REVIEW OF STRATEGIES FOR MODELLING BEAM-TO-COLUMN CONNECTIONS IN EXISTING PRECAST INDUSTRIAL RC BUILDINGS

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Abstract *In recent earthquakes, it has been observed that precast RC structures has shown, in several cases, a poor performance presenting damages on structural and non-structural elements, highlighting the vulnerability of industrial buildings. Beam-to-column connection was pointed as one of the main source of damage. Precast concrete buildings are common in the industrial parks. One-story industrial building constituted by a frame system of beams and columns, with hinged beam-to-column connection are the most common structural configuration. In this way, it is important to characterize this type of buildings to understand its seismic behavior in order to develop new methodologies and solutions for design this type of buildings and improve your performance. The presented work is focused on beam-to-column connections that play a determining role on precast structures. The proposed work is the review of the different strategies to model beam-to-column connections in a precast industrial RC building is presented. To perform the analyses, the structural software Opensees was chosen. Nonlinear static analyses were performed. The results are presented and discussed.*

1. INTRODUCTION

In recent earthquakes, it has been observed that precast reinforced concrete (RC) structures has shown in several cases a poor performance, presenting damages on structural and non-structural elements, highlighting the vulnerability of industrial buildings [1]–[5] and an important part was not designed with the consideration of the seismic action. Most of the

observed damages are related with structural elements, namely in the connections between horizontal elements (beams and roof) or beam and columns. In several buildings were observed significant failures and collapses. For example, in Emilia Romagna in 2011, more than a half of the existing precast structures exhibited significant damages [6]. Even in moderate and short duration earthquakes events, RC structures exhibit high levels of structural damages as Romão *et al*. described after field observations of 2011 Lorca earthquake [7].

In recent earthquakes, the structural failures most observed in RC precast industrial buildings were in columns, beams and connections.

The connections between structural elements are the most crucial aspect on precast structures [4]. In turn it is also the source of many failures. Many authors refer the connections on precast structures as the main source of structural failure [1], [4]–[6], [8]. The most critical failures due connections were those between: beam-to-column, roof-to-beam, column-to-foundation and cladding panel-to-structural element. Belleri *et al.* [9] refer as the most severe damage occurring during the Emilia earthquakes the structural element loss of support and consequent falling due to the lack of mechanical connection as seismic load transfer mechanics between beam-to-column and roof-to-beam. Bournas *et al.* [6] refer as the main issue related with beam-to-column connection allowing relative displacements without losing beam seating or the adequate transferring of lateral horizontal forces to the column and down to the foundation without losing capacity. Within the Safecast project, Bournas, Negro & Molina [10] presented the results concerning the evaluation of the mechanical connections on a full-scale 3-storey precast concrete building submitted to pseudo-dynamic tests. Within were experimentally investigated two types of beam-to-column connections: *i*) hinged beam-column connections by means of dowel bar (pinned beam-column were the most common connection system in the construction practice in Europe) and *ii*) emulative beam-column joints by means of dry innovative mechanical connections. The results of both solutions demonstrated the value of the new beam-to-column connection system and the better behavior of the precast RC frames when submitted to seismic loads and bring new concepts and solutions for the design of new buildings.

In Portugal, the most common system used in precast RC industrial structures are formed by parallel portals, which consist in fixed columns in the base, beams placed on corbel

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connections on top of the columns, and the beams present a variable section with spans up to 45 meters [11]. The capacity of a beam-to-column connection can be either due to friction force alone or a combination of friction force and dowels.

After this brief review of the most documented damages in precast RC industrial buildings, it can be concluded that the connections play an important role to assure a proper seismic behaviour, since they have been the source of much of the damages reported after seismic events. In this way in the present work, will discuss a modelling approach to these critical zones. In particular, will be focused on pinned beam-to-column connections by means of a dowel bar, which is the most common practice in Europe. In this study will be focused in important components of the connection such as the friction between the beam and the column, the dowel bar and the neoprene pad concluding about the influence that these components have on the connection and to what extent.

