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NODAL DISSIPATIVE DEVICES FOR SEISMIC PROTECTION OF PRECAST RC STRUCTURES

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Abstract

The low seismic performance level of precast reinforced concrete (RC) structures mainly depends on inadequate connections between structural elements. Seismic capacity of precast RC structures can be improved inserting dissipative devices in the nodes between structural elements. With reference to a new conception dissipative device named Joint Torsional Dissipative Device (JTDD) design abaci that represent the main correlations between the geometric and mechanical characteristics of the device are proposed. The design abaci constitute an operative tool that can be used to rapidly determine the optimal dimensions of the individual device as functions of the main characteristics of the structural system, e.g. angular rotation at the elastic limit, torsional stiffness and torsional moment at the elastic limit. The construction of the proposed design abaci is performed for a wide range of possible combinations of geometrical quantities characterizing the shape of the nodal devices.

Keywords: Precast RC Structures, Seismic Capacity, Nodal Dissipative Device, Torsional Behavior, Design Abaci.

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1 INTRODUCTION

In new precast reinforced concrete (RC) structures if typical isostatic schemes are adopted the fulfillment of the capacity requirements provided by current Italian code [1] is obtained only adopting very large column sections. This leads to high construction costs and low market competitiveness [2, 3, 4]. An improvement of the seismic capacity of precast RC structures can be obtained inserting dissipative devices in structural nodes [5, 6]. Many research works are available in technical literature [7], however the scarce application of the results to real precast RC structures suggests a necessary deepening of the constructive and economic aspects in order to ordinarily use these dissipative devices [2]. The research aim is that of defining the characteristics of a specific nodal device able to satisfy the requirements of energy dissipation, of adaptability to the current precast constructive systems and of cost containment. With reference to a device of new conception, described in the following paragraphs, the research activity has been focused on the definition of a design tool that allows to associate the nodal device mechanical characteristics to the geometric and dynamic characteristics of the precast system [8]. Indeed in previously performed studies [9, 10] it has been observed that a nodal dissipative device modifies the degree of constraint among the connected structural elements, producing a stress redistribution and a change of the dynamic characteristics of the precast system. Therefore in order to ensure that the device itself is effective in terms of dissipated energy and does not produce negative effects in terms of stresses, it must be designed appropriately for the specific precast structural system. In particular design abaci that represent the main correlations between the geometric and the mechanical characteristics of the device have been defined. The design abaci constitute an operative tool that can be used to rapidly determine the optimal geometric dimensions of the individual device as a functions of the demand parameters requested by the structural system (e.g.: angular rotation at the elastic limit, torsional stiffness and torsional moment at the elastic limit). The design abaci have been defined for a wide range of possible combinations of geometrical quantities characterizing the shape of the nodal devices.

2 DISSIPATIVE DEVICE DESCRIPTION

2.1 Operating principles

The JTDD are activated by the relative rotations that occur among the precast structural members (vertical and horizontal) following the system lateral deformation. The device allows horizontal and vertical displacements and restraints the nodal rotations through a hollow cylinder of steel or of a similar material that deforms in torsion in the elasto-plastic range. The amount of dissipated energy is therefore closely related to the extent of rotations and therefore to the floor drifts. This implies that the optimal working conditions of the device are those associated with structures undergoing large horizontal displacements under earthquakes. However the insertion of the JTDD modifies the degree of rotational constraint in the nodes among the structural elements with a consequent stress redistribution on them, that has to be accounted for in the verification of strength. A fundamental condition for a proper functioning of the devices is that the rotation at the elastic limit is larger than the nodal rotation induced by the vertical and horizontal service loads. For rotations lower than the elastic rotation the stress distribution on structural elements is a function of the device elastic stiffness. Therefore as the device constitutive law varies, stress distributions different from those associated to a scheme of isostatic columns and simply supported beams are obtained. In particular a constitutive law characterized by high values of elastic stiffness and plastic threshold leads to a late activation of the devices in the plastic field, transforming the devices in fixed support constraints and impeding them to dissipate the energy necessary to reduce the seismic action effects. Low values of elastic stiffness and plastic threshold allow an early activation of the device with hysteretic cycles characterized by a small dissipation. In the case of an early device activation a significant part of the seismic action would still affect the columns only. The device calibration is closely related to the geometric and dynamic characteristics of the structure, therefore the present study has the aim of defining design abaci that correlate the geometrical and the mechanical characteristics of the devices. Indeed an incorrect calibration of the devices can compromise the benefits resulting from their insertion in the structural system.

