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EFFECTIVENESS OF A DISSIPATIVE BEAM-COLUMN CONNECTION BASED ON CARBON-WRAPPED STEEL TUBES

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ABSTRACT

One of the most important seismic vulnerability of existing precast structures, widely used in Italy for one-storey industrial buildings, is due to the lack of mechanical connection between structural elements, as highlighted by the earthquakes that struck the Emilia region (northern Italy) in May 2012. The realization of dissipative connections is proposed as a solution for seismic rehabilitation of structures designed without anti-seismic standards, in particular for the beam-column joints. This work investigates the behavior of dissipative devices composed by carbon-wrapped steel tubes, able to guarantee a dissipative fuse effect. The aim of the study is to determine the effectiveness of the introduction of such devices in the beam-column connections. Incremental dynamic analyses have been performed on different case studies, in order to evaluate the behavior factor for structures with dissipative beam-column connections. The results of the numerical study show how the introduction of the dissipative devices produces, as expected, a significant reduction of forces transmitted to the structure, comparing the seismic response of simple structures equipped with dissipative devices with the response of the equivalent elastic systems.

INTRODUCTION

Seismic protection of structures using anti-seismic devices is one of the most important goals of structural engineers in order to save lives and minimize damages to structures in case of earthquakes of high intensity. The possibility to reduce the effects of the seismic action and to protect structures through the introduction of anti-seismic devices is particularly relevant in the seismic rehabilitation of existing buildings. The last earthquakes that struck the Emilia region (northern Italy) in May 2012 dramatically showed the seismic vulnerability of one-storey precast structures designed and built without anti-seismic standards. The reduction of damage is of primary importance for these types of structures, such as facilities and warehouses, where structural damage can determine high economic impact due to business interruption.

Since May 2012 a great deal of research has been focused on understanding the behavior of prefabricated structures and on finding strengthening solutions. The strategy that inspired this research is linked to the possibility to reduce the effects of the seismic action on structural elements and to concentrate damages in predefined parts of the structures through the use of anti-seismic devices. A Collaboration between the Interdepartmental Center for Industrial Research CIRI - Edilizia e Costruzioni of the University of Bologna and private companies lead to the development of a system

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(Sismocell) able to solve the lack of connection in friction-based beam-column joints. The system is composed by a device made of carbon-wrapped steel tubes and is proposed for the rehabilitation of connections of existing buildings with roof beam simply supported on the top of the column. The device provides an effective connection between the elements and in addition the capability to dissipate a determined amount of energy improving the seismic behavior of the entire structure.

This work refers to previous experimental investigations that permitted to characterize the monotonic and cyclic behavior of the devices, evaluating its dissipative capability. A simplified force-deformation relationship, equivalent in terms of absorbed energy, was deduced from experimental results to be implemented in numerical models. The present paper presents the results of numerical analyses performed on simple structures reinforced with the device to verify the effectiveness of its introduction to improve the seismic behavior.

EXISTING PRECAST STRUCTURES VULNERABILITY

The source of vulnerability of existing precast structures, widely spread among industrial buildings, is the lack of mechanical connection between structural elements. Friction-based connections are not able to guarantee an effective shear force transmission. For these structures, the contemporary effect of horizontal and vertical component of the seismic action can determine loss of supports and collapses (Figure 1). The main requirement to be considered in the design of the beam-column connection is to avoid changes of the original static scheme of the structure (Gruppo di Lavoro Agibilità Sismica dei Capannoni Industriali, 2012). The realization of a rigid connection can determine a high increase of forces transmitted to the rest of the structure, typically the columns. Consequently this may imply the need of intrusive and expensive strengthening interventions on columns or on foundations. These interventions are particularly difficult to carry out on industrial buildings because they often interfere with the production process.

The solution proposed in the present work is the realization of a dissipative connection through the use of devices that make the relative beam-column displacement possible only at a controlled value of force.

