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INNOVATIVE CONFIGURATIONS AND MORPHOLOGIES USING DISSIPATING BRACING SYSTEMS

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ABSTRACT

Bracing systems with the innovative variant of the use of energy-dissipating devices is a very effective solution for reducing the seismic response in framed buildings. The insertion of bracing systems within the frame grid significantly influences the aesthetics of the building and strongly interacts with the architectural morphology. The theme involves two aspects and is developed according to two approaches: to study innovative arrangements of the systems within conventional global morphologies; to apply the systems to non-conventional morphologies. The first approach, developed through numerical simulations on sample models, shows the possibility and effectiveness of different and "inventive" arrangements of the façade dissipating bracing system. The analyses aimed at investigating the effectiveness of the protection technique on guaranteeing the seismic adequacy of unconventional morphologies derived from contemporary architecture proposals, show that the application of "engineering conceived" dissipating devices allows for a satisfactory seismic behavior.

Introduction

A very effective technique for reducing the inter-story drift, the most critical seismic response parameters in framed buildings, consists of the use of bracing systems. These configurations provide for stiffening the frames with diagonal elements included within vertical alignments of the framed grid (Figure 1-a). The braced configuration can be varied with multi-story multi-bay solutions (Figure 1-b) and it can be also extended to the total width of the building becoming a whole single-bay braced frame (Figure 1-c). The braced structural scheme allows for a large lateral stiffness and strength, depending on the mechanical characteristics of the diagonal braces. It is especially effective for high rising building where both the ductile MRF and the wall-frame dual systems lose a large amount of their effectiveness.

An innovative application of the technique consists of using energy-dissipating braces. In this case, the ordinary stiffening and strengthening effect of the conventional bracing is improved by the energy dissipating capability (Soong and Dargush 1997) associated to the axial deformation of the braces, matching the inter-story drifts induced by the seismic action.

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Figure 1. (a) Cross bracing; (b) Mitsui Building, Tokyo; (c) John Hancock Center, Chicago.

Different types of dissipating devices exist: the elastic-plastic hysteretic ones, based on the plastic deformations of ductile metal elements; the viscous oil-dynamic ones, based on the viscosity of fluid materials flowing through controlled orifices; the viscous-elastic ones, based on the performances of viscous-elastic materials. All the devices are characterized by hysteretic force-displacement cycles having high dissipating capability.

Configuration aspects of the bracing

The bracing system, when shown in the façade of the building, becomes a significant element of the building aesthetics and it strongly interact with the architectural composition of the building. Figure 2-a reports a case in which it is evident the meaning, also aesthetic, of a conventional bracing system. Also the dissipating devices, can be used as a composition element, becoming a characterizing element of the building aspect, as in the case of the United Nation University in Tokyo, shown in Figure 2-b. Innovative and unconventional layouts of the bracing system was suggested in (Elsesser 2006) and some of the hypothesized schemes are reported, as a sample, in Figure 2-c.

The insertion of bracing systems within the frame grid significantly influences the aesthetics of the building and strongly interacts with the architectural morphology (Mezzi 2007). The theme involves two aspects and should be developed according to two approaches. The first one is related to the study of innovative arrangements of the seismic-resistant systems within conventional global morphologies, while the second approach concerns the application of the systems for enhancing the response of non-conventional morphologies. In this paper the first research approach is especially developed. Numerical simulations have been carried out on sample models of a medium-height building differing in the arrangement of the façade dissipating bracing system. They include some "creative" arrangements of the bracing layout, with the aim of accounting for some tendencies and expressions of the contemporary architecture. Considering the second aspect of the question it can be observed a significant regularization of the lateral response of buildings having irregular morphologies thanks to the insertion of dissipating devices even without a special and strategic location of the devices.

Figure 2. (a) Alcoa Building, San Francisco; (b) United Nation University, Tokyo; (c) Samples of alternative bracing layouts proposed in (Elsesser 2006).

Energy-dissipating braced sample building

The reference building, used as sample structure for studying the influence of the bracing configuration on the lateral response, is a 60 m high 18-story building. The plan shape is a square with 30 m wide sides. The global shape ratio (height/width) results 2:1. The structural scheme consists of a r/c 3D frame having inter-story height of 3.33 m and 6 bays, 5 m long, in the two orthogonal directions. The bare frame is shown on the left of Figure 3.