2. CHARACTERISATION OF BEAM-TO-COLUMN CONNECTIONS IN PRECAST RC BUILDINGS

2.1. Main typologies of beam-to-column connections

The global behavior of a precast structure, during a seismic event, is largely influenced by the connections between structural elements and between structural and non-structural elements [12]. Several authors referred connections failures in recent seismic events as one of the main source of structural failures [1], [4]–[6], [8]. Magliulo *et al*. [12] refer two points as the source of beam-to-column connections failure: *i)* the friction strength, if the connections do not provide mechanical devices in resisting horizontal actions; and *ii)* the deficient seismic detail of the connections due to the lack of the code design requirements.
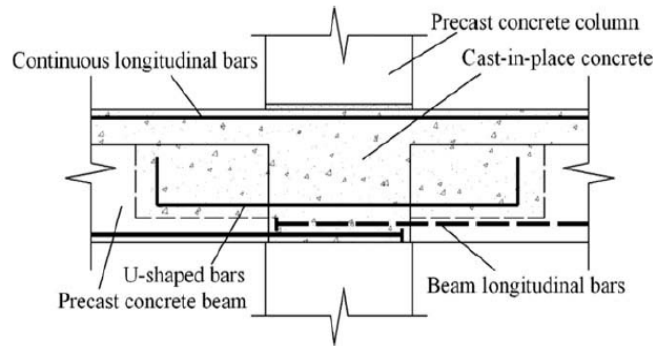
There are three types of connections mainly used in precast structures: *i)* Cast-in-situ (wet) connections; *ii)* Emulative with dry mechanical connections; and *iii*) Connections with dowels.

The system with wet connections uses cast-in-place concrete, having to follow the requirements of a monolithic RC construction [10] . Cast-in-situ connections, represented in Figure 1, provides a monolithic union, ensuring the transmission of internal forces and moments [13]This type of connections, have as advantages the cost, that is less when

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compared with dry connections, and require less workmanship experience [14].

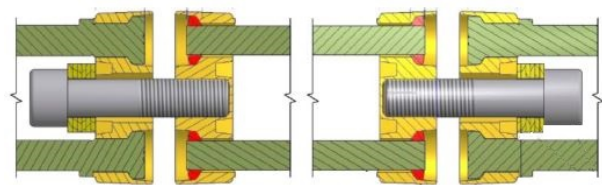a) Casting of the beam-to-column connection [15]   b) Scheme of a cast-in-situ beam-to-column connection [16]

Figure 1 – Cast-in-situ beam-to-column connections

The emulative connections are typically as represented on Figure 2, referred as dry mechanical connections. This type of connection aims to provide continuity to the longitudinal reinforcement, crossing the joint between the precast beam and the column. This system is constituted by four steel rebars, two plates and a bolt that connects the two steel plates, as the Figure 2b) represents. In Figure 2a) the connection in being activated by means of a proper screwed of the bolt. In the gap between the beam and the column a mortar is placed [17]. The Safecast project investigated this innovative connections, showing to be quite effective[18].

a) Activation of the loosen bolts to provide continuity   b) Scheme of mechanical couplers [19]
to the longitudinal bars crossing the beam-column [6]

Figure 2 – Connections with mechanical couplers

The most common type of beam-to-column connection in precast RC industrial buildings in Europe is the dowel beam-to-column connection. [10] The most conventional, and further

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analyzed in this work, is illustrated in Figure 3. The beam and the column are connected by vertical steel dowels, usually one or two. In a first stage these dowels were protruding from the corbel's column, then the beam seats in. In this stage the dowels were anchored, and the sleeves were filled with a proper grout. Between the column and the beam is placed a steel or a neoprene pad to permit the relative rotations[18].

a) Dowel beam-to-column connection [20]
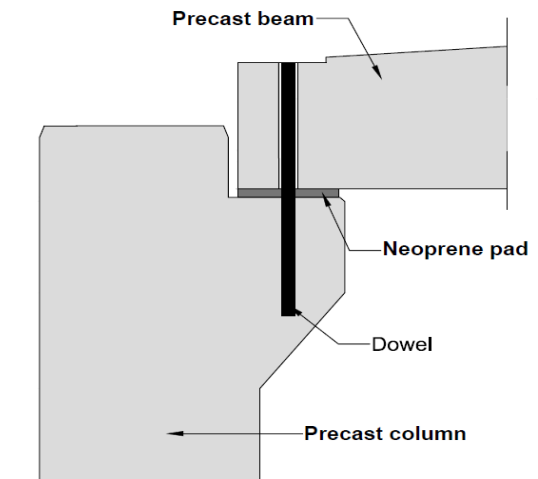
b) Scheme of conventional dowel beam-to-column connection

Figure 3 – Dowel beam-to-column connection

This type of connections aims to transfer shear and axial forces (shear connectors). Theoretically, they are not enabled to transfer moment and torsion, but they are able to transfer a residual moment [18]. In Figure 3b) it is possible to identify the three main components that ensure the transfer of forces between the beams and the columns: *i)* Friction; *ii)* Neoprene; and *iii)* Dowels. These components and its influence in the connection will be analyzed in this work.

