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METHODOLOGY FOR THE CHARACTERIZATION OF SEISMIC LIMIT STATES OF DAMAGE IN RC HOLLOW PIERS EXPERIMENT

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Abstract

Reinforced concrete hollow piers have a seismic behavior similar to the one observed in structural walls, where the damage pattern and failure modes can be associated with both bending and shear mechanisms. On that context, the definition of expected physical damages is not straightforward and, thus, considering a single parameter that is able to predict these trends is also a complex task. To this extent, the present work aims to establish a strategy to identify the seismic limit states of damage in RC hollow piers and to define a set of engineering demand parameters that are able to set up the damage thresholds. For this purpose, several experimental tests conducted at LESE (Laboratory of Earthquake and Structural Engineering) from FEUP (Faculty of Engineering of Porto University) regarding reduced scale specimens with cyclic behavior were analyzed, where the damage pattern observation is assessed and corresponding response parameters (EDP) estimated.

Keywords: Seismic damage, Limit states, RC Hollow piers, Non-linear cyclic behavior, Laboratory experiment.

1. Introduction

The hollow section piers are often used in high-rise bridges, particularly when it is necessary to ensure high stiffness and simultaneously low weight, thus leading to a more economical construction. The hollow piers can be compared to reinforced concrete walls, however when such components are subjected to high intensity seismic actions can, in certain circumstances, evidence a significant vulnerability associated mainly to the low shear capacity.

Due to the expected vulnerability of these piers, when subjected to seismic actions, it becomes urgent to assess the expected damage and its evolution with the increase of the intensity level. Additionally, it is noted that the focus of the scientific research dedicated to seismic behavior of these elements is still reduced, in particular with regard to damage and to the limit states of damage. This paper focus on the issue of damage to hollow piers due to the seismic action, proposing a methodology to characterize the limit states of damage under the perspective of the physical behavior. To establish a correspondence between physical damage states and structural parameters, a set of results of quasi-static experimental tests was analyzed, in hollow piers of reinforced concrete subject to cyclic loading (Delgado *et al*, 2009; Delgado *et al*, 2011 and Delgado *et al*, 2012).

2. Experimental tests

The experimental tests campaign was conducted in LESE (Laboratory of Earthquake and Structural Engineering), located in the Faculty of Engineering of University of Porto, where a test setup was developed and that served to several research work in this field.

2.1. Test Setup

The test setup, illustrated in Figure 1, is a structure constituted by two reaction frames constructed by steel profiles.

Fig. 1 – Test Setup

One of the reaction frames is equipped with a horizontal actuator which enables to apply loads up to 500 kN. The second frame is equipped with a vertical actuator for the simulation of axial loads, with a capacity of 700 kN. This second actuator is prepared to keep constant the axial load. The pier foundation and the reaction frames are connected to the rigid floor using high strength rods, pre-stressed to prevent undesirable displacements and rotations.

2.2. Tested piers

This experimental test campaign consisted for 12 piers, 6 squares (PO1) and 6 rectangular (PO2). The square piers have a section of 0.45x0.45m and the wall thickness is 7.5cm. The rectangular piers have a section of 0.90x0.45m also with a wall thickness of 7.5cm. All piers are 1.40m tall and were built with ¼ scale from the original size. The piers are all different by varying the characteristics of materials, arrangement of shear reinforcement or cross areas of reinforcement. Table 1 shows the characteristics of all piers (Delgado *et al*, 2009; Delgado *et al*, 2011 and Delgado *et al*, 2012).

Table 1 – Properties of tested piers

Designation	Geometry	f_{cm} (Mpa)	Longitudinal Reinforcement		Shear Reinforcement		
			area	f_{sy} (Mpa)	ø (mm)	f_{sy} (Mpa)	Type
PO1-N1	Square	19,8	40φ8	625	3,8	390	2 legs
PO2-N1	Rectangular	19,8	64φ8	625	3,8	390	2 legs
PO1-N2	Square	27,9	40φ8	435	2,6	437	2 legs
PO1-N3	Square	27,9	40φ8	435	2,6	437	2 legs
PO2-N2	Rectangular	27,9	64φ8	435	2,6	437	2 legs
PO2-N3	Rectangular	27,9	64φ8	435	2,6	437	2 legs
PO1-N4	Square	28,5	40φ8	560	2,6	443	2 legs
PO1-N5	Square	28,5	40φ8	560	2,6	443	2 legs (EC8)
PO1-N6	Square	28,5	40φ8	560	2,6	443	4 legs (EC8)
PO2-N4	Rectangular	28,5	64φ8	560	2,6	443	2 legs
PO2-N5	Rectangular	28,5	64φ8	560	2,6	443	2 legs (EC8)
PO2-N6	Rectangular	28,5	64φ8	560	2,6	443	4 legs (EC8)