The braced configuration of the building provides for introducing a dissipating bracing systems on the four façades, consisting of a couple of braces at each story. With the aim of studying the influence of the bracing configuration on the seismic response, seven different bracing layouts have been hypothesized. The façade layouts of the studied bracing systems are reported in Figure 3. The first four variants are representative of usual regular layouts of the braces, vertically aligned along the height of the building: in the first variant (EX) the diagonal braces are located in the most exterior bays, in the second variant (IN) the braces are located in the two internal bays, in the third variant (XD) the braces are located in the most interior bays, but the braces connect two alternate floors, in the fourth variant (SP) the braces follows a spiral line along the façades of the building. The other three variants (R1, R2, R3) represent three different bracing layouts where the braces are randomly located in the mesh of the façade frame, not respecting any regularity rule.

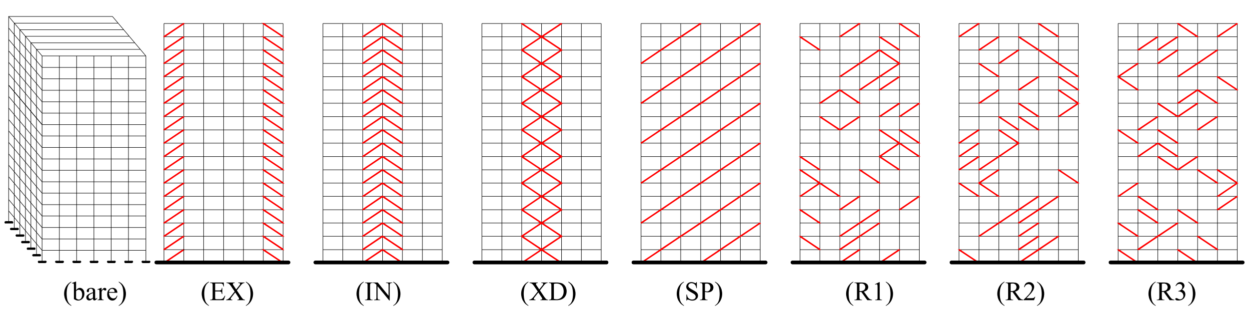

Figure 3. Bare 3D frame and façade layouts of the considered variants of the bracing system.

A preliminary dimensioning of the frame members is carried out by designing the basic frame according to the European guidelines (Eurocode 8 2004). A high seismicity zone, PGA equal 0.35 g, and a class B soil (medium stiff soil) are assumed for defining the reference seismic action, expressed through the elastic response spectrum. The consequent design spectrum is computed for a structure factor q = 5.85, resulting for a regular high-ductility r/c frames. The design of the r/c members is carried out assuming a R45 concrete (cubic strength R_{ck}=45 MPa, design strength f_{ck} =23.3 MPa) and a steel with yielding strength 430 MPa (design strength 374 MPa). The following unitary loads are assumed. Dead and permanent floor load: 5 kN/m^2, live load at the intermediate floors: 3 kN/m^2, snow load at roof floor: 1 kN/m^2, perimeter cladding load: 2 kN/m^2. The dynamic characteristics of the bare frame are resumed by the values of the modal parameters: the period, T, and the participating mass ratio, ρ. The first mode has T_1 = 2.25 s and ρ_1 = 78.8%, the second mode has T_2 = 0.73 s and ρ_2 = 9.8%, the third mode has T_3 = 0.41 s and ρ_3 = 3.7%. A total base shear of 33.3 MN results from the multi-modal analysis using the elastic response spectrum.

The assumed and checked member dimensions are 700x700 mm for the columns (kept constant along the height in anticipation of the study development) and 300x500 mm for the beams. The damage limit state is checked using a response spectrum reduced 2.5 times with respect to the elastic design spectrum. A maximum story drift ratio, at the 4th floor, equal to 3.63$^0/_{00}$, suitably lower than the allowable damage limit of 5$^0/_{00}$, is computed.

An empirical criterion has been then applied for defining the characteristics of the inelastic braces. A number of methods are reported in literature, and others continue to be developed, aimed at defining an optimum distribution of the characteristics of the dissipating devices along the building height, with the goal of minimizing the seismic response of the building. The characterization derived from an optimization process is then usually revised accounting for constructive reasons and market availability of devices. In the present case, the adopted empirical criterion provides for assigning, to each of the two braces present at each story level, a yielding force approximately corresponding to the 5% of the seismic shear force computed from the elastic response spectrum on the unbraced reference frame. For avoiding a detailed unrealistic differentiation of the single braces, their characteristics have been grouped for all the three adjacent levels. Table 1 reports the yielding force value and the corresponding percentage of the elastic story shear of the bare frame. The stiffness value of the braces is assigned corresponding to a yielding deformation of about 1.25 mm.