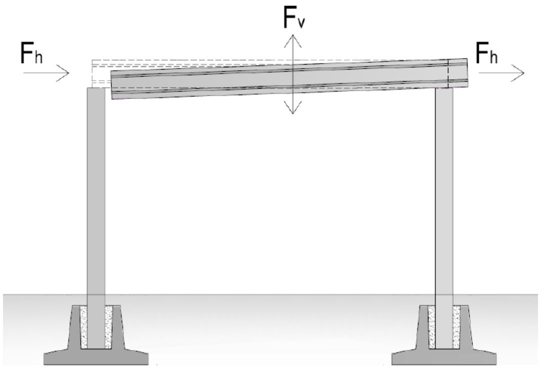

Figure 1. Typical mode of collapse of one-storey precast structures with friction-based beam-column connections

DISSIPATIVE DEVICE

In order to obtain the dissipative fuse behavior the device is composed by plasticity controlled cells made of steel tubes wrapped with carbon fiber. The choice of such an element comes from the need to develop a device able to absorb a high amount of energy in small dimensions and following a constant mode of collapse. A series of studies, conducted for many years for automotive industry (Lima et al., 2011), shows how the combination of metal and composite materials in a thin section tube guarantees excellent properties in terms of energy absorption if under axial loading of compression. The circular shape is the most suitable because axi-symmetric and, under determined conditions, permits the development of a regular buckling. The buckling of the section is controlled if ratios between thickness, diameter and length respect fixed limits. A circular metal section under axial loading of compression collapses by buckling and folding which involves extensive plastic deformation. Composite materials fail in a brittle mode with high stress levels. The combination of the two materials in a metal tube wrapped with composite material proved to be a good solution for catching the benefits of both, increasing energy absorption and assuring a constant behavior of primary importance for the reliability of such an application. Among composite materials, carbon fibers with high values of strength and stiffness maximize the axial loading and the absorption of energy, keeping geometric dimensions limited (Song et al., 2000).

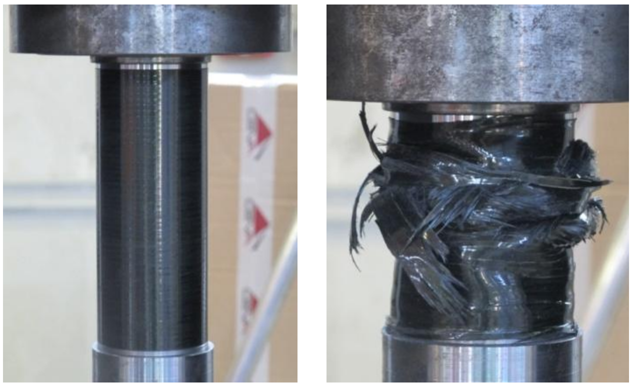

Figure 2. Carbon-wrapped steel tube before and after compression experimental test

Experimental tests of compression on the cells (Figure 2) showed a force-deformation curve that can be schematized with an elastic-perfectly plastic behavior. The device works firstly in an elastic range like a fuse restraint. Once overcoming a preset force threshold, the device enters the plastic range, characterized by the formation of a series of folds along its section after the beginning of the buckling. In the experimental compression load-deformation curve this mode of collapse presents a series of load oscillations that have been approximated with a value of force equivalent in terms of energy absorption. This constant value of force, indicated as equivalent force of plasticization F_{eq}, was calculated in order that the energy absorbed is the same as the experimental behavior, once fixed a determined deformation limit (Pollini et al., 2013). Figure 3 shows the experimental force-deformation curve and its elastic-perfectly plastic equivalent curve for a device with F_{eq}=50 kN.