For instrumentation LVDT´s were used, on one of the lateral faces. Images and videos were also recorded, from outside and inside the pier. Figures 2 and 3 illustrate the detail of the reinforcement and arrangement of LVDT´s, respectively.

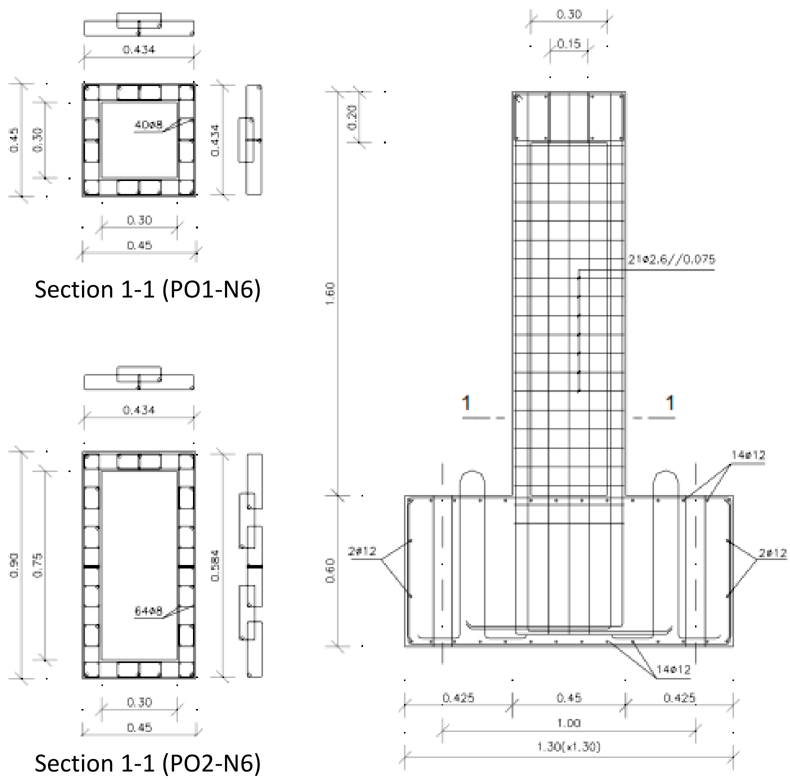


Fig. 2 – Detail of the reinforcement (Delgado *et al*, 2009; Delgado *et al*, 2011 and Delgado *et al*, 2012)

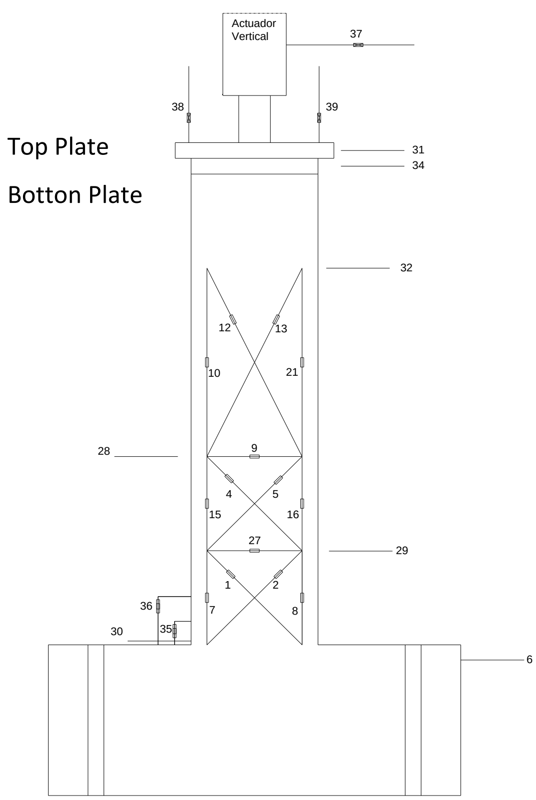


Fig. 3 – Disposition of the LVDT´s (Delgado *et al*, 2009; Delgado *et al*, 2011 and Delgado *et al*, 2012)