These type of connections were object of many numerical and experimental work due to the weak behavior in the past seismic events [12], [21]–[24]. These connections have two main problems associated: *i)* a local one associated to the yielding of the dowel and the crushing of the concrete; *ii)* a global one, related to the spalling of the concrete between the dowel and the edge of the structural element. The difference between this failures is mainly due to the position of the dowel in the structural element [25].

2.2. Connection behavior under horizontal loads

RC precast connections may experience different failure modes depending on the strength, size and position of the dowel. A strong steel bar in a weak element or placed with a small concrete cover, may induce a fail due to the spalling of the concrete cover. However, when the bar is placed in well-confined concrete, the dowel pin normally fails in bending by the formation of a plastic hinge in the steel bar [26]. In this type of connections, the transfer of the forces between the beams and columns is essentially ensured by the dowel action and friction between the beam and column. The following sections present a brief description of each of these mechanisms.

2.2.1. Friction

The friction force developed between two surfaces can be described by the product of the friction coefficient (μ) and the axial force acting on that surface. Previous studies attempted to quantify the friction coefficient between concrete-concrete and concrete-neoprene connections. According to Magliulo *et al.* [27], the friction coefficient depends on the axial force and the shear rate velocity. On the other hand, the same authors concluded that the nominal area of neoprene pad, time of prepressing and bearing's shape does not impact on the friction coefficient.

In 2011, Magliulo *et al.* [27] conducted an experimental campaign considering conditions identical to those find the real precast structures. Based on the results of different experimental studies, the authors verified that the friction coefficient between the concrete and the neoprene can be described through Equations (1) and (2), which are in line with the values proposed in PCI [28].

$$\mu = 0.49, if\ \sigma_c \leq 0.14\ MPa \tag{1}$$

$$\mu = 0.1 + \frac{0.055}{\sigma_c(MPa)}, if\ 0.14 < \sigma_c \leq 5\ MPa \tag{2}$$

It should be noted that the experimental tests on the basis of the previous equations were conducted increasing the displacement with a low shear loading rate equal to 0.02 mm/s, which, according with [29], should conduce to a lower estimation of the friction coefficient since it is expected an increase in the friction coefficient as the shear loading rate increases.

When compared with connections between two concrete surfaces, the values of the friction coefficient for neoprene-concrete are relatively lower, varying between 0.1 and 0.5, under traditional loading condition, whilst the friction coefficient between two concrete surfaces range from 0.5 to 1.2, depending on surface roughness and normal stress [30].

2.2.2. Dowel

Dowel connections may experience two main possible failure mechanisms: local failure characterized by the simultaneous yielding of the dowel and crushing of the surrounding concrete , and global failure, characterized by spalling of the concrete between the dowel and the edge of the column or the beam [25].

In the recent years, several researchers (e g. [12], [22], [31], [32]) have studied the behavior of beam-to-column dowel connections. Along with these studies different modes have been proposed to represent the dowel contribution in RC precast beam-to-column connections.

Fischinger *et al*., 2013 [32] introduced a phenomenological model to estimate force and displacement at yielding and maximum capacity associated with the local failure of the steel dowels (Equations (3) to (6)).

$$F_y = \frac{k_{conf} f_{cc} d_d (8 \cdot 0.314 d_d)}{2} \tag{3}$$

$$u_y = 2F_y \frac{(1 - \beta e)}{(2\beta^3 E_s I)} \tag{4}$$

$$F_{max} = k_{conf} f_{cc} d_d \left(a + \frac{(2.5d_d - a)}{2} \right) \tag{5}$$

$$u_{max} = 2 \tan(rot_{max}) a \tag{6}$$

In the previous equations, k_{conf} is the coefficient of confinement, f_{cc} is the concrete compressive strength, d_d is the diameter of the dowels, I is the moment of inertia of the dowel section, E_s is the elastic modulus of the steel used in the dowels, e is the eccentricity of the dowels (assumed half the thickness of the neoprene pad) and rot_{max} is the maximum rotation of the dowels. The equations include also the parameters β and a whose expressions can be consulted in [32].

