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COST OF REPAIR AND RETROFIT OF SEISMIC DAMAGE OF RC HOLLOW-PIERS

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Abstract. *Reinforced concrete hollow piers are well known for the shear effects they so often reveal to be subjected to. This aspect is particularly true in the case of hollow piers where the failure modes usually relate to shear behavior. Very few studies have devoted their attention to the economic consequences of repairing and retrofitting the physical damages existing in RC hollow piers subjected to the seismic action. This information is deemed crucial when cost-benefit analysis is concerned for the definition of measures for repair and retrofit of seismic damage.*

Therefore, the present work intends to discuss adequate strengthening strategies and their costs, associated with each seismic physical limit state of damage. An extensive review of numerous cyclic experimental works on RC hollow piers conducted at the University of Porto will be performed, and in liaise with specialized construction companies, the repair costs will be estimated.

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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. 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 devoted to seismic behaviour of these elements is still reduced, in particular with regard to damage and to the limit states of damage. This paper focus on the analysis of damages on hollow piers due to the seismic action, proposing a methodology to characterize the limit states of damage under the perspective of the physical behaviour. To establish a correspondence between physical damage states and structural parameters, a set of results of quasi-static experimental tests was analysed, in hollow piers of reinforced concrete subject to cyclic loading [1-3].

2. DESCRIPTION OF THE EXPERIMENTAL TESTS

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

2.1. Test Setup

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

Figure 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 of 12 piers, 6 with a squares cross section (PO1) and 6 with a rectangular section (PO2). The square piers have a section of 0.45x0.45m and a wall thickness of 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. All the piers have different characteristics of materials, arrangement of shear reinforcement or cross areas of reinforcement. Table 1 shows these characteristics of the piers [1-3].

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)

Table 1 :Properties of tested piers

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.

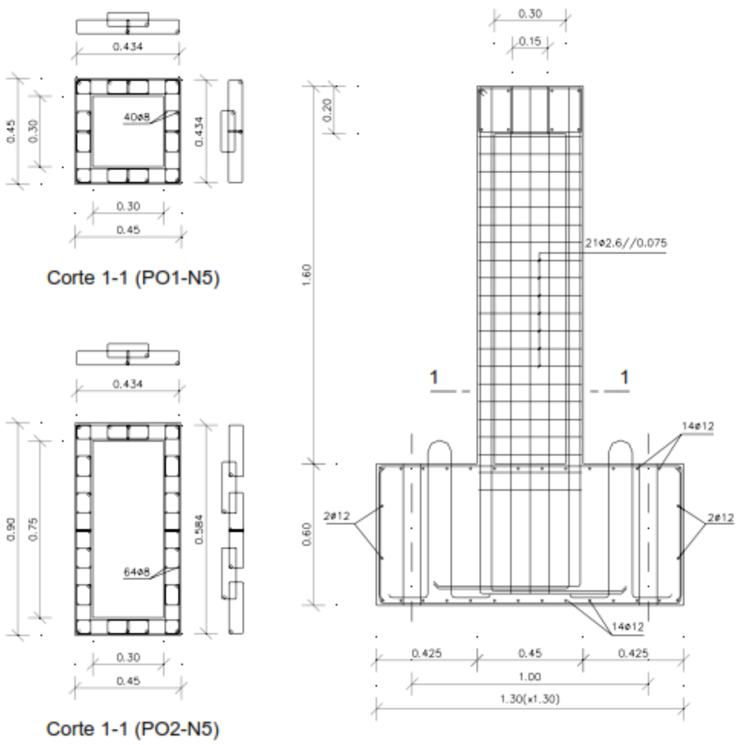


Figure 2: Detail of the reinforcement (Delgado, 2009)