2.3. Loads / Displacements applied

In the tested piers were always applied two loads, one axial load of 250 kN, that corresponds to a normalized axial force of 0.08 constant over time, and one horizontal load responsible for the piers top displacement, variable over time, depending on the target displacement. These values resulted on the displacement time history, and correspondent drifts, shown in Table 2, repeating three times for each intensity.

Table 2 – Target displacements and drifts during the tests.

Displ. (mm)	1	3	5	10	4	14	17	7	25	30	33	40	45
Drift (%)	0.07	0.21	0.35	0.7	0.28	1.0	1.2	0.5	1.8	2.1	2.4	2.9	3.2

3. Physical damage observed

The characterization of the seismic performance of the reinforced concrete hollow piers by experimental tests conducted in FEUP, as mentioned in the previous section, provides crucial information for the identification and detailed analysis of the damage observed in these elements. Former studies devoted on the assessment of physical damages in structures were mainly focused on frame buildings (Kappos *et al.*, 1998 and Gunturi *et al.*, 1993), which were used to characterize fragility and vulnerability functions (Silva, 2014) or to estimate the economic losses due to earthquakes (Ramirez *et al*, 2012 and Martins *et al.*, 2015). The most common physical damages in reinforced concrete hollow piers due to the seismic action are: concrete cracking; concrete spalling and concrete crushing. The methodology proposed in this paper is based on the results of the PO2-N6 pier, regarding the results analysis of the deformation and strength capacity, as well as the assessment of physical damage associated with each drift level. Figure 4 shows the evolution of the pier damage due to the drift value, where W_K means crack width. It is visible that the first cracking occurs for a pier top displacement of 5 mm, corresponding to 0.36% of drift. The damage limit, concrete crushing, correspond to the last cycle test load. This cycle was set isolated to each pier corresponding to the cycle for which the observed damage level required total pier reinforcement. In Figure 5 is illustrated the cyclic response of the pier, in terms of the evolution of lateral forces versus displacement applied on the pier top.