Regarding the global type of failure (concrete spalling) [33] proposed a factor to reduce the

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maximum strength of dowel connections if small cover thickness is provided. Hence, when the ration between the concrete cover thickness (D) and the dowel diameter (d_d) is between 4 and 6, the maximum strength of the dowels should be estimated according with Equation (7):

$$F_{max} = (0.25 \frac{d_d}{D} - 0.5)k_{conf}f_{cc}d_d \left(a + \frac{(2.5d_d - a)}{2} \right)$$ (7)

3. DESCRIPTION OF THE PROPOSED NUMERICAL MODEL

3.1. Overview

The numerical simulation of beam-to-column connections have be addressed following different approaches, considering both macro (e.g., [8], [26], [34], [35]) and more refined numerical models (e.g., [36]–[38]).

The use of refined models tends to offer more precise results given the ability to explicitly consider the phenomenological mechanisms involved in the connections. However, these models are computationally demanding and, therefore, unsuitable to conduce parametric and probabilistic studies and to be included in global building analysis.

The present study is focused on the definition of a simple macro-element that can be easily defined to connect conventional beam-column elements, lumped or distributed plasticity, numerical analysis software packages, and is capable of accurately describe the main mechanisms identified in the previous section.

Figure 4 illustrates the idealization adopted to simulate the different resisting systems, namely the steel dowels, the friction between the different elements and the neoprene pad. On the left-hand side, is shown a typical configuration of beam-to-column connections in existing precast RC buildings, while on the right-hand side is a mirrored scheme of the idealized numerical model.
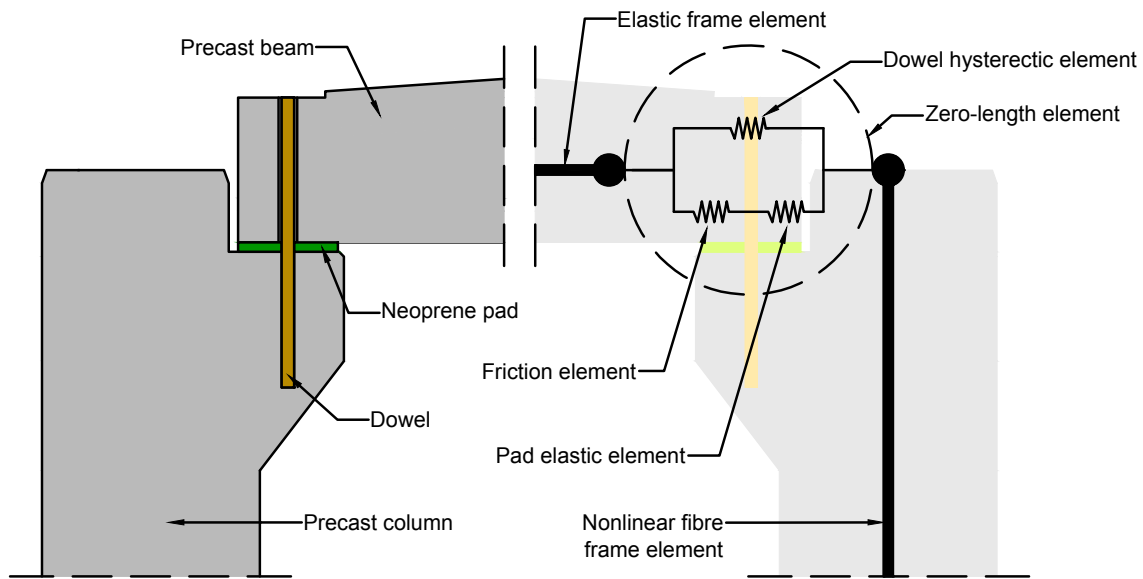
Figure 4 – Beam-to-column connections in conventional precast RC buildings: common configuration (left) and numerical arrangement adopted (right)

The numerical model consists of a zero-length element, i.e., the end node of the beam and column have the same coordinates, that includes three different axial springs aligned in series or in parallel, depending on the manner these are activated in real structures. This spring arrangement is defined for both horizontal directions, while the rotations in the three principal directions are released. In the vertical direction it is admitted a very large stiffness.