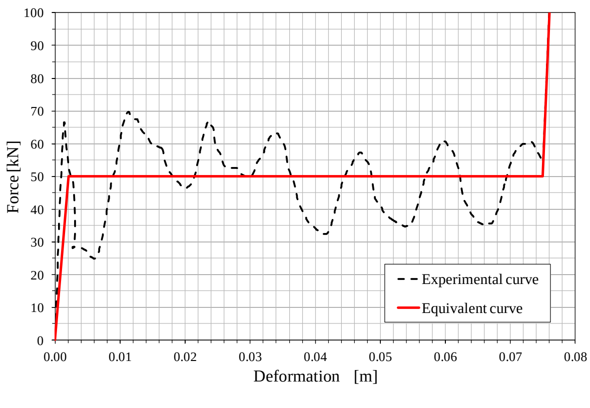

Figure 3. Experimental and equivalent force-deformation curve for a device with F_{eq}=50 kN

DESCRIPTION OF THE BEAM-COLUMN CONNECTION

The carbon-wrapped steel tubes of the presented dissipative device have at their ends steel heads with a central hole to allow the insertion of a threaded rod. The function of the threaded rod is to provide a guide and a support for the tubes themselves and for the anchor elements of the devices to structural elements. The dissipative device provides that, up to a target value, the relative displacement between structural elements determines the compression of the devices, dissipating energy during their plastic deformation (Figure 4). In this way it is possible to avoid the realization of a rigid joint that can determine considerable transfer of forces to the columns. The purpose is to cut the effect of the main peaks of the seismic acceleration and to reduce the effects of the earthquake on the structure.

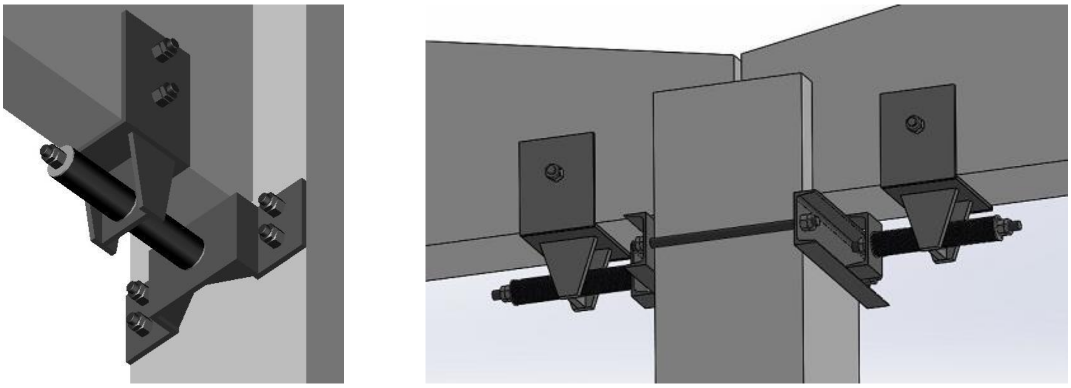

Figure 4. Examples of the introduction of dissipative devices with anchoring elements to the structure

The device avoids relative displacement between the structural elements below a certain pre-established force threshold. Above this preset force threshold, the plastic deformation of the device takes place, accompanied by energy dissipation. In this way the relative displacement between the beam and the column takes place at a controlled value of force, basing the design of the anchoring system to structural elements on well-defined stresses. The design of the device required a particular attention to the limit deformation control. The deformation of the device and consequently the energy absorption is due to the slide of the beam over the column, once overcome the friction force in correspondence of the joint section. For this reason in order to avoid collapses it is necessary to limit the deformation of the device, making the joint work like a rigid connection after a limit value of relative displacement. The maximum relative displacement between the beam and the column is controlled by the maximum deformation of the device.

Numerical analyses expect to prove a reduction of stresses at the base joint of the column, comparing this dissipative connection with a rigid beam-column connection.

NUMERICAL MODEL

The effectiveness of the introduction of carbon-wrapped steel tubes in the beam-column connection of precast structures has been investigated with numerical analyses. Different types of numerical analyses have been performed on simple structures reinforced with the device to verify its dissipative fuse effect. Analyses have been carried out using the FEM software OpenSees.