Table 1. Mechanical characteristics of the braces.

Group of stories	Yield force (kN)	Elastic shear Ratio
1 - 3	1600	9.8 %
4 - 6	1500	10.4%
7 - 9	1200	9.5%
10 - 12	1000	9.2%
13 - 15	800	9.2%
15 - 18	400	8.6%

Nonlinear analyses

The seismic response of the braced frames is computed, considering the structure symmetries, assuming an unidirectional behavior and ignoring accidental non symmetrical mass distributions. Under these assumptions the structure can be analyzed considering a simpler 2D model consisting of only two plane frames equivalent to one half of the total building: the first frame reproduces one façade frame, the second one reproduces the internal frames and is characterized by 2.5 times the stiffness and strength of a single internal plane frame

With the aim of carrying out step-by-step dynamic analyses for evaluating the response of the building, a simplified non linear elastic-perfectly-plastic behavior of the dissipating devices has been assumed. This model reproduces the actual behavior of devices characterized by the plasticization of metal element, as in the case of buckling-restrained devices. It can be considered also to approximate the behavior of viscous dampers characterized by a low value of the velocity exponent, as it actually results in many commercial devices. In this kind of elements the force threshold does not practically depend on the velocity, but only on the viscosity coefficient, so resulting in a practical elastic-plastic cycle. The elastic-plastic cycle is characterized by two parameters: the yielding force and the initial stiffness, that shall be defined at the design level for all the braces of the building.

The analysis procedure adopted in the present study utilizes an intensity-based definition of the seismic input. It provides that a response spectrum, representing the intensity for which the performance is to be assessed, and a suite of ground motions, matching the spectrum are available for the nonlinear dynamic response analysis. A set of seven single component recorded acceleration histories have been used, selected in (Iervolino et al. 2006) from the European Database for matching, with their average 5% damped acceleration elastic response spectrum, the reference response spectrum, used in design, representing the intensity at the site.

Response comparison

The influence of the different location of the braces within the exterior frame of the building has been investigated, controlling the response parameters of the building subjected to a dynamic input consisting of the seven recorded accelerograms previously defined. The average value of the responses to the seven time histories has been considered. The first considered response parameter is the inter-story drift ratio.

Figure 4 reports the histograms of the inter-story drift ratio: at each of the eighteen stories, seven bars indicate the drift value, expressed in ${}^{0}/_{00}$ of the story height. In general. the drift values are limited for all the considered variants, so confirming the expected good behavior of the dissipated configuration. Most of the solutions give maximum values included between $5^{0}/_{00}$ and $6^{0}/_{00}$, or slightly larger than $6^{0}/_{00}$, compatible with the values currently assumed as representative of the absence of significant damage ($5^{0}/_{00}$). Only the EX variant gives values, from the third to the seventh story, larger than $6^{0}/_{00}$ but lower than $7^{0}/_{00}$. The spiral configuration (SP) of the bracing system gives the lowest drift values practically at all the stories. Apart from the spiral configuration, the random distributions (R1, R2, R3) give drifts of the same entity and often even lower than the regular distributions.

