) is related to the energy dissipated in one cycle

These are such as to satisfy the equation:

$$\tau(t) = \gamma_0 \left(G' \sin \omega t + G'' \cos \omega t\right) \tag{11}$$

We also define:

1) The equivalent damping ratio

$$\xi_{eq} = \frac{G''(\omega)}{2G'(\omega)} \tag{12}$$

2) loss factor: measuring the phase shift δ between the strength and phase; it is a measure of material's ability to dissipate energy.

$$\eta = \frac{G''(\omega)}{G'(\omega)} = 2\xi_{eq} \tag{13}$$

The behavior of a material viscoelastic is usually approximated by the Kelvin-Voigt model shown in Fig.6.

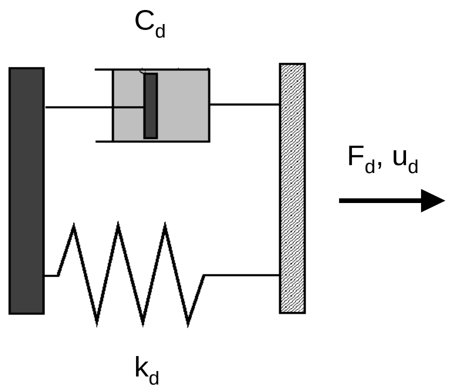


Fig.6: Kelvin-Voigt Model.

The following relations between the parameters of the Kelvin model and experimental parameters can be found:

$$k_d = \frac{F_{d,\max}}{u_0}\cos\delta = \frac{AG^{'}(\omega)}{h} \tag{14}$$

$$C_d = \frac{F_{d,\max}}{u_0}\sin\delta = \frac{AG^{''}(\omega)}{\omega h} \tag{15}$$

where:

- A = shear resistant area
- h = thickness of the layers of the polymer

Parameters G 'and G" are defined at the frequency of the first mode of vibration and depend on the compression force acting on the polymer:

$$\eta = \frac{G^{''}(\omega)}{G^{'}(\omega)} = \frac{\omega C_d}{k_d} = \tan\delta \tag{16}$$

A SPECIFIC CASE OF APPLICATION

Maintain the structure in the elastic range is impossible and expensive; so the classical concept of seismic protection is based on of flexibility, although the economic losses and costs of a structure unfit for use, or simply damaged in the non-structural parts, are very high. The design based on user's safety represents a particularly effective procedure for most civil buildings, even if the structure is unusable: basically you should avoid brittle fracture, involving a sudden structural collapse.

In a planning of seismic risk is necessary to consider the protection of certain types of buildings of strategic importance for the population, as a building that permits a resumption of production, or service, that would normally take place, in a short time after the event; a large proportion of these buildings is represented by construction made of prefabricated structures.

Dissipative systems, designed *ad hoc* for this purpose, allow you to preserve the structure from damage caused by the occurrence of a seismic event and its possible replication in time; some other aspects should be examined, before the choice, such as:

1) to protect a building without denaturing;
2) find an application easily repeatable;
3) allow movement between the elements, without forgetting *firmitas, et utilitas venustas*[1];
4) to obtain a significant reduction in costs (in short and long time).

The idea was to insert an elastomeric pad between the beam and column, using a cable-stayed bracket.

This inclusion seemed to meet all the requirements set forth above. For this solution:

1) the foundations were not involved;
2) a direct view of the device was prevented.

A circular parking garage, built entirely in prefabricated concrete elements, has been analyzed. In order to compare the results obtained with and without the dissipative devices.

The individual devices were placed below each of the support of prestressed beams which support the floors (each beam, with T-shape cross-section, is 16 m long). The data of Table 1, obtained from laboratory tests and used as source for the seismic pad models, are used.

Table 1: experimental setup for the seismic pad.

Elastomeric pad 27 cm x 27 cm (height 3.6 cm)	
Vertical exercise's load	700 kN
Vertical statical exercise (SLE)	1000 kN
Vertical load in case of earthquake	700 kN
Seismic horizontal displacement	± 30 mm
Horizontal stiffness	k=3150 N/mm
Damping	ξ=16%

THREE DIMENSIONAL MODEL OF THE DISSIPATIVE DEVICE

According to the criteria adopted in a classic design, the node must be flexible and resistant to bending and links away from areas with a non-linear behavior, thus it can not rule out congestion of reinforcement.