The present study presents the results of nonlinear dynamic analyses performed in OpenSees on different case studies representing the most common precast portal frames. Nonlinear dynamic analyses permit to evaluate the stress and deformation time histories of structural elements and the nonlinear behavior of the device. The aim of the work is to evaluate the behavior factor of the structure with dissipative devices in the beam-column connection.

CASE STUDIES

The definition of the parameters of the model started with an analysis on typologies of existing precast concrete structures. This preliminary analysis was based on design guidelines and standards, original structural designs, precast manufacturers documents and a literature review on the same theme (Mandelli Contegni et al., 2008). Main geometrical and structural characteristics have been collected in a database with the aim to identify some significant examples of industrial buildings built in Italy starting from 1960 (Figure 5). The analysis concerns those structures designed and realized without anti-seismic standards, with structural elements simply supported without mechanical connections.

The parameters considered are span length and height, geometry of structural elements, masses and loads, materials characteristics and steel reinforcement of columns.

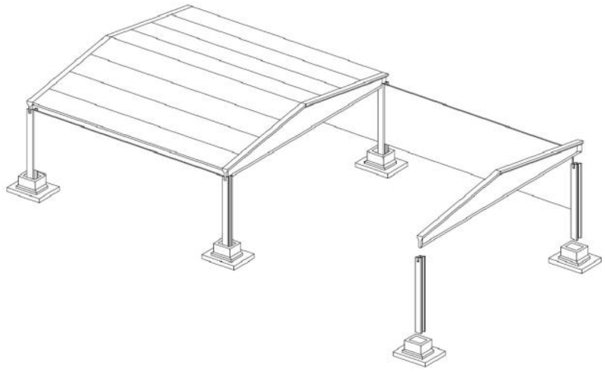

Figure 5. Example of one of the most widespread typology of one-storey precast buildings

Three different case studies have been identified as representative of the most widespread typologies of existing precast structures. Characteristics of structural models used for analyses are indicated in Table 1. The choice of the device for each of the three models is related to the capacity of the column and its reinforcement steel bars. The value of the equivalent yielding force F_{eq} considered in the analysis is designed as the maximum value of force that can be transferred to the top of the column before reaching the yield moment at its base. Therefore, all analyses have been performed a linear behavior for the columns.

Table 1. Parameters of the three case studies considered in the analysis (see Figure 6)

		MODEL A	MODEL B	MODEL C
Span Length **L**	m	12	20	25
Column Height **H**	m	8	7	6
Column Section	m	0.5x0.5	0.5x0.5	0.45x0.45
Beam Load	kN/m	33	30	48
Device $\mathbf{F_{eq}}$	kN	10	30	50

The three case studies identified during the preliminary typological analysis were schematized modeling simple portal frames with fixed base joints and different kinds of beam-column connections. Analyses have been performed according to the model schematized in Figure 6. Distributed masses and loads have been defined through a discretization of structural elements in multiple segments. The most significant part of the models concerns the definition of the properties for the simulation of the nonlinear behavior of the dissipative devices in the beam column joint. The devices are modeled using a combination of “zeroLength” elements with the material “ElasticPPGap” to reproduce its force-deformation relationship. This material is able to simulate an elastic-perfectly plastic behavior and to accumulate the progressive damage for each cycle of loading and unloading, increasing the gap along the axis of deformation. The correct hysteresis cycle is implemented using two elements with this type of relationship: one element works in compression, the other one in tension. In this way the model can simulate the possibility to dissipate energy in both direction of the seismic action. Numerical parameters implemented in the model are based on experimental test results.