2.2 Possible applications

In the last years numerous dissipative or isolation devices able to increase the energy dissipation of a structural system and to reduce the damage have been developed [7]. This approach allows to increase the performance level of precast structures keeping the construction cost at acceptable levels. The possible applications of the JTDD mainly concern new precast RC structures having a static scheme with isostatic columns and simply supported beams. Seismic protection devices can also be installed in existing structures for their seismic retrofitting. As already mentioned in previous paragraphs the proposed dissipative device works as a rotational constraint. Therefore with reference to precast structural system with isostatic columns and simply supported beams the natural positioning of the device is at the beam extrados in correspondence of the beam-column joint and laterally to the columns at the column-foundation joint (Figure 1). In this last case the device can be installed when columns are inserted into sleeve plinths and the internal hollow space between the column and the plinth is constituted by deformable material.

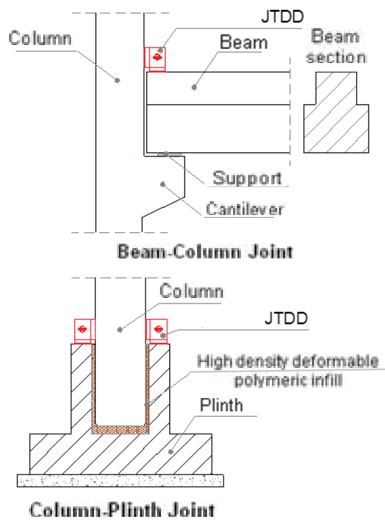

Figure 1: Installation example of the JTDD in the beam-column joint and in the column-plinth joint.

2.3 Geometrical and rheological characteristics

All elements constituting the proposed JTDD are made of steel type S275 (Table 1). It has been also studied the possibility of making the hollow cylinder, that is subjected to torsion, with different steel types or different materials characterized by a low elastic modulus and a low plastic threshold as the lead or the aluminum. The use of materials different from the steel type S275 allows to produce devices with lower stiffness and plastic threshold but with a larger dissipative capacity in the plastic field.

Material	E (N/mm^2)	G (N/mm^2)	f_{yk} (N/mm^2)	ε_y (%)
Steel S275	210000	80000	275	0.13
Aluminium	70000	26000	150	0.21
Lead	5000	1785	25	0.50

Table 1: Material mechanical characteristics.

The device is constituted by a hollow section cylinder arranged with the longitudinal axis in the horizontal direction. The cylinder is constrained to a central plate connected to the vertical structural element and to two lateral plates connected to the horizontal structural element. The central plate has a vertical slotted hole, while the lateral plates have horizontal slotted holes. The presence of the slotted holes in the plates allows the structural elements connected by the device of sliding in the horizontal and vertical direction without inducing shear stresses in the hollow cylinder. The steel plates are connected to the structural elements through suitably dimensioned mechanical or chemical anchors (Figure 2). The length, the outer diameter and the internal thickness of the hollow cylinder vary as a function of the geometrical and dynamic characteristics of the precast structure. Indeed the geometrical parameters of the hollow cylinder together with the utilized material type determine the elastic stiffness, the plastic threshold and the ultimate angular strain of the torsional device.

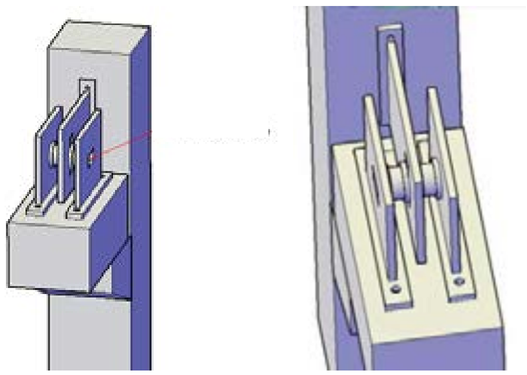

Figure 2: 3D views of the JTDD.