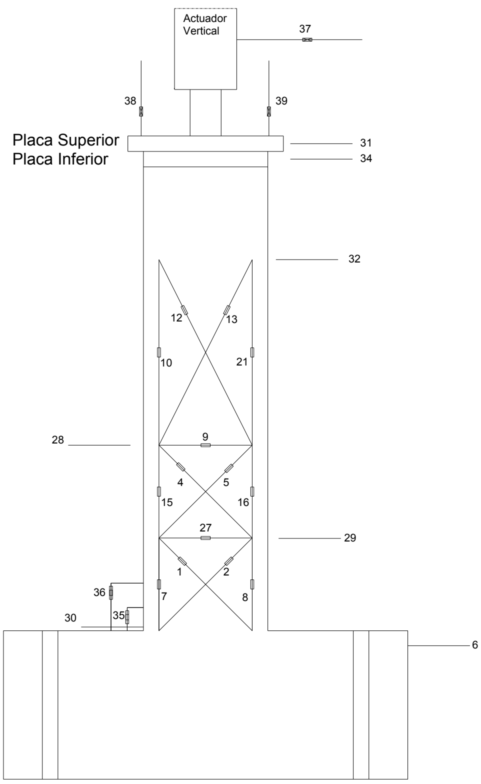


Figure 3: Disposition of the LVDT´s (Delgado, 2009)

2.3. Loads / Displacements applied

In terms of loads, were applied 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 from the displacement load pattern, and correspondent drifts, shown in Table 2, repeating three times for each intensity.

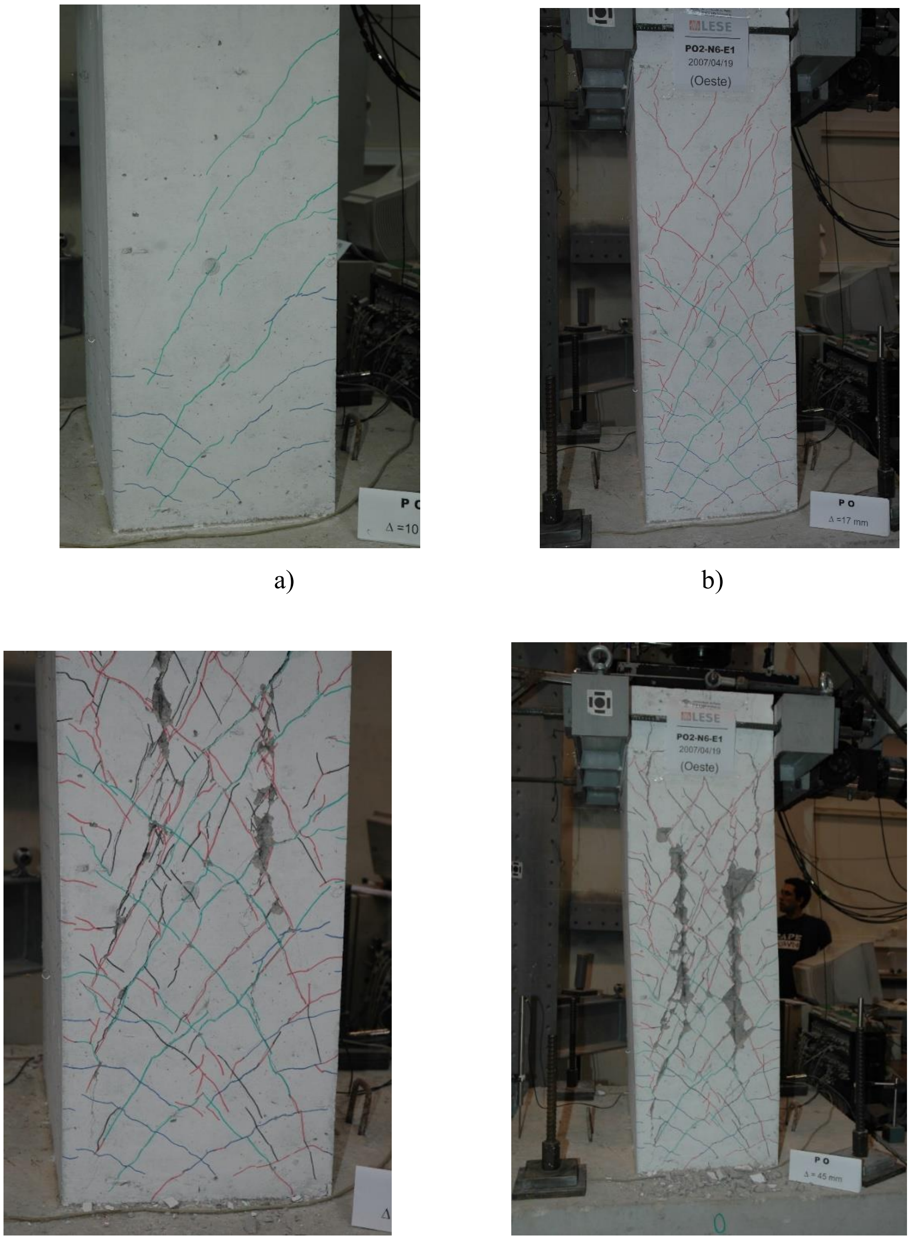
Displ. (mm)	1	3	5	10	4	14	17	7	25	30	33	40	45
Drift (%)	0.07	0.21	0.35	0.7	0.28	1.0	1.2	0.5	1.8	2.1	2.4	2.9	3.2