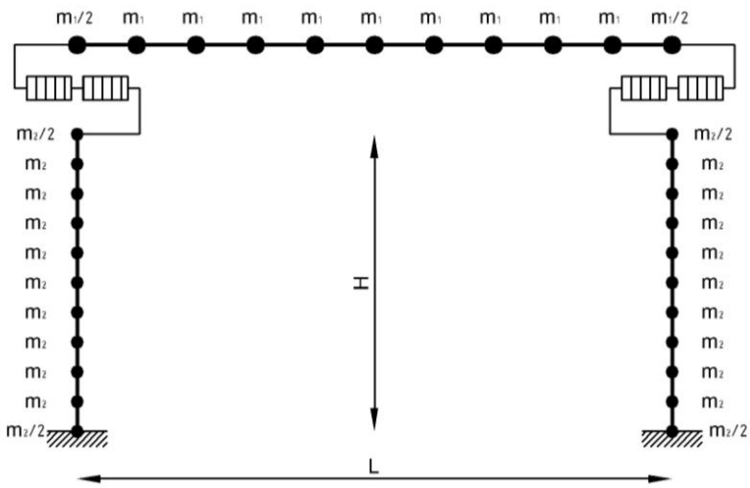

Figure 6. Scheme of structural model used for numerical analyses

In the present work we decided not to introduce friction models in the beam-column joint. This choice respects international standards according which it is not possible to rely on friction in the design of precast connections for new structures. As shown by records of Emilia earthquake of May 2012 the vertical component of acceleration can reduce or nullify the friction effect, determining losses of support of structural elements without mechanical connections (Biondini et al., 2013). In addition, in order to have a better control of the transfer of horizontal forces induced by seismic actions, rehabilitations of existing precast structures with the presented device should be accompanied by interventions that permit to control and, if necessary to reduce, the presence of friction. An accurate friction control permits to maximize the effectiveness and the benefits associated to the introduction of the dissipative device. The very low coefficient of friction supposed to be present consequently to this assumption, was conservatively not taken into account, not considering its positive dissipative effect.

EVALUATION OF THE BEHAVIOR FACTOR USING IDA

Performing nonlinear dynamic analyses permits to investigate the dynamic behavior of the device during ground motions and its effects in terms of relative beam-column displacement and forces transferred to the column. In particular, the purpose of this study is to evaluate an equivalent behavior factor for structures equipped with the dissipative device by comparing the behavior of portal frames with dissipative connections with equivalent elastic systems. To reach this goal we performed Incremental Dynamic Analyses (IDA).

Referring to the IDA methodology illustrated by Vamvatsikos and Cornell (2002), in the present work the ground motion Intensity Measure considered (IM) is the 5% damped spectral acceleration at the structure's natural period, while the Damage Measure (DM) is the deformation of the dissipative device, i.e. the beam-column relative displacement. In the present work two different deformation values were considered: 0.07 m and 0.12 m. The deformation of the device is in general a design parameter, defined as a function of the size of the beam-column support in order to prevent loss-of-support collapses of structural elements. In the model the target deformation of the device is in fact coincident to the relative displacement value between the beam and the column. This target value permits to control the entire range of behavior of the dissipative device, from elastic to inelastic, until the end of its deformation and consequently the end of its dissipative capacity.

The input seismic considered for time history analyses are recorded accelerograms from the 2012 Emilia earthquake. Two main events struck the region: a 5.9 M_w earthquake on the 20th May and a 5.8 M_w earthquake on the 29th May with epicenter 15 km northwest of the first one. For each main event the North-South (which is the strongest one) component of acceleration recorded in the stations closest to the epicenter was used (Figure 7).