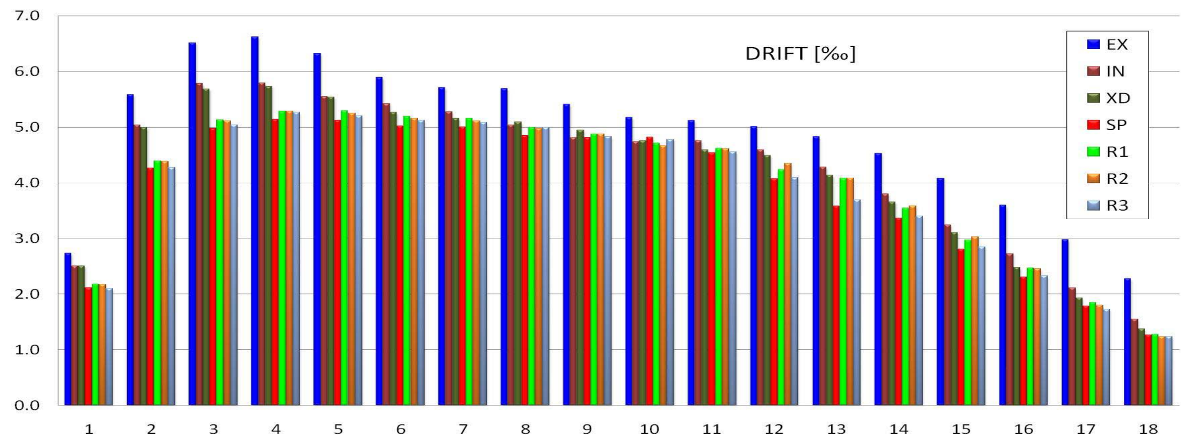

Figure 4. Inter-story drift ratios for the seven variants.

The other parameters are the forces in the members. Particularly, the monitored quantities were: the bending moment of the lateral and central beams, the axial force and bending moment of the edge, intermediate and central columns. The quantities are monitored for both the exterior (façade) and the interior frame. Figure 5 reports the graphs of the bending moments and axial forces of the monitored columns (external, internal and central) of the façade frame, that is of the braced frame. In general, it can be observed that the bending moments show a strong increase at the first three levels for all the column alignments. The bending moment of the edge columns does not vary significantly for the different variants. A little larger variation results for the intermediate column correspondently to the EX variant, giving values 12-15% greater than those from the other variants. This result is also confirmed for the central column. In these elements a reduction is evident for the variants IN and XD. In general, with reference to the variants representing regularly distributed bracing system, a moment reduction results for the columns corresponding to the alignments where the bracing elements are directly connected.

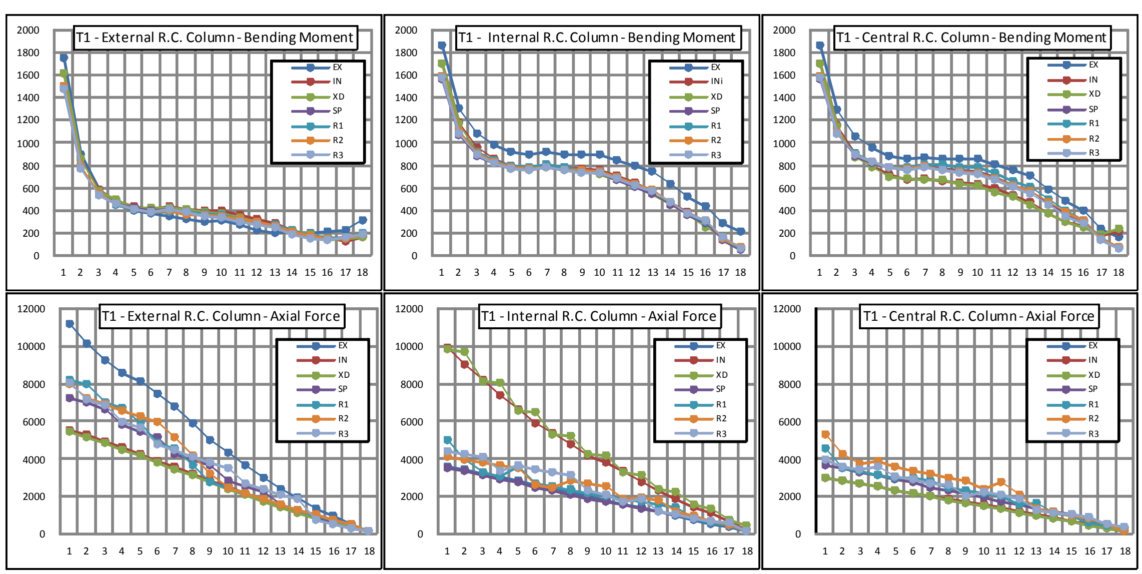

Figure 5. Columns of the façade frame: bending moments [kNm] and axial forces [kN]

As it is expected, largest differences can be found for the axial force variation induced in the columns by the bracing. If considering the regularly braced variants, a strong variation of the axial force results in the columns of the directly braced alignments: the edge columns for the EX variant, the interior columns for the IN and XD variants. Due to the symmetry, the axial force does not vary significantly in the central column, for all the variants. The SP variant never gives large axial forces. Randomly braced variants tend to give values at the minimum or medium level, in the variation range of the column forces for all the variants.