3 NONLINEAR BEHAVIOUR

The linear and nonlinear behavior of the device is assimilable to the elastic-plastic behavior of the hollow cylinder subjected to torsional strains. The equations governing the device elastic behavior are those of the torsion classic theory for circular hollow section reported in the following. With reference to Figure 3 the following equations can be defined:

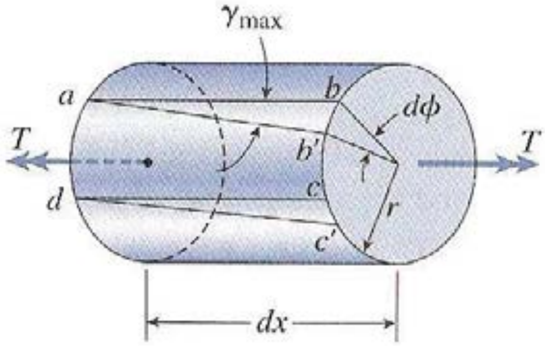

Figure 3: Infinitesimal cylindrical element subjected to torsion.

torsion angle per length unit

$$\vartheta = \frac{d\phi}{dx} \tag{1}$$

outer fiber slip

$$\gamma_{\max} = a\tan\left(\frac{\overline{bb'}}{\overline{aa'}}\right) \approx \frac{Rd\phi}{dx} = R\vartheta \tag{2}$$

linear variation of the distortion γ as a function of r. In the section the torsion angle is independent of r, therefore

$$\gamma(r) = r\vartheta = \frac{r}{R}\gamma_{max} \tag{3}$$

The JTDD has a hollow circular section therefore with reference to Figure 4 the following equations are defined:

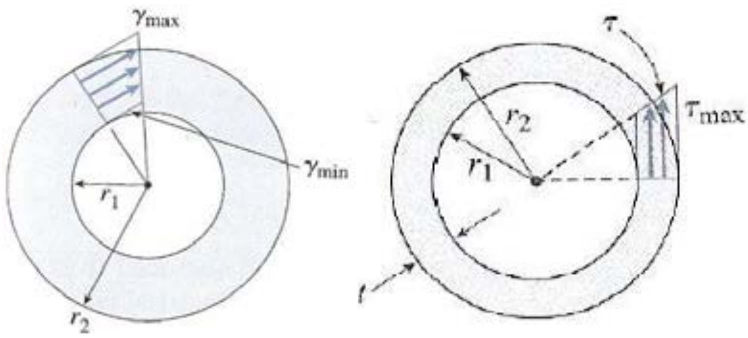

Figure 4: Section of hollow cylindrical element.

polar torsional inertia

$$I_{Pol} = \frac{\pi}{2}\left(r_2^4 - r_1^4\right) \tag{4}$$

unit torsion angle

$$\vartheta = \frac{\gamma_{max}}{r_2} \rightarrow \vartheta = \frac{M_t}{GI_{pol}} \tag{5}$$

where Mt = torsional moment and G = shear modulus;

total torsion angle between two section placed at a distance L

$$\phi(L) = \frac{M_t L}{GI_{pol}} \tag{6}$$

Assuming the τmax of the outer fiber equal to $\frac{f_{yk}}{\sqrt{3}}$ the torsional moment at the elastic limit can be evaluated with the following relation:

$$M_{ty} = \frac{\tau_{max}}{r_2} I_{pol} \tag{7}$$

In order to develop a design procedure for the selection of the device type to install in the precast structural system, the study of the JTDD plastic behavior has been performed in the first instance with a simplified analytical method. The evaluation of the device ultimate angular rotation is based on the maximum axial deformation of the diagonal of the unit element of the hollow cylinder outer fiber (Figure 5).