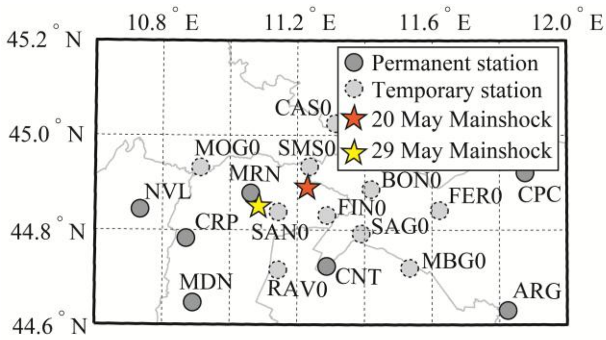

Figure 7. Ground-motion recording stations. Temporary stations were installed after May 20

An algorithm that uses IDA and bisection was adopted in order to identify, for each accelerogram considered, the scaling factor required in order to achieve the target deformation in the dissipative devices. The so obtained scaling factor was then used to perform dynamic analyses on an equivalent elastic system, i.e. the same model without the devices and therefore with simple hinges at the ends of the beam. The behavior factor *q* was then computed as the ratio between the maximum base shear in the equivalent elastic system and the one in the system with dissipative devices.

As an example, the following figures illustrate the results of the nonlinear dynamic analysis, performed on the N-S accelerogram recorded in the station SAN0 during the 29th May earthquake, with the scaling factor required to reach a displacement of 0.07 m in model B. Comparing the results of the dynamic analysis for the models with the dissipative devices allows to evaluate the effectiveness dissipation system. The difference in base shear values between the model with dissipative devices and the equivalent elastic system is shown in Figure 8. Figure 9 shows the relative beam-column displacement time history and the forces on the dissipative device. The deformation of the devices and consequently the relative beam-column displacement takes place, as expected, only for the highest values of seismic acceleration. Figure 10 shows the hysteresis cycle of the dissipative device.

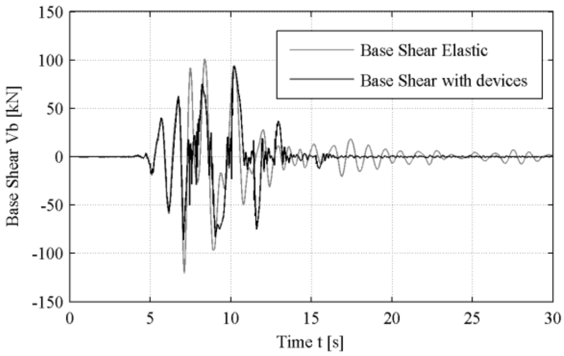

Figure 8. Base shear values for the model with dissipative devices and the equivalent elastic system