In cases where the connection does not include dowels, the transfer of horizontal forces from the beam to the adjacent column (inertial force in case of an earthquake) is ensured essentially by friction between these two elements and the neoprene pad. If this force is lower than the one corresponding to the static friction, the connection deformation equals the transverse deformation of the neoprene pad. Once the applied force equals the static friction one, the connection cannot sustain higher lateral forces and the lateral deformation increases, through sliding of the beam, while the neoprene pad deformation remains constant with a magnitude corresponding to the application of the static friction force. This described behavior is ensured by the two springs aligned in series in the zero-length model represented in Figure 4.

In cases the connection features also steel dowels, the transmission of the horizontal force is ensured by the dowels and the friction mechanism, previously described. Idealizing a system with a perfect bond between the dowels and the RC elements, the deformation of the dowels

equals the deformation of the pad plus the sliding one - the latter only in case the horizontal force is higher than the static friction one, as described before. This effect is consistent with a parallel mechanism, where the forces sustained by each mechanism is defined based on the relative stiffness between each one.

The constitutive relation adopted for the different springs is described in the following points, adopting constitutive models available in OpenSees [39], a platform for structural modelling and assessment.

3.2. Neoprene model

The transverse deformability of the neoprene pad is modelled through the uniaxial "Elastic" material, whose stiffness corresponds to the transverse stiffness of the pad defined with Equation (8).

$$K_{pad} = \frac{F}{\Delta} = \frac{GA_{pad}}{t} \tag{8}$$

Where G is the shear modulus of the neoprene, assumed equal to 1MPa according with Fischinger *et al.* [32], A_{pad} and t are the contact area and the thickness of the pad, respectively.

3.3. Friction model

The definition of the friction model comprehends two main steps: the definition of a model that enables the accurate estimation of the friction coefficient and the incorporation of this model into a zero-length element.

In order to account for the dependence of the friction coefficient on the axial load, it was considered the "VelNormalFrcDep" friction models available in OpenSees. According with this model, the friction coefficient is computed based on the axial force and velocity experienced in the connection during the analysis. This option is particularly suitable to simulate the structural response under earthquake actions given the natural variation in velocity and axial load resulting from the vertical component of ground motions.

According with this model, the friction coefficient μ is defined according with the following equation:

$$\mu = a\, N^{(n-1)} \tag{9}$$

where, N is the axial force and a and n are adjustable parameters. In order to approach the model proposed by [27], defined through Equations (1) and (2) (see Section 2.2.1.), the parameters a and n are defined as:

$$a = \frac{0.445}{A_{pad}^{-0.163}} \tag{10}$$

$$n = 0.837 \tag{11}$$

It is noted that the parameters a and n reflect already the conversion of the empirical equation to match the format of the model, namely the conversion of axial stress in the contact region (σ_c as defined in the empirical model) as an equivalent axial force and the description of the friction coefficient as a power function of the axial force (N). The latter was approached through the least square's method.

Considering the limited information available regarding the effects of the velocity on the friction coefficient, the model considered in this study disregards the effects of the velocity and simply to reflect the variation in the axial load in the connection.

Once defined the model to establish the friction coefficient, this model was associated with the "flatSliderBearing" element. Despite being especially devoted to simulate flat sliding surfaces, the properties of this element fits the purposes of the present study, namely its ability to adjust the friction coefficient, and hence the lateral strength, during the analysis according with the variation in the axial force and velocity. In addition, it allows the definition of an arbitrary initial stiffness.

This latter option of the "flatSliderBearing" element allows the simplification of the zero-length element, merging the two springs defined in series: the neoprene pad and the friction model. This can be achieved considering the elastic stiffness corresponding to the neoprene pad (K_{pad}) as the initial stiffness of the "flatSliderBearing" element, as illustrated in Figure 5.
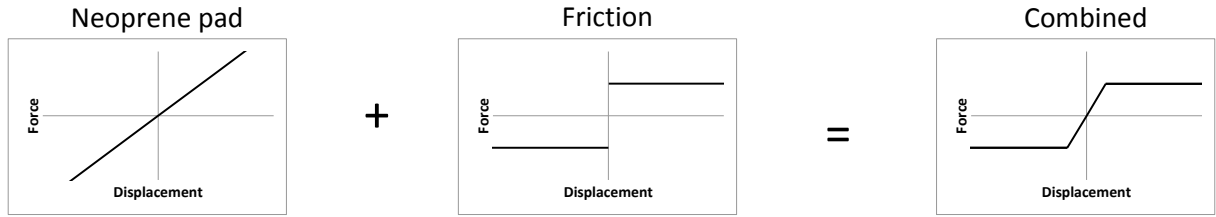
Figure 5 – Incorporation of the neoprene pad flexibility in the friction model