The element *abcd* in Figure 5 is considered deformed in torsion

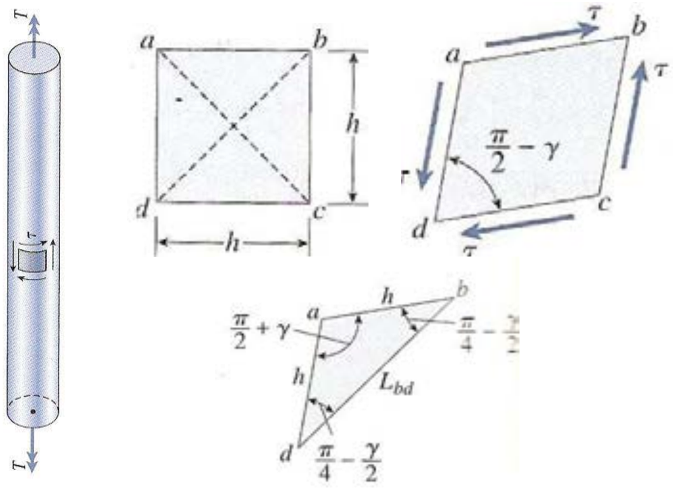

Figure 5: Unit plane element deformed in torsion.

With reference to Figure 5 it is obtained:

$$L_{bd} = \sqrt{2h(1+\epsilon_{max})} \tag{8}$$

the same length can be determined w the cosine theorem applied to the *abd* triangle:

$$L_{bd} = h^2 + h^2 - 2h^2 cos\left(\frac{\pi}{2} + \gamma\right) \tag{9}$$

Using both relations it is obtained:

$$(1+\varepsilon_{\max})^2 = 1 - \cos\left(\frac{\pi}{2} + \gamma\right) \rightarrow 1 + 2\varepsilon_{\max} + \varepsilon_{\max}^2 = 1 + \sin\gamma \tag{10}$$

With this last equation it is possible to relate the ultimate axial deformation of the material ε_{max} with the ultimate slip γ_{max}. Being linear the slip pattern with the radius, in that it derives from the congruence and is independent of the material behavior, it is possible to find the ultimate angular rotation associated to the ultimate slip.

4 DEVICE PROPERTIES

As already introduced in the previous paragraphs the JTDD mechanical characteristics are directly relatable to the elastic stiffness, the plastic threshold and the ultimate rotation of the hollow cylinder subjected to torsional strains. In order to provide an operative tool design abaci for different material types have been defined. They graphically reproduce the analytical relations among the length, the outer radius and the thickness of the hollow cylinder and the and the mechanical parameters describing the device operation. For this purpose two shape factors, named S1 and S2 respectively, that represent the ratios of the geometric quantities defining the hollow cylinder have been defined. In particular S1 = rm/S and S2 = rm/L where rm is the average radius, S is the thickness and L is the length (Figure 6). Relating the shape factors S1 and S2 with the elastic stiffness, the angular rotation at the elastic limit, the plastic threshold and the ultimate angular rotation of the hollow cylinder it has been possible to define the above mentioned abaci. The material constitutive law has been assumed elastic-perfectly plastic. To determine the plastic torsional moment a tangential stress uniform distribution within the thickness of the hollow cylinder has been assumed. This last hypothesis implies that also the moment-angular rotation diagram of the hollow cylinder will show an horizontal plastic branch.

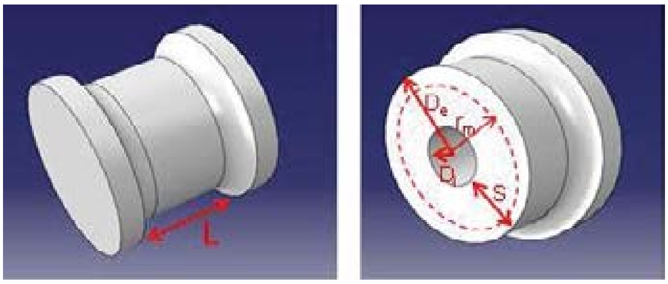

Figure 6: Geometrical quantities of the hollow cylinder.