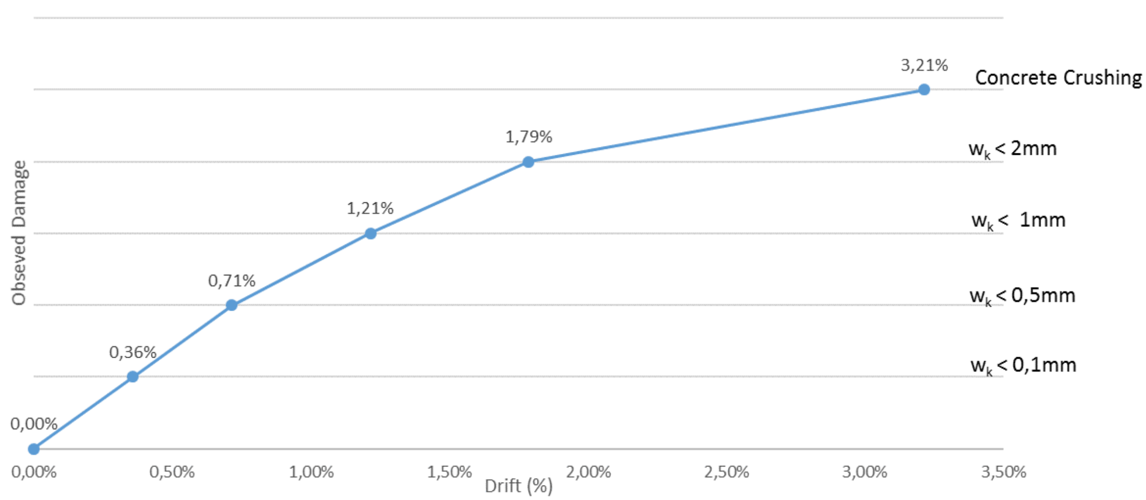


Fig. 4 – Damage observed in the pier due the drift level

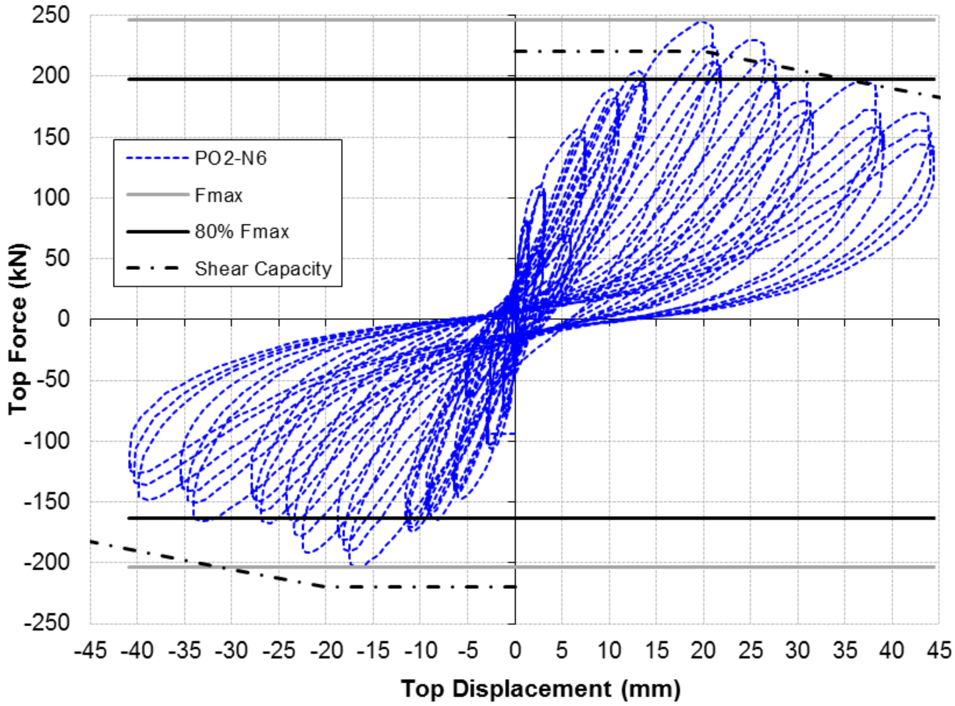
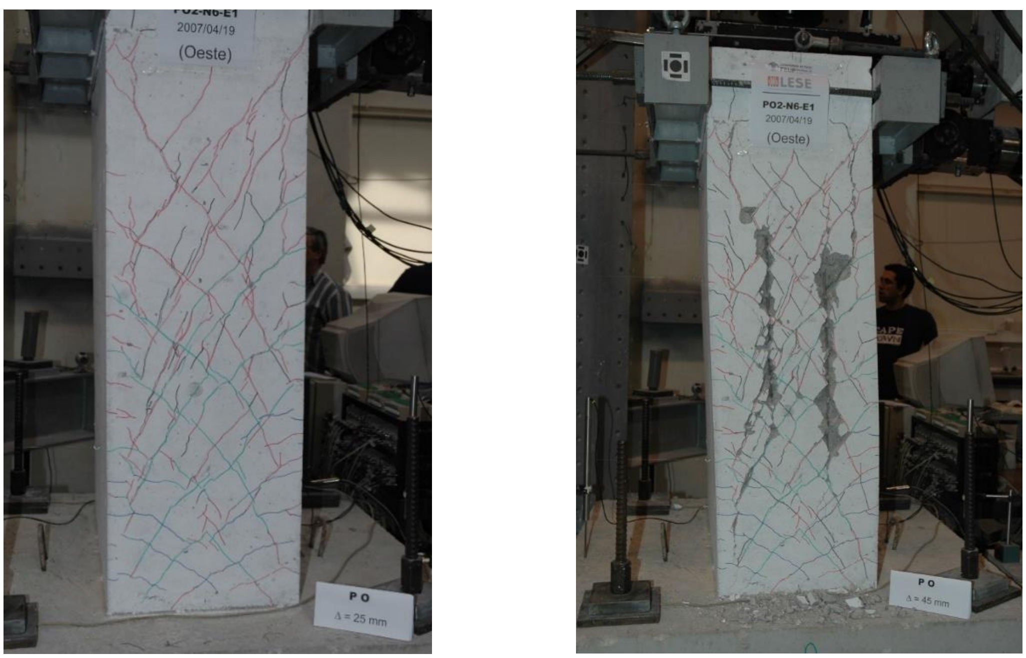