3.4. Dowel model

The contribution of the dowels was modelled assuming a tri-linear force-displacement relation through the "hysteretic" uniaxial material available in the OpenSees platform. As illustrated in Figure 6, the backbone curve of this material is defined by six force-displacement pairs (3 in the first and third quadrant).
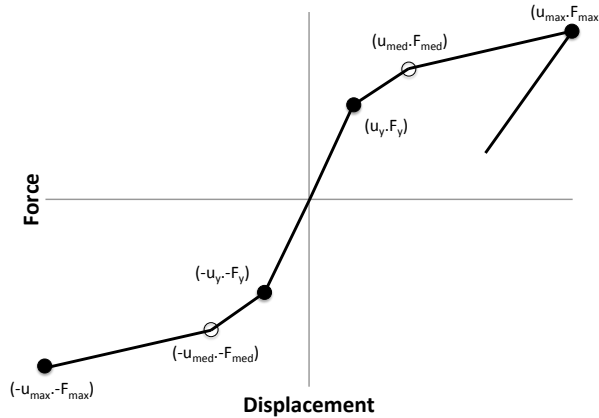

Figure 6 – Generic backbone curve of the model adopted to model the dowel component of the connections

In this study, the values corresponding to the yielding (u_y, F_y) and maximum (u_{max}, F_{max}) strength were determined with Equations (3) to (6), proposed by [32], while the intermediate values (u_{med}, F_{med}) were defined according with Equation (12) and (13).

$$F_{med} = \frac{F_y + F_{max}}{2} \tag{12}$$

$$u_{med} = u_y + \frac{u_{max} - u_y}{4} \tag{13}$$

In addition to the values defining the backbone curve, the model considers also 5 additional parameters to account for the degradation of the dowels resulting from large deformation demand and cyclic degradation.

4. VALIDATION OF THE NUMERICAL RESULTS

In order to access the validity of the proposed numerical model, the results of two experimental tests were selected as benchmark. The experimental tests selected were performed by [21], [22], and features different setup and connection characteristics. Each specimen was subjected to cyclic loads of increasing amplitude up to collapse. Figure 7 presents the experimental setup of the two tests while the main material and geometric properties are summarized in Table 1.
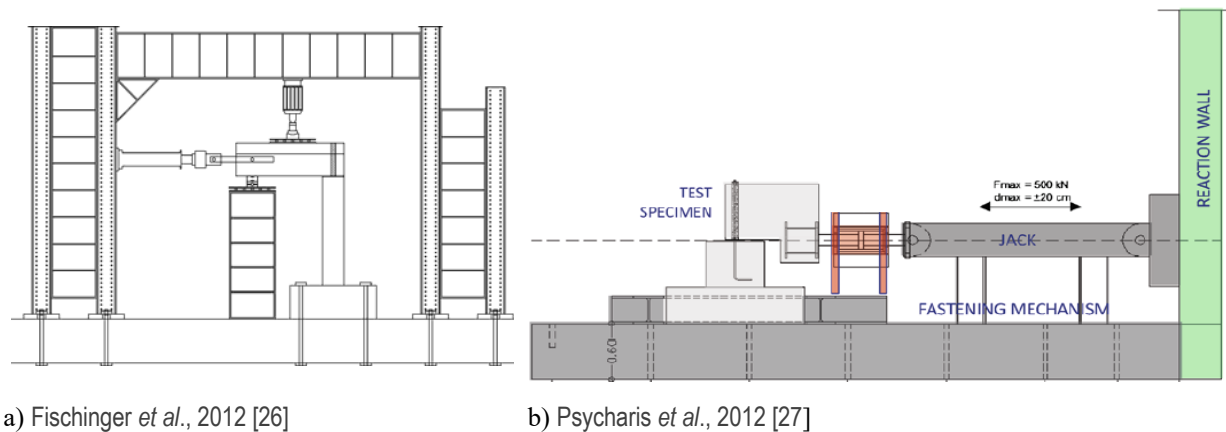

a) Fischinger *et al*., 2012 [26]   b) Psycharis *et al*., 2012 [27]