Table 2 : Displacements and drifts load pattern.

3. SEISMIC DAMAGE STATES

With the analysis of the experimental test it was possible to perform an evaluation of the damages in the columns. The types of damages that were observed correspond to: concrete cracking, concrete spalling and concrete crushing. After quantifying and analysing the damages due to the displacement applied on the top of the column, it was possible to identify several response levels corresponding to the seismic damage limit states. The seismic damage limit states chosen for the present study were those defined by Delgado *et al.* [4]. These seismic damage limit states are in line with other studies and documents, e.g. [5] and [6].

The methodology proposed by Delgado *et al.* [4] defines a total of four damage limit states. The first state of damage corresponds to slight damage. In this state, the damage is barely visible and does not compromise the structural stability. The visible damages are essentially the beginning of cracking, in a small extension and density, concentrated on the lower third of the columns. The second state of damage, referred to as moderate damage, is distinguished from the previous state limit by the increase in cracking. The cracks have reduced openings, smaller than 1mm, being a large part of the typical cracks, shear cracking, which reach a maximum of 1mm of opening. The third state of damage is the state of extensive damage. When a pier reaches this level of damage the element already requires attention and a significant repair. The most visible damages in the piers are the appearance of cracks openings of up to 3 mm and with a high density. In this state of damage the cracks are essentially due to shear in the webs and to bending in the flanges also noting the effect of "shear lag effect". The cracks are evenly distributed over the entire section of the pier. It is also possible to observe some concrete spalling. The ultimate damage state is the collapse. When damage to the pier reaches this level, it is no longer economically and feasible to repair the structural element and its structural safety is seriously compromised. Between this state and the state of extensive damage, there is a significant evolution of damages, with emphasis on the concrete crushing and an increase of the detachment of the concrete cover. Numerically, this state is defined when the shear stress is higher than the theoretical resistant value or the conventional shear occurs. Figure 4 illustrates the evolution of damage, in the various limit states of damage, of the PO2-N6 piers.



a) b)

c) d)

Figure 4: a) Slight damage, b) Moderate damage, c) Extensive damage, d) Collapse

After defining the several damage states, it is necessary to identify a response parameter capable to translate the evolution of the physical damages of the column in each of the above limit states. Thus, and with the purpose of using a single structural parameter for all limit states, which can be easily evaluated in any numerical model, the drift response parameter was selected. The correspondence between the four previously defined limited states of damage and the drift values was established from the analysis of the experimental tests of the hollow piers, and considering a description of each boundary state. The analysis of the experimental tests had a main focus on the PO2-N6 piers. Table 3 translates the drift limit values associated with each physical damage state.

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

Table 3 :Limit states and corresponding drift value

4. REPAIR AND REINFORCEMENT TECHNIQUES

Once the seismic damage limit states are defined, it is possible to analyse the best techniques for the repair or strengthening of the piers. In the following points, will be described the best techniques of repair and strengthening for each state of damage. This study was followed by the approach and characterization of repair techniques proposed in the research project "PRISE - Evaluation of Losses and Seismic Risk of Buildings in Portugal" [7], funded by the Portuguese Foundation for Science and Technology, in which the authors of this study were involved, and as presented in the work conducted by Delgado *et al.* [4]. In this project was built a database of unit repair costs for each repair technique, which includes materials and labour costs, obtained from surveys collected from several construction companies existing in Portugal and specialized in repairing/strengthening these damages. It should be noted that in this study, the indirect costs, such as access to the pier to be repaired and assembly of the work platform, were neglected.