Fig. 5 – Response of pier PO2-N6

It is noted that the conventional rupture, corresponding to 80% of maximums force applied, occurs when the pier still has medium crack (1.5mm), but with a high density of cracks, as visible in Figure 6a). When the concrete is crushed to a high drift, it is visible that the pier damage increased significantly, as identified in Figure 6b. This concrete spalling occurs in the pier webs as it caused by shear effects.



a) b)

Fig. 6 – Evolution of the pier damage: a) conventional rupture; b) concrete crushing

4. Seismic damage states

4.1. Introduction

A limited number of existing studies is devoted to the seismic analysis of hollow piers, in particular with what regards to the characterization of the physical damage of these elements subjected to a cyclic excitation. Thus, and with the objective of defining thresholds for the limit states of damage of these reinforced concrete elements, the present works is sought to also characterize the evolution of damage in a gradual scale of importance, in agreement with what is considered in code provisions and other studies (e.g. FEMA, 2003 and Rodrigues et al. 2013), namely: slight damage, moderate damage, extensive damage and collapse.

To determine the damage limit states and their transition, different response parameters were analyzed, such as the crack width and extension, the existence of concrete spalling and the collapse of the piers. The increasing levels of the crack width were classified as follows: microcracking, up to 0.5mm; small crack, for widths between 0.5 and 1mm; medium crack, widths between 1.5 and 2mm; and large cracks, ranging from 2.5 to 3mm. In what regards to the collapse of the pier, it was assumed a conventional rupture corresponding to 80% of the maximum shear capacity, as defined in Delgado (2009), in which the theoretical shear force is calculated from Priestley et al. (1996).

In the next section, the evolution of damages is described for each limit state, in accordance with the observations from the cyclic experimental tests conducted to the piers, in the laboratory facilities of the University of Porto.

4.2. Description of the damage states

4.2.1. Slight damage

In this limit state of damage it is considered that the structural stability of the element is not in risk. In terms of visible physical damages it is observed essentially the start of cracking in a limited extent, for both length and density (between 20% and 50% of the surface of the pier). The referred cracks can be shown in Figure 7, in particular in the region of connection between the foundation and the pier.