Different types of JTDD have been designed parametrizing some geometrical quantities of the hollow cylinder to the varying of the utilized materials. The main results obtained with the performed analyses are reported in the following. In particular for different device types Figures 7, 8 and 9 report the torsional moment-total angular rotation diagrams while Figures 10, 11, 12 and 13 report the abaci relating the yielding torsional moment Mty and the elastic stiffness Kt with the shape factors S1 and S2.

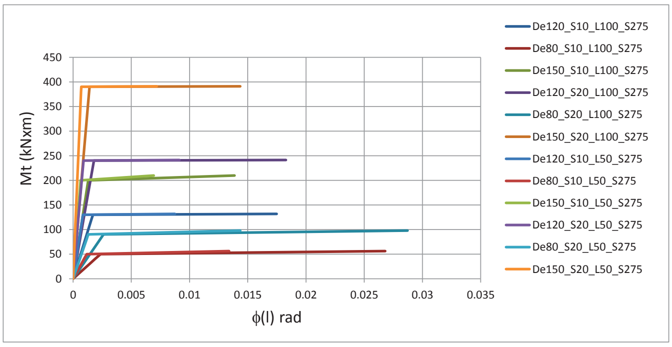

Figure 7: Torsional moment - total angular rotation diagram of steel devices.

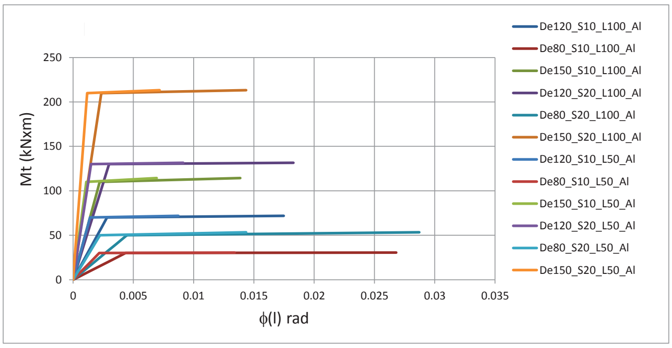

Figure 8: Torsional moment - total angular rotation diagram of aluminum devices.

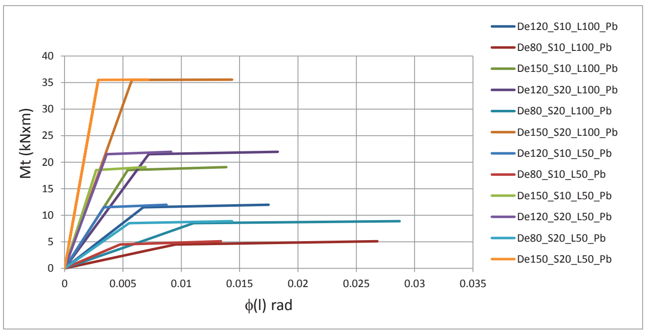

Figure 9: Torsional moment - total angular rotation diagram of lead devices.

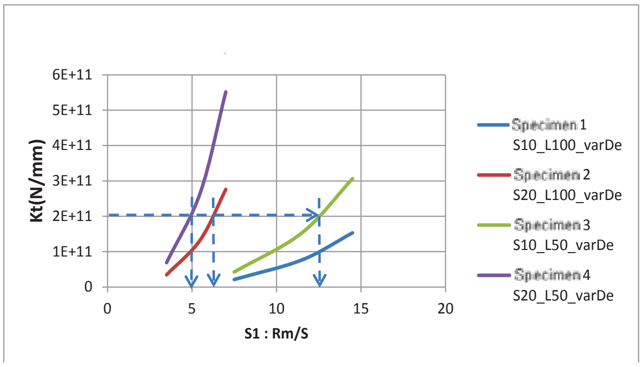

Figure 10: Torsional stiffness Kt - shape factor S1 abacus for steel devices.