4.1. Slight Damage Limit State

As previously stated, this state is characterized by minor or irrelevant and visually imperceptible damages. The damages are characterized by very small cracks, up to 0.5mm of opening. For such pattern, with crack width less than or equal to 0.1mm, three possible repair techniques are identified and may or may not occur together, namely: surface painting; Surface plaster of the piers; Scrub surface with epoxy resin. If the environmental conditions of aggression are zero, no repair is necessary. For crack width between 0.1mm and 0.5mm, the most appropriate repair technique is the injection of epoxy resin.

The painting of the concrete surfaces of the piers must be carried out through water-based monolayer paint scheme. This painting should be done in two coats, with a smooth finish, resistant to the alkalis of the hydraulic binders and complying with the minimum requirements of EN 1504-2 [8]. This painting should be done with elastic paints to prevent further fissure of the piers. The surface plater repair technique consists of a generalized treatment of the cracks at an unspecified location. The same plastering should be done with an adjuvant mortar. The last repair technique, applied on crack width lower than 0.1mm is to scrub the surface with epoxy resin. This technique consists on the application of impregnation product with one coat, resistant to the alkali of the hydraulic binders and fulfilling the minimum requirements of EN 1504-2, [8]. Figure 5 illustrates the three repair techniques described above. For larger crack openings, less than or equal to 5mm, the most appropriate repair technique is epoxy resin injection. This injection of epoxy resin must comply with EN 1504-5 [9], which concerns injections in reinforced concrete structures. Figure 6 illustrates the execution of this same technique.

a) b) c)

Figure 5: a) painting , b) plaster , c) ; Scrub surface with epoxy resin

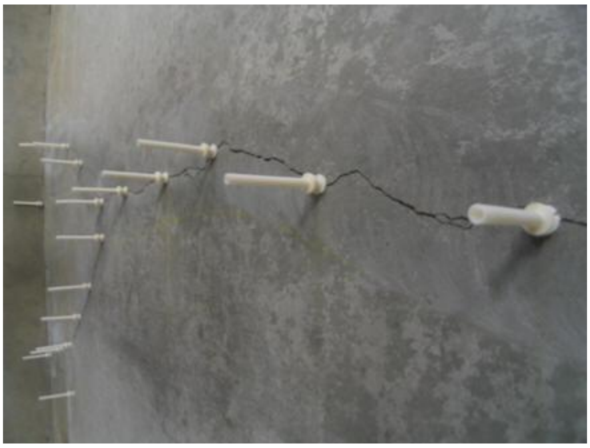


Figure 6: Injection of epoxy resin

4.2. Moderate Damage Limit State

The present state of damage shows cracks greater than that of the previous state, but does not concerned the structural stability of the element. In this state of damage the cracks vary between 0.5 mm and 1 mm of opening. In relation to the repair technique to be used, it is the same that was identified in the previous damage state (epoxy resin injection), for larger cracks, i.e. width up to 0.5 mm

4.3. Extensive Damage Limit State

In the limit state of extensive damages the crack width is, approximately, between 2 to 3 mm, and is visible some concrete spalling. When a pier reaches this state of damage it already requires some attention, and needs to be repaired in a short term in order not to compromise the structural stability. For this reason, it is necessary to proceed with a structural reinforcement of the element. The repair technique for the cracks consists of the injection of epoxy resin, respecting EN 1504-5 [9], as previously mentioned. When the pier has cracks and some spalling, it is necessary to proceed with the reconstruction of the piers. With respect to the structural reinforcement of the element this can be realized in three distinct ways: increase of the section with the use of reinforced concrete; Bonding of metal sheets and Pier engagement with carbon fibre blankets (CFRP).

When the piers have some concrete spalling, it is necessary to replace this same concrete. It is first necessary to remove the damaged concrete, to clean and to perform a surface treatment with a needle hammer. Once the degraded concrete has been cleaned, it is necessary to place a new concrete in compliance with EN 1504-2 [8]. Figure 7 illustrates the concreting process of areas where concrete detachment occurred, [11].