Figure 6 reports the graphs of the bending moments and axial forces of the monitored columns of the interior unbraced frame. In this case the bending moments are quite invariable for the different variants, but it is confirmed the large increase at the first three stories. The axial force variation is practically invariable, but for the edge columns, where a very slight variation results at the lowest stories. The entities of the bending moments are similar to those of the exterior frame, while the axial force values do not overcome the minimum values computed for the façade frame. These results were expected due to the absence of bracing interacting with the columns of the internal frames.

Analogous graphs, not reported here for the sake of brevity, have been produced for the bending moments and shear forces in the beams. The maximum forces result in the beams at the levels where the story drift is maximum. The beam forces are reduced in the bays corresponding to the vertical alignment of the bracing and are larger in the unbraced bays. The values in the variants with random layouts are intermediate between the maximum and minimum values of the regularly braced configuration. A similar result is obtained for the SP variant.

The opportunity of enhancing the outlined configuration through some modifications to the basic braced structural scheme has been investigated: the introduction of a stiff bracing system on the entire width of the building at the third level dramatically reduces the bending moments at the column base due to the reduction of the cantilever behavior of the first stories.

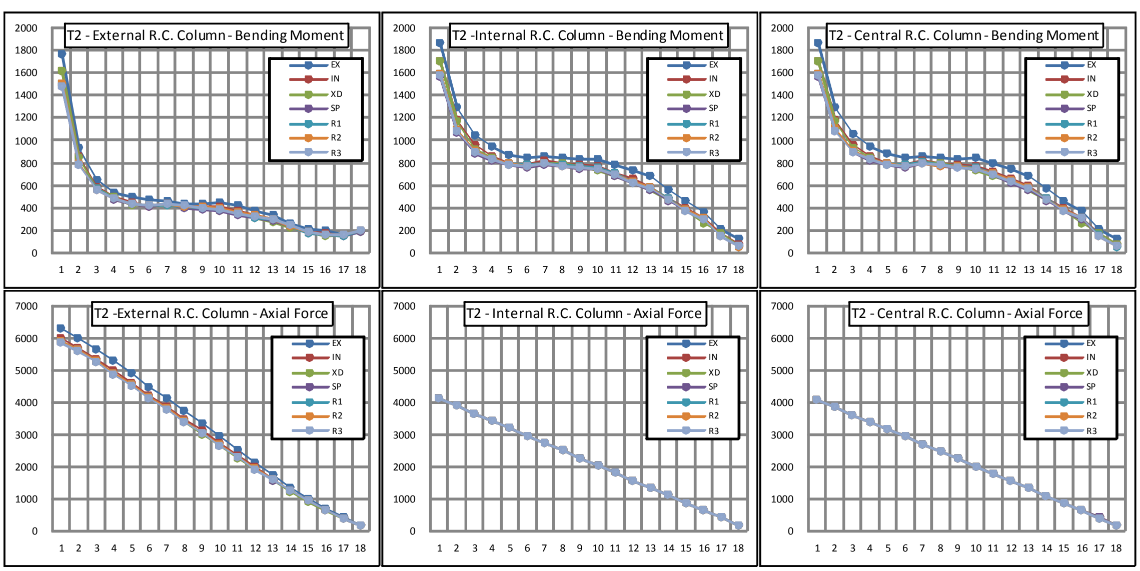

Figure 6.   Interior frame: bending moments [kNm] and axial forces [kN] of the columns

Irregular morphologies

The second aspect of the research is devoted to investigate the possibility to pursue the seismic adequacy of irregular morphologies through the use of suitable and regular placement of dissipating devices allowing for an effective earthquake protection. Simulation analyses have been carried out on models of irregular buildings. Figure 7 shows the global morphology of one sample case characterized by a significant elevation irregularity, causing a relevant torsion in the lateral response. The base grid of the framed structure has bay length of 6 m and story height of 3.6 m. The first 5 stories have a squared plan with 6 by 6 bays. At each 5 stories the building presents a reentrance of two bays along two adjacent sides in plan. The bracing system of the building consists of inverted-V braces located within the corner mesh of the perimeter frames, as shown in Figure 7. Two bracing variants have been considered: conventional bracing and dissipating solution (with devices inserted between the top of the braces and the upper beams).