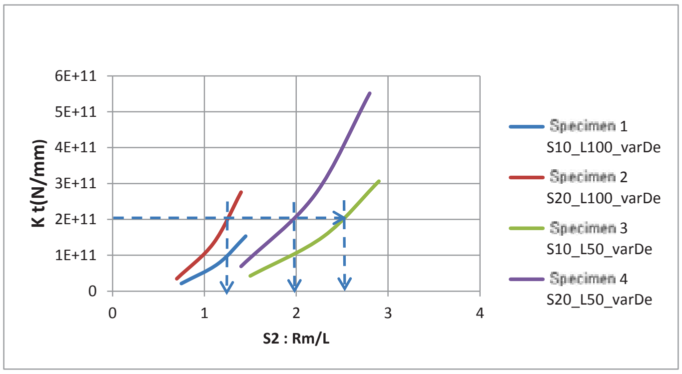

Figure 11: Torsional stiffness Kt - shape factor S2 abacus for steel devices.

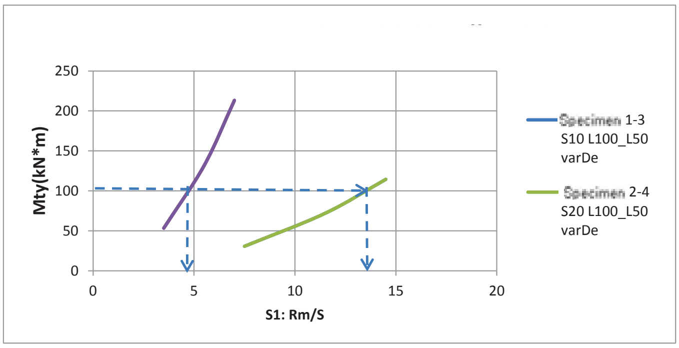

Figure 12: Yielding torsional moment - shape factor S1 abacus for aluminum devices.

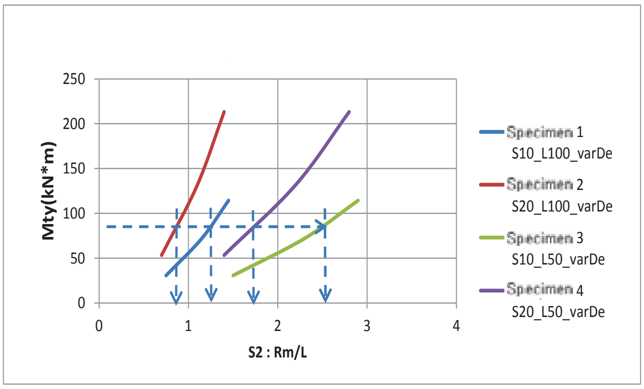

Figure 13: Yielding torsional moment - shape factor S2 abacus for aluminum devices.

Where the symbols used in the figure legend have the following meaning:
De = outer diameter, S = thickness and L = cylinder length.

In the diagrams reported in Figures 10, 11, 12 and 13 the quantity parametrized to define the devices is De.

Therefore the abaci relating the device mechanical characteristics to the S1 and S2 shape factors and the moment-total angular rotation diagrams constitute an operative tool to design the JTDD. Indeed once defined the device geometry through the S1 and S2 shape factors it is possible to determine the corresponding mechanical characteristics as elastic stiffness and yielding moment. For each device characterized by specific S1 and S2 shape factors it is moreover possible to determine the constitutive law in terms of torsional moment and total angular rotation.

5 CONCLUSIONS

- Aim of the present work is the definition of abaci for designing rotational dissipative devices to be placed in the nodes of precast reinforced concrete (RC) structures.
- The insertion in the structure of dissipative devices also at the column base leads to an increase of displacements under seismic action and although the natural consequence is the increase of energy dissipated by the devices, to contain the floor drifts below the thresholds allowed by code it is necessary to calibrate the device cycles also as a function of this last parameter.
- Moreover it has to be noticed that the insertion of these rotational devices produces a benefit in terms of reduction of retrofitting costs and unused costs of the structure subsequent to a seismic event.
- For what concerns the construction costs of a new structure, the proposed device has a low cost, their operation is of mechanical type and their installation and maintenance do not request particular precautions.
- Quick comparison calculations have been performed to evaluate the reduction of the construction costs after the insertion of the dissipative devices. The comparison of the construction costs, relative to the columns only, has shown a savings of about 35%.

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