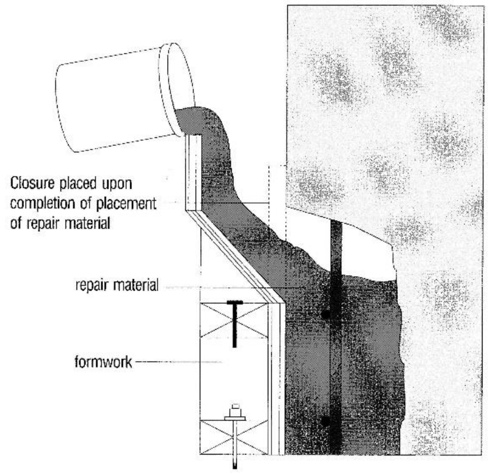


Figure 7: Concreting process of areas with problems of concrete spalling(Kamran, 2006)

Regarding to the structural reinforcement, it is possible to increase the section with the use of reinforced concrete. This increase shall consist of a minimum increment for each side of 50 mm in the case of projected concrete and 70 mm in the case of cast concrete, i.e. it is necessary to increase the cross-section by at least 100 mm. With respect to the steel reinforcement to be added, the longitudinal reinforcement should have a diameter of more than 8 mm and the minimum transverse reinforcement should be ø8 // 0.15 cm. If metal profiles are used, the minimum thicknesses are 40 mm and 60 mm, respectively, for projected concrete and cast concrete. With respect to the metal profiles to be incorporated, the longitudinal sections must be angled with equal flanges with a minimum cross-section of L 50.50.5 mm and cross-sections of a rectangular cross-section with a cross-section of at least 25.4 mm or bars of ø10 // 0.10 Cm. If this type of reinforcement is used, it is necessary to have special attention to the anchorage of the new reinforcement. Figure 8 illustrates the reinforcement technique using reinforced concrete, showing in detail the additional outer reinforcement.

Figure 8: Detail of additional reinforcement in reinforcement technique using reinforced concrete.

The reinforcement using metal profiles is a technique used when there is no alternative to increase the section of the piers. In this type of reinforcement, it is necessary to be careful with the connections to the existing nodes. Figure 9, illustrates the end result of a reinforced column with addition of metal profiles.

Figure 9: Reinforced pier with metal profiles

The last reinforcement technique proposed corresponds to the sectioning with composite materials. This reinforcement technique has the advantage of causing a minimal increase of the section and greatly increasing the strength of the same. This technique consists of bonding carbon fibre blankets using epoxy resins and then finishing them with a self-adhesive mortar. In this type of reinforcement, it is necessary to ensure that the ends are well bonded, which is always more burdensome in the case of slabs and beams. Figure 10 illustrates the result of a CFRP-reinforced piers. All of these glues referred to in the previous reinforcements must comply with EN 1504-4 [10].

Figure 10: Pier reinforced with CFRP

4.4. Collapse Limit Damage State

As previously mentioned, the damage limit state corresponding to the collapse is characterized by a large concrete spalling and in which the theoretical resistance is exceeded. Thus, when a pier reaches this state of damage, it becomes economically impracticable to repair. If the demolition operation is not possible, there is no feasible repair techniques and only structural reinforcement is possible, using the reinforcement techniques described above.

5. ESTIMATION OF REPAIR COSTS AND STRUCTURAL REINFORCEMENT BY TECHNIQUE

This chapter presents the costs associated with each repair and reinforcement technique to be applied to damaged piers. The evolution of the costs of repair per damage states and the relationship between costs of repair / reinforcement and the costs of demolition and construction of a new pier will be presented. It is worth to mention that the unit repair costs associated with each work and technique were quantified under the scope of the PRISE research project and presented in detail for this study in [11]

5.1. Slight Limit Damage State

In this state of damage, the painting works of the surfaces of the columns are included in the estimation of costs, being reflected in the total cost of the technique: the supply, loading, transport, discharge and application. Considering that the entire surface of the pier under study (PO2-N6) will be painted, the cost of painting will be 37.80 €. If it is also necessary to plaster the surface of the piers with an adjunct mortar, the total cost of repair would additionally be 30.24 €. If, on the other hand, it is necessary to scrub the surface application of epoxy resin on the whole surface, the cost of repair using this technique would be 49.14 €.

If the cracks have a minimum opening of 0.5 mm, the epoxy resin injection should be used. Thus, assuming a crack density of 10.12 m / m^2 of surface, this technique will represent a cost of 101.20 €

Table 4 illustrates the repair costs for the limit state of slight damage.