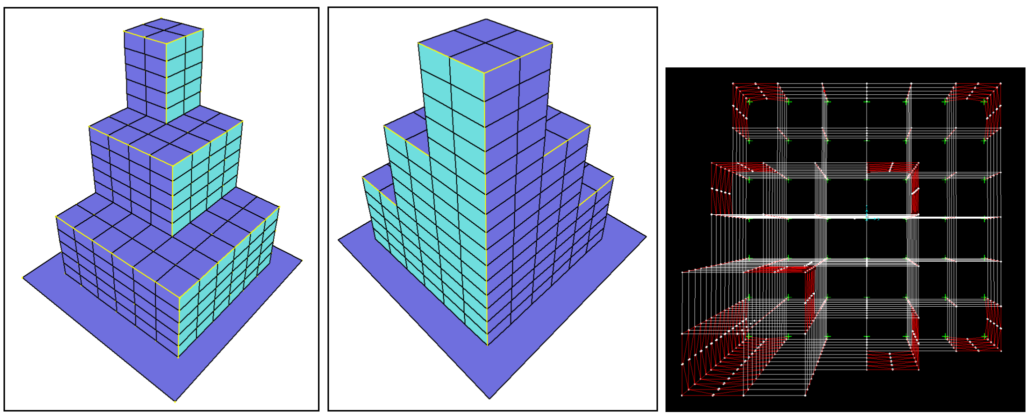

Figure 7. Model of the irregular sample building

Building has been roughly designed with respect to the vertical and lateral loads according to the current European guidelines. An acceptable inter-story drifts ratio at the damage limit equal $5^{0}/_{00}$ was assumed. The yield forces of the dissipating devices were empirically assigned with the criterion that the plastic threshold at a story level is equal to 0.1 the story shear computed from the spectrum analysis using the elastic response spectrum. Dynamic analyses have been then carried out on the two variants using seven generated accelerograms fitting the elastic spectrum used in design and applied along one direction considering the mass eccentricities provided by guidelines. Only the non linearity of the dissipating devices has been considered, modeled through a bi-linear elastic-plastic force-displacement relationship. The comparison of some response parameters shows the mitigation of the torsion behavior of the building obtained through the protection system. The graph (a) on the left of Figure 8 reports, for the two variants, the history of the torsion rotation of the top floor for one of the seven time-history used. It is evident the practical absence of torsion in the model with dissipating braces (red diagram), with respect to the conventional one (blue diagram). The consequence in terms of displacements can be observed on the two graphs (b) and (c) of the same Figure 8, reporting the displacement history at the two corners of the top floor for, respectively, the conventional and dissipated variant. In the latter case the two displacements are practical equal due to the absence of torsion, with a reduction of the maximum value from 700 to 600 mm.

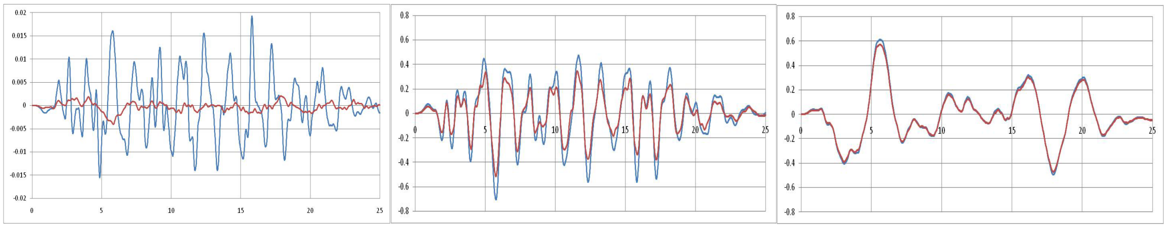

Figure 8. Irregular sample building: (a) rotations [rad] at the top floor for the two variants; (b) corner displacements [m] at the top floor of conventional variant; (b) corner displacements [m] at the top floor of dissipated variant.

Also some unconventional morphologies - irregular, but geometrically coherent - according to some contemporary architectural proposals have been considered, identified as *twisted-shapes*, *wave-shape*, *emptied-shape* (Figure 9). The aim was to show that the application of dissipating devices allows for a satisfactory seismic behavior of unconventional morphologies.