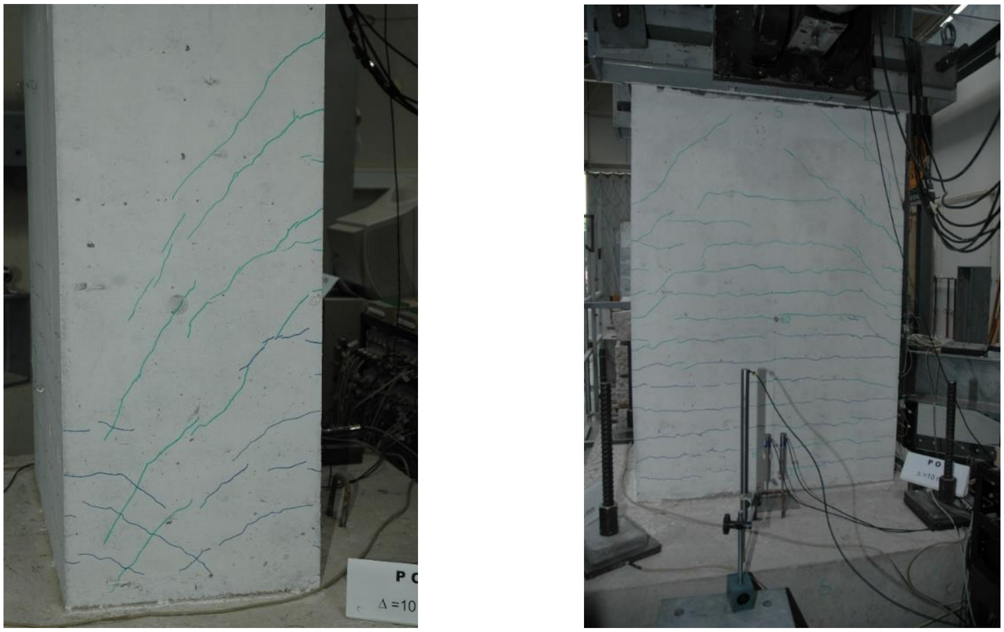


Fig. 7 – Limit state of light damage

4.2.2. Moderate damage

This state is characterized by visible cracks, that are exist in high density, although with small width (less than 1mm). Moreover, in this limit state of damage it is also possible to identify the initiation of some shear cracks, Figure 8. In what regards to the classification of crack widths defined in the previous section, small cracks (1mm) are observed.

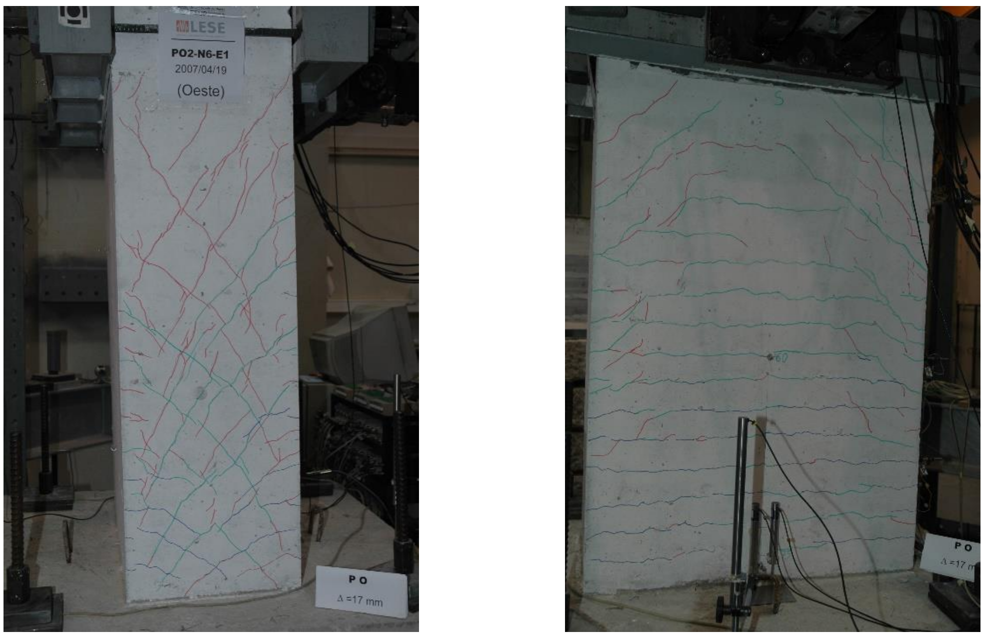


Fig. 8 – State limit Moderate damage

4.2.3. Extensive damage

The observed physical damages in the extensive limit state are associated to a significant repair cost, and may also compromise the structural stability of the pier. The damage is characterized by the appearance of medium and large cracks, which are dense to very dense along the surface of the element. Furthermore, concrete spalling is observed and the shear cracks are at this stage clearly developed, which in some cases can be found to expand into the piers height, Figure 9.