The elastomeric pad was placed between the base plate of the cable-stayed bracket (of the type shown in Fig.7-8 as studied by Bontempi et al., 2008) and the beam, thereby creating a dissipative zone for each of the horizontal element extreme.

So this integration has produced an independent shift of the floor (which can be considered infinitely rigid) from the columns that sustain it, and the latters seem exactly like isostatic shelves, wedged at the base.

To obtain a finite element model as much as possible representative of the nodal region, it was necessary to create a three-dimensional dissipation, to ensure the dissipation in two perpendicular directions. In the modeling process, developed with Straus7/Strand7 (HSH), the one-dimensional elements used are the following:

- Beam;
- Connection;
- Spring-Damper.

Each element was modeled as devoid of specific gravitational weight; only masses present on the FEM model were laid across the beams near the device, and neglecting the mass of the dissipative pads.

Dissipation of other structural elements was fixed at 5%, via Rayleigh coefficients.

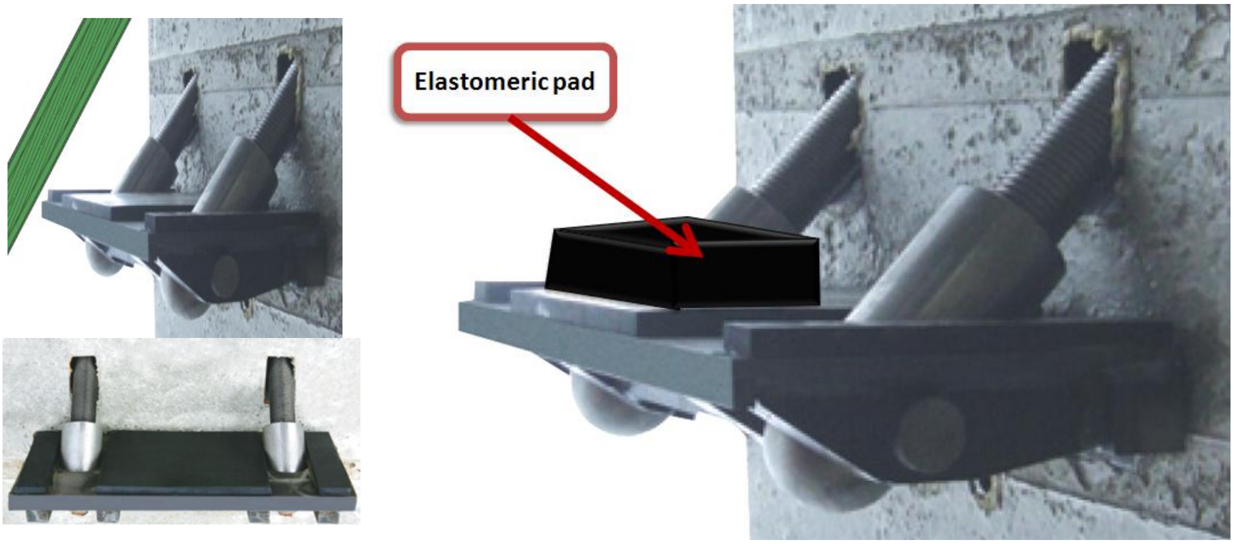
Once fixed the horizontal stiffness (k_H) and damping ratio desiderate for the devices (ξ), the natural frequency of the system (ω) was obtained through the modal analysis, and the damping coefficient is calculated according to the equation:

$$c = \xi 2 m \omega \tag{17}$$

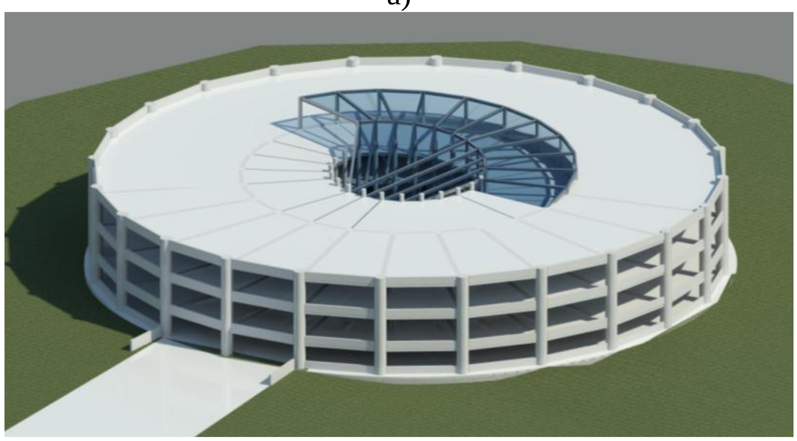
The considered frequency ω is the frequency of the first significant mode of vibration of the structure, while the masses are the masses competing in a single device: so, within the same FEM model, there was a differentiation of individual elements forming the Kelvin model in different nodes.

It is important to observe that the focus in this work is on the exploration of dissipative capacity of this device arrangement. The important aspects of the overall seismic design of precast structures regarding structural integrity, with reference to evolution of the design of this cable-stayed bracket, were specifically considered in Bontempi et al, 2008.

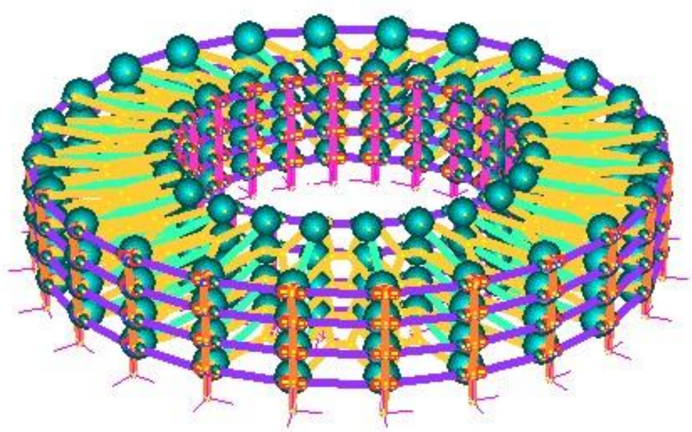
At the same time, also if the disposition of pad as the interface between precast element parts is quite common, it seems that little attention was devoted in the past to exploit the dissipative potentiality of these pads.



a)



b)



c)

Fig.7: Cable-stayed bracket (Bontempi et al., 2008) with elastomeric pad (a) applied on a circular prefabricated structure used as parking garage (b).