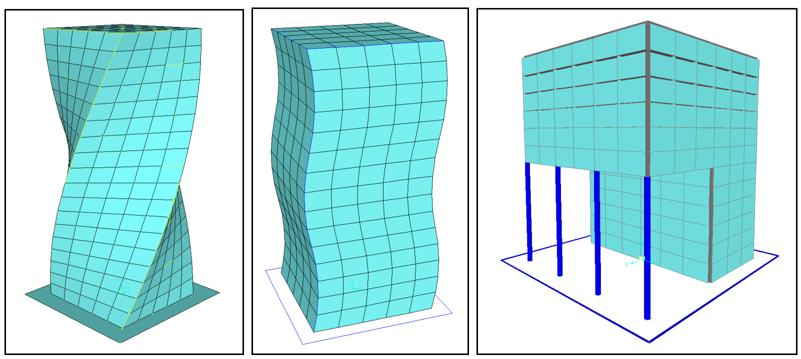

Figure 9. Non-regular morphologies: (a) *twisted-shape*, (b) *wave-shape*, (c) *emptied-shape*.

Concerning the mentioned shapes, some preliminary considerations are required. Indeed, if analyses are performed on the lateral behavior of such buildings, even surprising results can be found, evidencing some unexpected regularities of the lateral response. This behavior can depend on the effective regularity derived from the geometric rules of the morphology and on the appropriate sizing of the stiffness and strength of elements, suitably defined with respect to the forces expected from vertical and lateral loads. Some of these aspects, observed in the considered morphologies, are briefly resumed in the following.

For the *twisted-shape* building, the shapes of the first two modes, Figure 10 (a) and (b), on each of the two main in-plan directions are completely free from torsion and give a total participating mass ratio larger than 85%. The two main modes, Figure 10 (c) and (d), of the *wave-shape* building along two orthogonal in plan directions are practically exempt from torsion and have a participating mass ratio of about 80%. The response of the *emptied-shape* building for the seismic analysis with spectrum acting parallel to the giant columns, Figure 10 (e), is characterized by a deformed shape practically exempt from torsion. In these cases the insertion of dissipating devices is not crucial for the regularization of the lateral response, but it can only improve the natural behavior. An actual improvement, not presented here for the sake of brevity, can be found if the non-linear behavior is considered under the extreme expected seismic input.

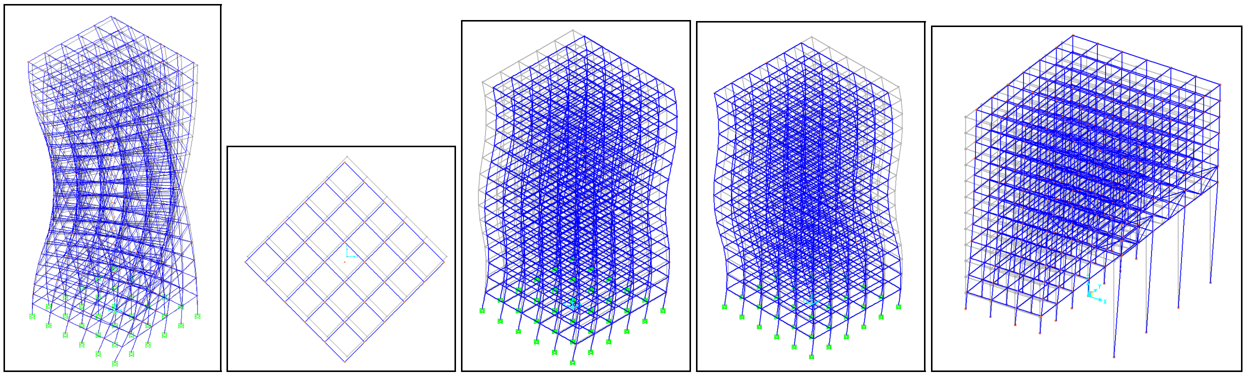
(a) (b) (c) (d) (e)

Figure 10. Lateral response of non-regular morphologies. *Twisted-shape*: (a) 3D view of the first mode; (b) plan view of the second mode. *Wave-shape*: 3D view of the first (c) and second (d) mode. *Emptied-shape*: (e) deformed shape for the longitudinal spectral seismic action.

Conclusions

The comparison of the seismic performance of variants of a building differing in the layout of the dissipating braces show that innovative configurations of the braces, like multi-story or spiral arrangement, can give better performance than a traditional regular distributed bracing. Thanks to the spreading of the dissipation capacity, unconventional "creative" layouts, modeled by randomly located braces, offer performance comparable with those of the regular configuration, or even better. On the other hand, a regular placement and sizing of dissipating devices allows to achieve the seismic adequacy of irregular morphologies thanks to an effective regularization of their seismic response.

Acknowledgments

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