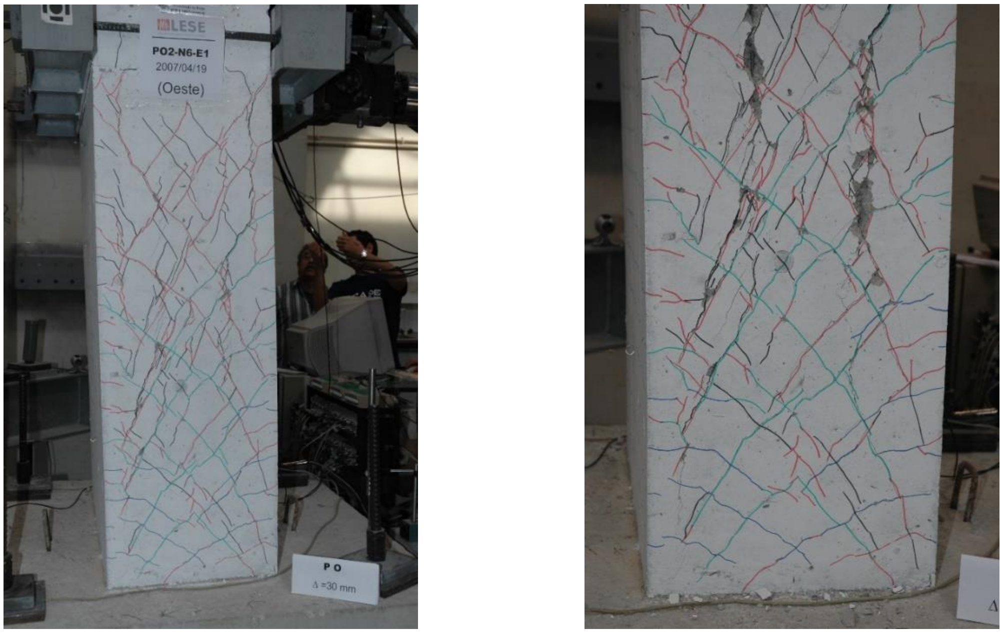


Fig. 9 – State limit Extensive damage

4.2.4. Collapse

This limit state is characterized by a cost of repair that is close to the total cost of replacement of the structural element, thus not being feasible to repair the structural element, unless it is sought to increase its performance. Herein, the structural safety is seriously compromised. A significant evolution of the aforementioned damages is depicted, with particular emphasis on the concrete crushing. Numerically this state is set when the base-shear exceeds the theoretical value of shear capacity or the conventional rupture occurs, Figure 10.

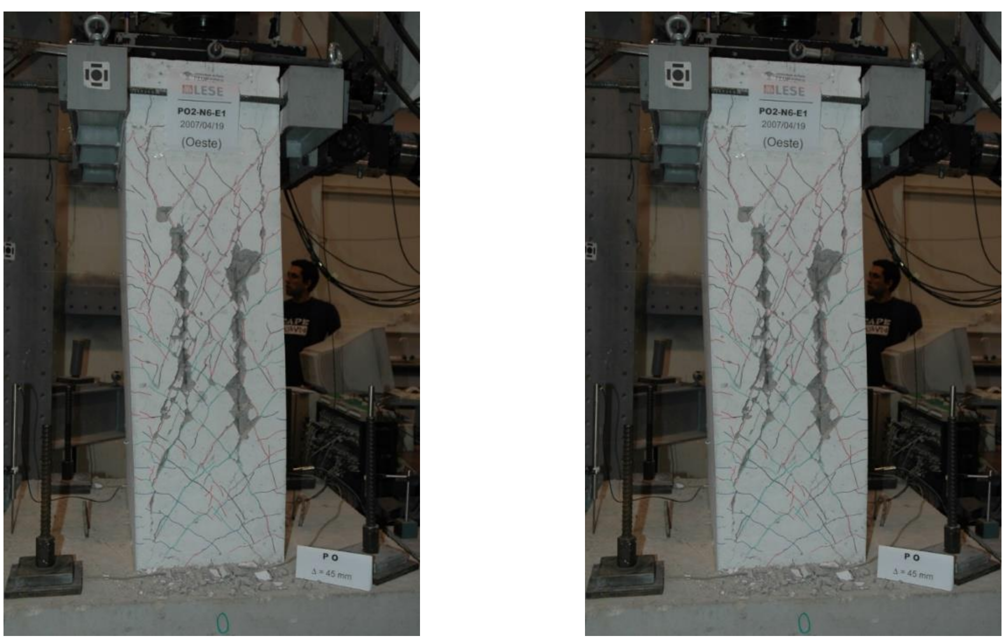


Fig. 10 – State limit Collapse

4.3. Definition of thresholds for states of damage

In order to achieve the objective of this work, which is to present a methodology for the characterization of the limit states of damage of hollow piers subjected to cyclical loading, an engineering demand parameter is sought to be identified in order to characterize the evolution of damages along the limit states.