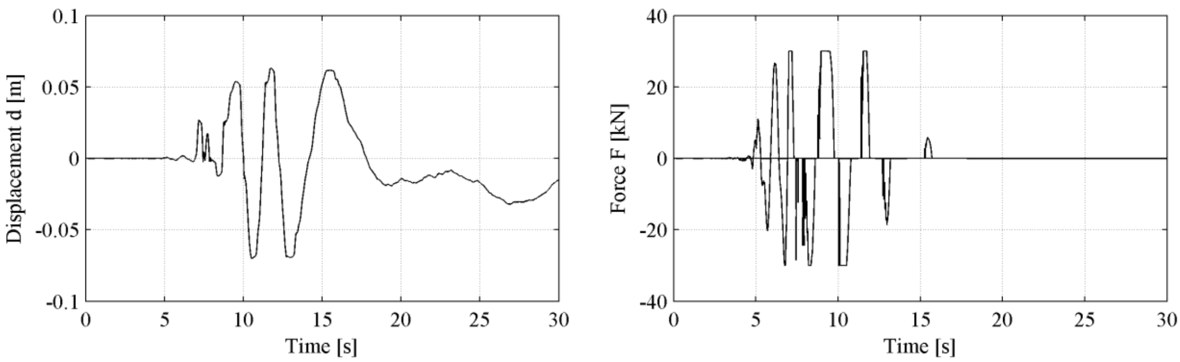

Figure 9. Relative beam-column displacement and forces on the dissipative device

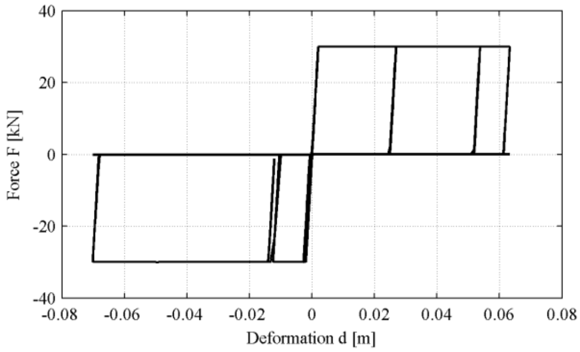

Figure 10. Hysteresis cycle of the dissipative device

The same analyses have been performed for each recorded acceleration time history on the three models representing the case studies considered. In all performed analyses the maximum value of base shear of the model reinforced with the devices is lower than the maximum value of base shear of the equivalent elastic model with hinges at the ends of the beam, proving the fuse effect of the devices.

Table 2 shows the behavior factor *q* for each analyses performed to reach a target deformation of 0.07 m and 0.12 m. The behavior factor for a target deformation of 0.07 m is indicated as q_1, the one for a target deformation of 0.12 m as q_2. The reduction of base shear values is significant. The range of *q* values is 1.23 – 2.72 for q_1 and 1.27 - 3.79 for q_2. The plastic behavior of the force-deformation relationship of the devices permits to have a well-defined shear value at base joints of the column, much lower than the one of the scheme with rigid beam-column joints. As expected, *q* values increase for a target deformation of 0.12 m respect to 0.07 m.

Table 2. Behavior factor *q* for a target deformation of 0.07 m and 0.12 m

recorded acceleration time history	**MODEL A**		**MODEL B**		**MODEL C**	
	q_1	q_2	q_1	q_2	q_1	q_2
20May-MRN	2.72	3.79	2.27	2.89	2.01	2.67
29May-MRN	1.47	2.18	1.48	1.68	1.84	2.15
29May-SAN0	1.23	1.27	1.29	1.29	1.37	1.58
29May-SMS0	1.99	2.98	2.34	2.69	1.53	1.70

The *q* values listed in Table 2 are linked only to the effect of the introduction of the dissipative devices, since column in the model have a linear elastic behavior. In a structure in which inelastic deformation in the column are allowed we expect to find a larger behavior factor.

CONCLUSIONS

Numerical analyses have been performed in order to verify the dissipative fuse effect of the devices composed by carbon-wrapped steel tubes. The effectiveness of the introduction of dissipative devices was evaluated performing incremental dynamic analyses (IDA). Recorded acceleration time histories from Emilia region (northern Italy) earthquake of May 2012 were scaled until the achievement of a target deformation of the device, assumed as damage measure. The behavior factor of the structure was investigated comparing the seismic response of a portal frame equipped with dissipative devices with the response of the equivalent elastic system.

Results of analyses showed a significant reduction of base shear values due to the capability of energy absorption of the devices, respect to the scheme with simple hinges in beam-column joints. Most of behavior factor *q* values, computed as the ratio between the maximum base shear in the equivalent elastic system and the one in the system with dissipative devices, are in a range between 1.3 and 2.3 for a target deformation of 0.07 m and 1.7 and 2.9 for a target value of 0.12 m. The *q* values identified are linked only to the effect of the introduction of the dissipative devices, since column in the model have a linear elastic behavior. In a structure in which inelastic deformation in the column are allowed we expect to find a larger behavior factor.

First findings of numerical investigation show that the dissipative devices seem to be a good solution to combine the need to connect elements and to maintain a low level of stresses in existing structural elements. Analyses will be extended considering an higher number of acceleration time histories and different target deformation values. The study will then continue including friction and vertical component of seismic acceleration in order to provide a more complete model of dynamic behavior of precast connections and to better understand the effectiveness of the introduction of the devices.

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