Limit States	Technique	Unit	Unit cost	Amount	Cost
Slight damage	Painting	m^2	10,00 €	3,78	37,80 €
	Plaster	m^2	8,00 €	3,78	30,24 €
	Scrub epoxy resin	m^2	13,00 €	3,78	49,14 €
	Injection of epoxy resin	m/m^2superficie	10,00 €	10,12	101,20 €

Table 4 :Costs of techniques in the state of slight damage

5.2. Moderate Limit Damage State

As previously mentioned, the repair technique to be applied for this level of damage corresponds to the injection of epoxy resin. The unit cost of this technique includes cleaning the surrounding surface, all work and materials. Considering that the crack density is 16.79 m / m2 surface, this technique will cost 167.90 €.

Table 5 illustrates the repair costs for the limit state of moderate damages.

Limit States	Technique	Unit	Unit cost	Amount	Cost
Moderate damage	Injection of epoxy resin	m/m^2superficie	10,00 €	16,79	167,90 €

Table 5 :Costs of techniques in the state of moderate damage

5.3. Extensive Limit Damage State

In this damage state, it is possible to distinguish two types of costs. The first one refers to the superficial repair of the piers and a second that refers to the structural reinforcement. In this state of damage, as previously mentioned, there are cracks and some concrete spalling. The repair technique for cracks is also the injection of epoxy resin. Considering that the crack density is 20.84 m / m2 of surface, this part of the cost will be of 208.47 €. The repair technique for the concrete spalling is the cleaning of the damaged concrete area and the application of a new concrete. The cost of this repair technique includes repairing the piers with application of a mortar, including the removal of degraded concrete, cleaning and surface treatment using needle hammer, supply, placement, materials, equipment and execution. Considering this state of damage, it is expected a detachment of 0.05 m^2 over all surfaces, with a cost of 0.75 €.

About the structural reinforcement of the pier, there are three types of reinforcement. In order to determine the cost it is necessary to design the reinforcement so that the cost of the technique can be directly related to the increase of resistance whatever will be the reinforcement.

If the technique of increasing the section with the use of reinforced concrete is used, the cost will be of 86.80 €. If instead of using this technique, one would use metal sheets, the cost will be of 286.74 €. Lastly, if a reinforcement technique with carbon fibre blankets (CFRP) is applied, the cost will be 172.80 €.

Therefore, the final cost of this state of damage will be the sum of the two repair techniques with the respective reinforcement technique to consider. Thus, if the first repair technique is used, the cost will be 295.96 €, if the technique using metal sheets is used, the cost will be € 495.90, if the last technique is used it will be 381.96 €.

Table 6 illustrates the repair costs in the state of extensive damages.

Limit States	Technique	Unit	Unit cost	Amount	Cost
Extensive damage	Enrollment with BA	ud.	295,96 €	1	295,96 €
	Metallic plates	ud.	495,90 €	1	495,90 €
	CFRP	ud.	381,96 €	1	381,96 €

Table 6 :Costs of techniques in the state of extensive damage

5.4. Limit State of collapse

In this state of damage, the piers are already so degraded that it is economically unfeasible to repair/reinforce it, and the best solution is to replace the piers. Thus, the total cost will reflect the demolition of the pier with the respective sorting in the work itself, recycling of all materials, loading, transport and unloading, all the accessory tasks necessary for the completion of the work, as well as for the cleaning of the place. The construction cost includes the concrete, including the execution of a standard reinforced concrete pier, including the supply, placement, compaction and cure of the concrete. The concrete has waterproofing incorporation; Transport, assembly, decoeing oil and formwork cleaning for plain concrete with smooth surface and shoring. Relative to the steel reinforcement, the cost reflects the supply, placement, loading and unloading, wastes and splices and elements of reinforcement assembly and all work, materials and execution. Unit prices for the construction of the new pier were taken from Top Informática generator price [12]. Thus, the replacement cost of the pier will be 454.69 €.

Table 7 illustrates repair costs in the collision damage state.

Limit States	Technique	Unit	Unit cost	Amount	Cost
Collapse damage	Demolition and construction of a pillar	ud.	454,69 €	1	454,69 €

Table 7 :Costs of techniques in the state of collapse damage

5.5. Evolution of structural intervention costs

After analysing the costs of each structural repair and reinforcement technique, it is necessary to understand how the cost evolution occurs as a function of the structural response, considering in this case the drift as a response parameter. Thus, it will be possible to quantify the economic weight of each state limit for the repair or reinforcement of the piers. This information is shown in Figure 11.