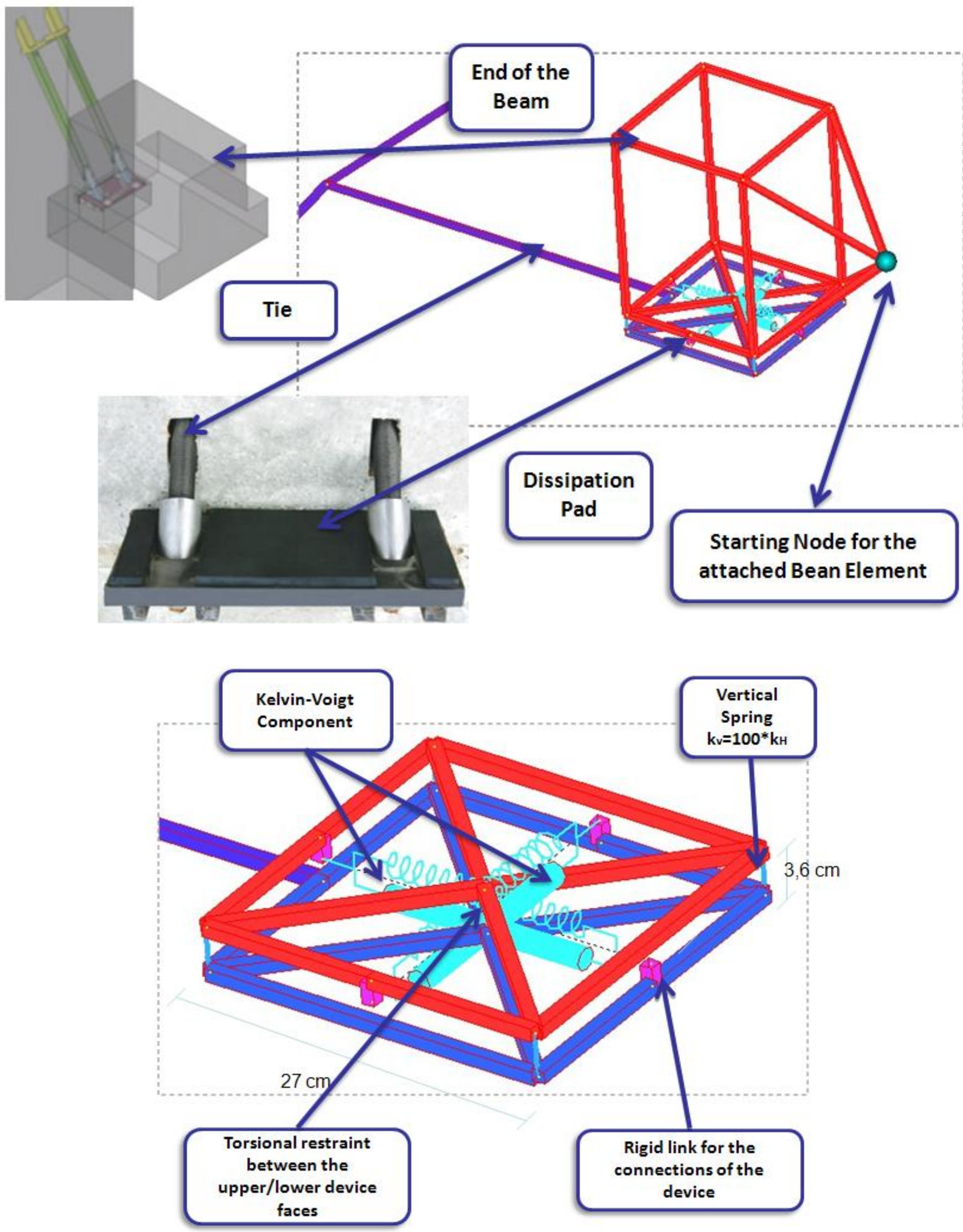


Fig.8: Device model FEM.

THE ANALYSIS

The tests followed the logical flowchart proposed in Fig.9. Specifically, three values were chosen for the damping (ξ = 10%; ξ = 16%; ξ = 20%) and five for the horizontal stiffness of the rubber (0.5k, 0.75k, k, 1.5 k, 2k – see table 1), starting from the value of the experimental data k. For each signal were conducted 15 analyses, according to the various combinations. Both modal and linear transient dynamic analyses have been carried out. For the latter have been used ten accelerograms corresponding to as many earthquakes in the world from 1970 to 2010. In particular, five were Italian earthquakes (http://itaca.mi.ingv.it/ItacaNet/) and the other ones were international (http://peer.berkeley.edu/smcat/): the random choice is fell on those who possessed a peak acceleration of more than 4 m/s^2.

The performance parameters are checked as follows:

1) moving the internal column on the top floor;
2) the movement of the head of the beam on the top floor;
3) the cut at the base of the column;
4) the moment at the base of the column;
5) acceleration on the column inside the top floor.

To see an immediate benefit of the introduction of the device in the original structure, a certain safety factor α has been monitored; α has been defined as the ratio between the yielding moment (M) and the seismic acting moment (M_s) at the critical column, namely:

$$\alpha = \frac{M}{M_s} \tag{18}$$

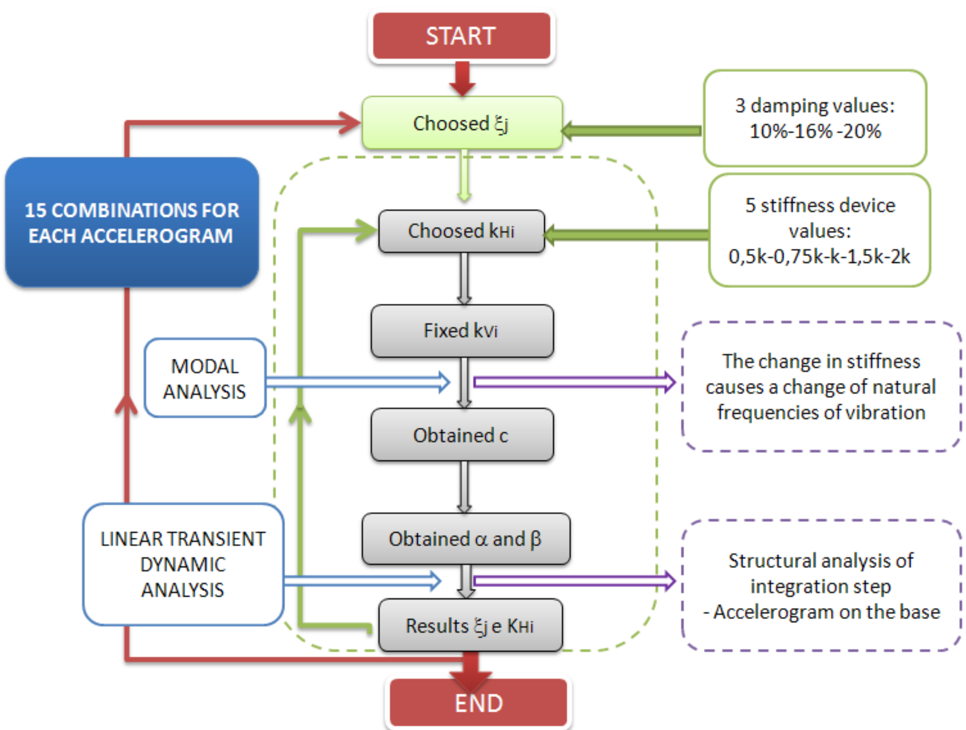


Fig.9: Analysis flowchart..

MODAL ANALYSIS RESULTS

The horizontal and vertical elements have a different movement: if the column acts as a shelf wedged on the base, the floor, being infinitely rigid, moves horizontally (moving much more than the vertical elements).

With changes in the global stiffness, also the structure's fundamental 1st natural period changes as shown in Fig. 10.

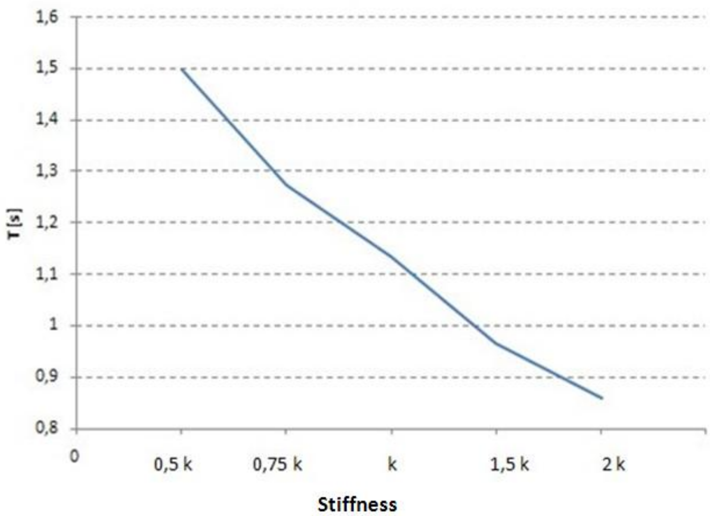


Fig.10: 1st structural period versus the stiffness of the device.

LINEAR TRANSIENT DYNAMIC ANALYSIS RESULTS

As can be seen from the Figure 11 - only a part to those obtained in the course of analysis - the model behaves according to the characteristics required.

The acceleration of the base of the building is usually amplified with increasing distance from the ground: on the top floor the response to the acceleration is equal to the maximum input value. At the base the value of shear increases with the increase of stiffness - or at least it has small fluctuations around a mean value - while the damping decreases. The same effect appears for the acting moment.