Thus, and bearing in mind the major existing applications on seismic vulnerability, in the context of seismic risk assessment, the use of drift was considered in this study. Although recognizing that the use of a single structural parameter for all the limit states has some limitations regarding the best correlation with damages, the authors propose the use of drift for the sake of simplicity and in order to permit its assessment by simplified 2D numerical models.

The correspondence between the four damage limit states defined and the respective drift values were established from the detailed analysis of experimental tests on the reinforced concrete hollow piers, and taking into account the description of each limit state. Table 3 reflects the drift limit values associated with each physical state of damage, as obtained from the experimental tests. Similarly, Figure 11 represents graphically the evolution of damage in terms of drift values, for the PO2-N6 specimen.

Table 3– State limit and corresponding value of drift

Limit State	*Drift* (%)
Slight	0.71
Moderate	1.21
Extensive	2.14
Collapse	3.21

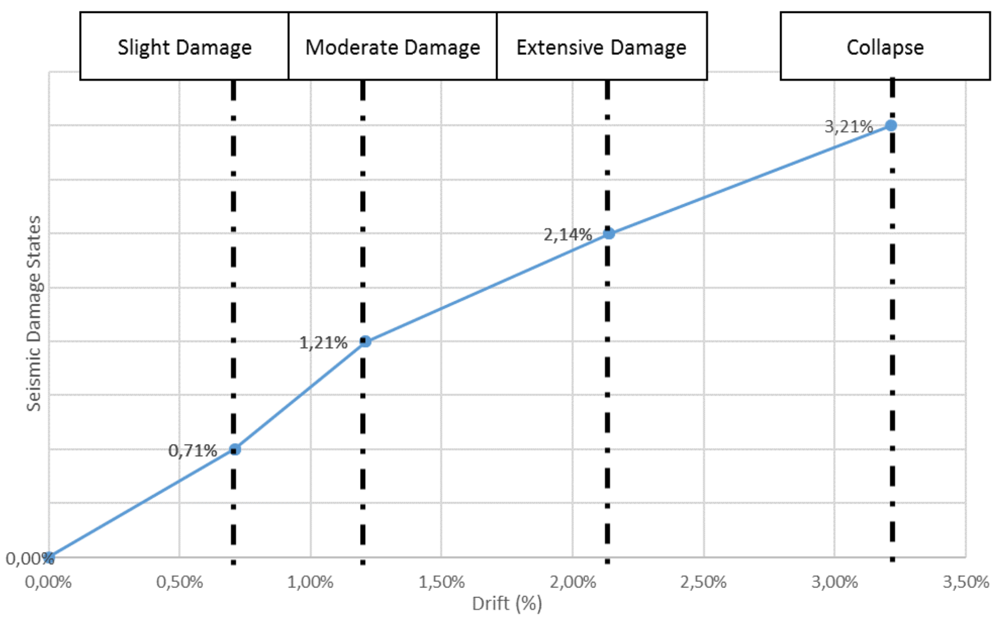


Fig. 11 –Limit state of damage in terms of drifts

5. Conclusions

The study presented in this article aims at proposing a methodology for the characterization of the limit states of damage for reinforced concrete hollow piers subjected to cyclic excitation. As such, several experimental tests on piers with similar characteristics and behavior were analyzed at the Laboratory of Earthquake and Structural Engineering, from the Faculty of Engineering of Porto University.

This study also focused on identifying an engineering demand parameter that can represent the structural response of the piers and that is correlated to the existing damages. The drift of the piers was considered as a damage indicator.

From the analysis of the evolution of the physical damages and the structural performance of the piers, it was possible to identify a total of 4 limit states, in which different repair techniques are associated and corresponding repair costs to restore the structural performance and capacity of the elements to its originals.

The results are particularly useful for estimating damage repair costs due the seismic action in these structural elements and may be applied for earthquake risk assessments at both regional level and structure-specific.

However, it should be noted that these results should be considered as part of a preliminary study that has set up a methodology and assumptions for the characterization of damage states in reinforced concrete hollow piers subjected to cyclic load. Therefore, this work should be complemented with a detailed analysis of a higher number of piers, as well as including additional engineering demand parameters associated with each damage state. Finally, the use of mathematical models which are able to adequately represent the seismic behavior of the structural elements should be assessed, which is particularly crucial when no experimental results exist.

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