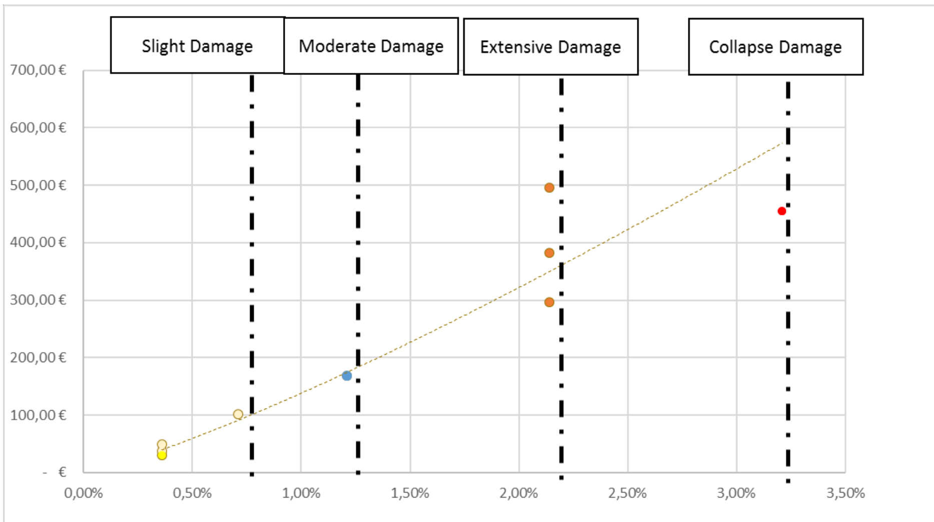


Figure 11: Evolution of repair and reinforcement costs due to drift

The previous figure tries to represent the costs disaggregated by technique of repair or reinforcement, for each limit state of damage. Analysing this information, we can estimate the evolution of repair costs along the increase of damages in the column. It should be noted that the costs in the state of slight damage are very clustered and in the state of extensive damage greatly dispersed. The evolution of costs by the different states of damage is translated by the expression (1) (coefficient of determination R2 = 0.96).

$$y = 38200x^{1.2209} \tag{1}$$

To better identify the impact of each boundary state on the cost of repair and to verify its economic viability, it was chosen to represent the same evolution in terms of the repair cost ratio by the replacement cost of the pier, illustrating this in Figure 12. Table 8 shows the cost of each technique as well as the ratio previously described.