In Fig.12, the safety α (the ratio between the yielding moment (M) and the seismic acting moment (M_s) at the critical column) obtained for different damping ratios has been reported, together the original value: there is a positive effect a part the case of Turchia and Friuli.

The efficiency of the devices in terms of maximum accelerations suffered by the floors is shown in Figure 13.

If the insertion of the device is possible it is necessary to pay attention to the movement of individual elements. The prefabricated structures tolerances are very restrictive, so it is necessary:

1) to contain the movement of the columns within the limitations imposed;
2) to ensure that the displacements of the beams (*ergo* the plan) are actually feasible in the construction practice.

For these reasons, a restrained optimization process should be considered, where relative displacements among columns and beams must be taken into account. As shown in Fig. 11.c, for example, for that case the magnitude of relative displacements are around 15-20 mm that can be considered acceptable for damage limitations.

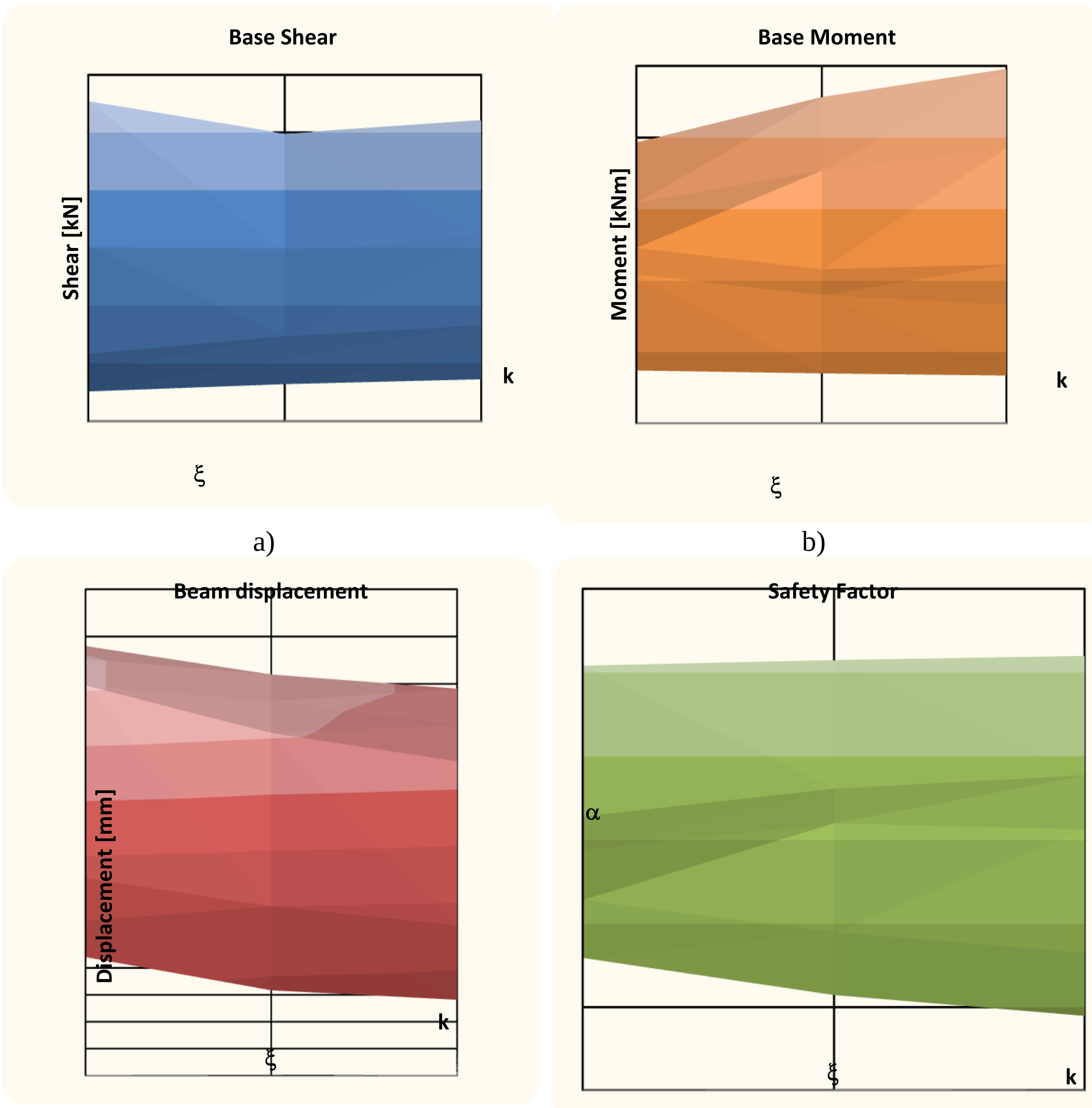


Fig.11: L’Aquila accelerogram 7-4-2009: base shear (a) and the moment (b) at critical column; top floor displacement (c); trend of the safety factor (d) (critical column).