Figure 7 – Setup of the experimental tests considered for numerical validation

Table 1 – Main properties of the experimental tests

	Fischinger *et al*., 2012 [26]	Psycharis *et al*., 2012 [27]
f_{cc} (MPa)	50	35
K_{conf}	2.5	2.5
d_d (mm)	28	25
No Dowels	1	2
D (mm)	200	100
F_y (MPa)	580	640
F_u (MPa)	696	768
T_{neo} (mm)	10	20
A_{neo} (mm^2)	88000	80000
G_{neo} (MPa)	1	1
Axial load (kN)	50	3

In addition to the force-displacement thresholds determined based on properties of the experimental tests, the numerical model requires the definition of 5 damage parameters, which were calibrated based on the experimental results. The values adopted are summarized

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in Table 2.

Table 2 – "Hysteretic" model parameters adopted

pinchX	pinchY	damage1	damage2	β
0.67	0.5	0.005	0	0.2

Figure 8 shows the comparison between the experimental results and the numerical estimations obtained the proposed macro-element.

a) Fischinger *et al*., 2012 [26]   b) Psycharis *et al*., 2012 [27]
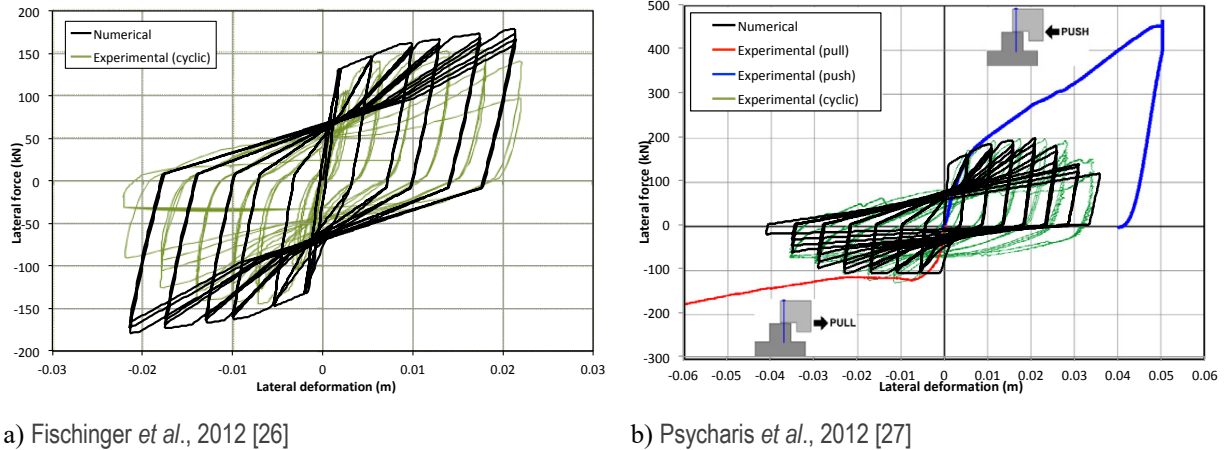
Figure 8 – Comparison between experimental response and numerical predictions of the models tested

The results show that the numerical approach proposed estimates the cyclic response of the experimental tests with reasonable accuracy. Despite the small overestimation of the maximum strength in the connection tested by [26], the model captured the overall response of the test conducted by [27], namely the reduction in the horizontal force in the pull direction (third quadrant) resulting from the concrete spalling around the dowel. In both cases, the energy dissipation, measured through the area of the hysteretic loops appears to be relatively well captured.

5. CONCLUSIONS

The post-seismic assessment of RC precast structures showed that beam-to-column connections represent one of the most vulnerable elements of this typology of structures.

The main objective of this work was to define a numerical approach for the definition of a simplified macro-model, to be used within beam-column (lumped or distributed plasticity) numerical analysis software packages, capable of accurately describe the main mechanisms developed when these elements are subjected to seismic loads.

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The proposed numerical approach accounts for the different load transfer mechanisms involves in the system, namely the dowel effect, friction between the contact surfaces and the deformability of the neoprene pad.

The accuracy of the macro-element proposed was validated against two experimental tests featuring different geometric, mechanical and loading conditions. The comparison of the results demonstrated the ability of the model to estimate the maximum strength of the connections taking into account the two main failure mechanisms (dowel rupture and concrete spalling). The comparison against additional experimental tests will permit the optimization of the different calibration parameters assumed in the model, namely the ones associated with the strength degradation associated with the dowel model.

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