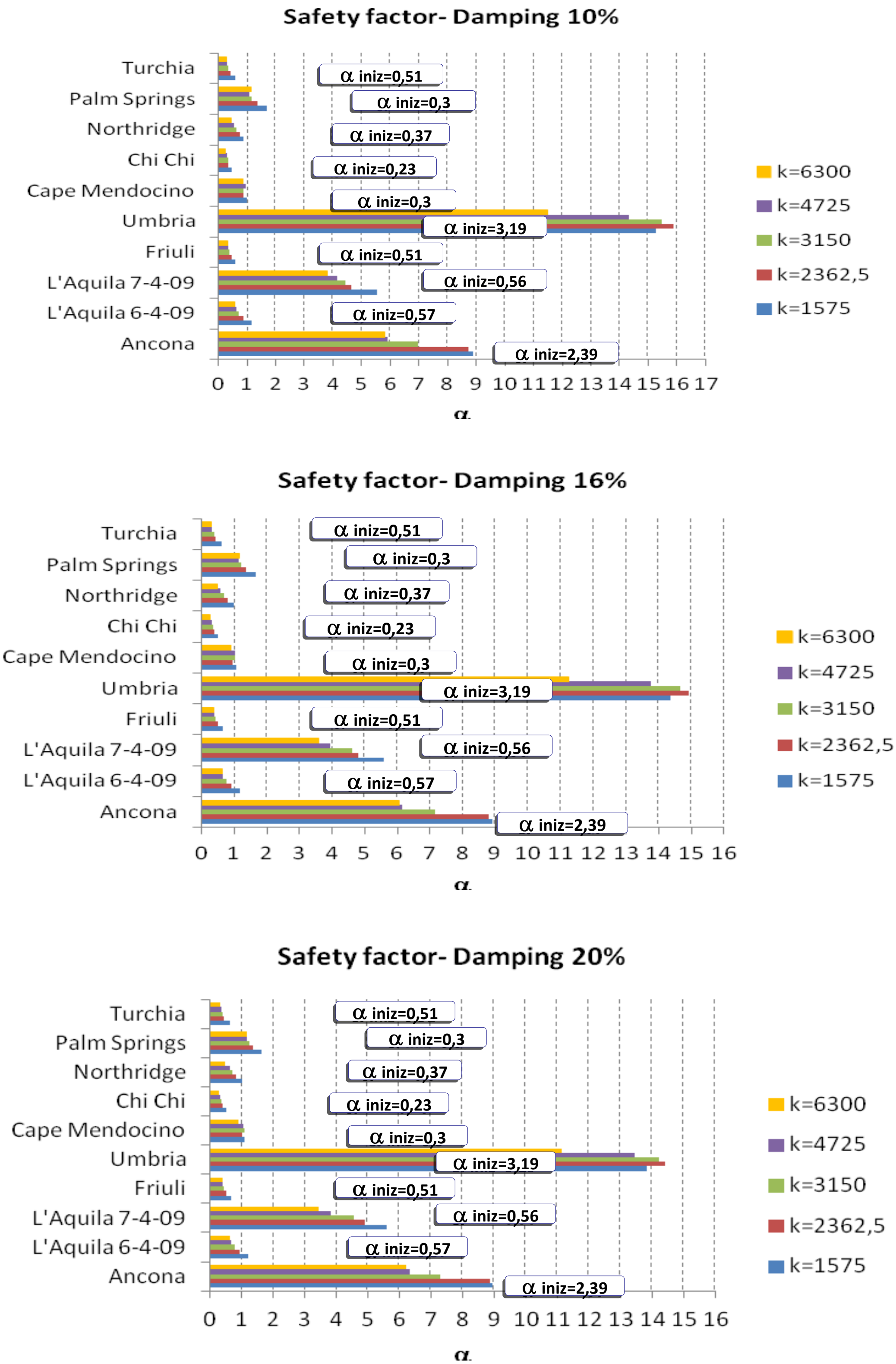


Figure 16: Results of analysis carried out.

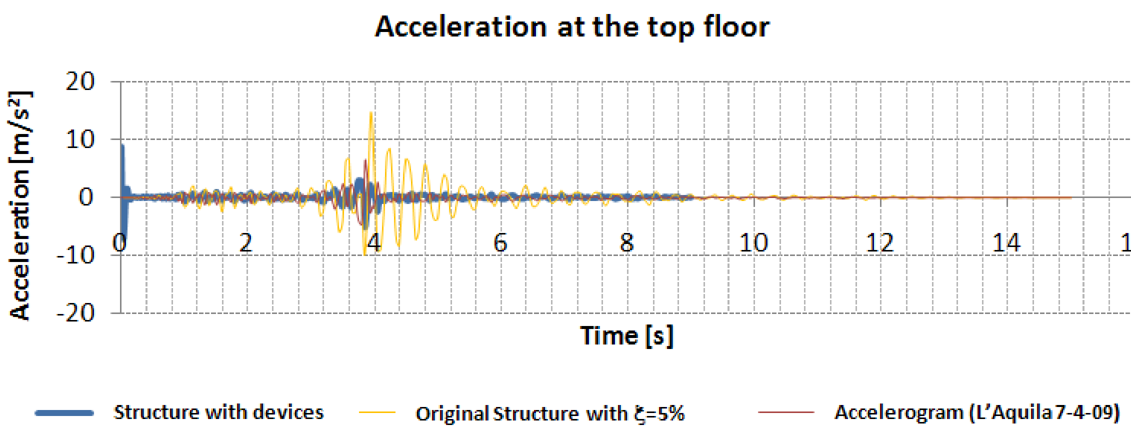


Fig.13: Comparison of acceleration, at top floor, between the original structure and the controlled one, both subject to L'Aquila accelerogram 7-4-2009.

CONCLUSION

In this paper an innovative solution for seismic protection of precast structures has been introduced. The design strategy is simple and basic. It use already available and common component to take advantage of economic benefit and to be suitable to be adopted rapidly by Industry and Constructors.

The main concept is to insert at each node of a precast structure a suitable dissipation pad. If it is true that the single pad has a small and very limited dissipation capacity, it is also true that in a generic structure there are several hundreds of this pads. In this way, a distributed dissipation mechanism is developed, taking also the advantage to realize a sort of tuned mass dampers by the isolation of full floors.

The focus in this work is on the exploration of dissipative capacity of this device arrangement. The important aspects of the overall seismic design of precast structures regarding structural integrity, with reference to evolution of the design of this cable-stayed bracket, were specifically considered in Bontempi et al, 2008. At the same time, also if the disposition of pad as the interface between precast element parts is quite common, it seems that little attention was devoted in the past to exploit the dissipative potentiality of these pads.

The majority of considered cases confirmed the supposed positive behavior for the device, although one can't forget the arbitrariness of the input data.

The solution also seems to favor a reduction in initial costs for design and repair post-event.

It can be said, however, that the device dissipation can be considered effective for certain types of signal, because it helps to reduce stress on the columns, to avoid the formation of plastic hinges and the structural integrity.

The present work may represent a sound starting point for future research scenarios, modeling and prototype development of a reliable structurally connection and potentially competitive market. In fact, the choice for this form of structural control has not been detrimental to the benefits that were originally lean toward a prefabricated building and open interesting possibilities as the realization of tuned mass dampers by floor isolation.

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