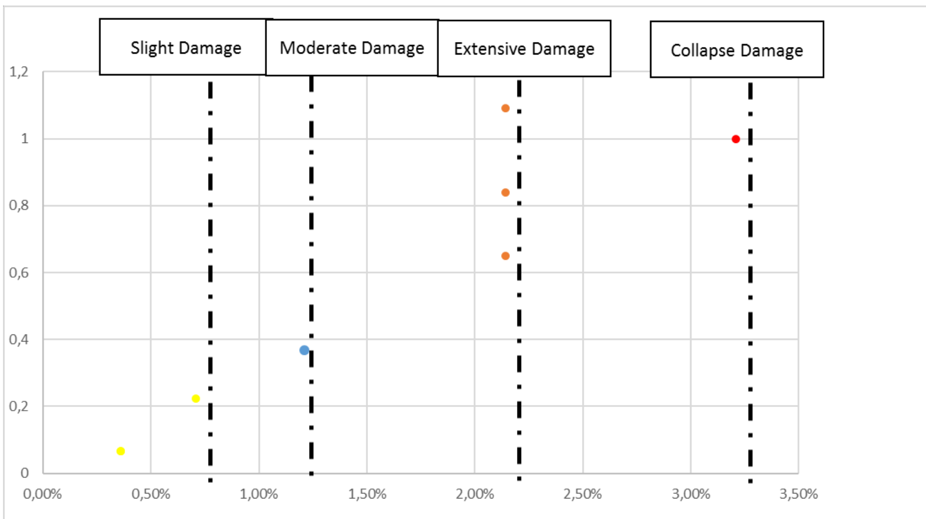


Figure 12: Ratio price Repair / price new pier vs drift

Limit States	Repair / reinforcement technique	*Drift*	Price	Ratio
Slight damage	Painting	0,36%	37,80 €	0,08
	Plaster	0,36%	30,24 €	0,07
	Scrub epoxy resin	0,36%	49,14 €	0,11
	Injection of epoxy resin	0,71%	101,20 €	0,22
Moderate damage	Injection of epoxy resin	1,21%	167,90 €	0,37
Extensive damage	Enrollment with BA	2,14%	295,96 €	0,65
	Metallic plates	2,14%	495,90 €	1,09
	CFRP	2,14%	381,96 €	0,84
Collapse damage	Demolition and construction of a pier	3,21%	454,69 €	1,00

Table 8 :Cost and ratio of each reinforcement / repair technique

Analysing the ratio of all repair techniques and structural reinforcement, it can be verified that there is a constant and increasing evolution between the different damage states. However, a large difference in the ratio between the moderate and extensive damage status is noted. This is due to the state of extensive damage requiring reinforcement, which greatly influences the final cost of the technique.

Figure 13 shows the evolution of the drift ratio for each repair / reinforcement technique. The evolution of cost, as previously shown, increases and it is possible to adjust a potential function to this trend.

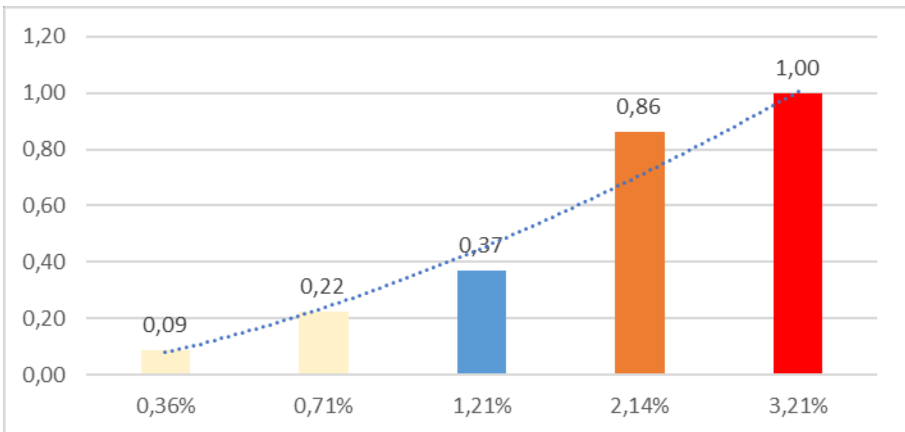


Figure 13: Evolution of the ratio per the limit drift of the repair techniques

As shown in the previous figure, the quality of the adjustment is high (coefficient of determination of R2 = 0.98), which makes this continuous cost transfer function an important indicator for any estimate of costs in hollow piers of reinforced concrete. Additionally, it allows to evaluate the impact and efficiency of each repair or reinforcement technique.

$$y = 0.0799x^{1.5738} \quad (2)$$

6. CONCLUSIONS

In the present study, the evolution of structural damage in hollow reinforced concrete piers (whose behaviour is also representative of reinforced concrete walls) due to the action of earthquakes, with the purpose of defining limit states of damage, is based on a previous study of the authors of this study Delgado *et al.* [4]. This information was associated with repair and reinforcement techniques, which are commonly applied in Portugal. Finally, the respective costs were estimated, which allowed to characterize the evolution of the costs of repair and reinforcement of the piers as a function of the structural response. This work uses the construction techniques and their unit costs established under the PRISE project.

In this way, it was possible to observe the trend of increasing evolution of the type of structural damage (quantified by the drift response parameter), and limit state, with the cost of repair estimated for the proposed techniques. At the same time, it was identified that this evolution of the cost is potential, being translated by equation (1).

The evolution of the ratio repair cost (or reinforcement) by replacement cost of the pier allowed to conclude on the feasibility of introducing a specific repair technique. Through this evolution, which can be translated by a potential curve, equation (2), we can also conclude that between the state of moderate and extensive damage there is a great gap, which greatly increases the cost. It should be noted that in this study indirect costs were neglected, and if they were considered the costs would be much higher.

Thus, the present study intends to be a starting point for a more detailed analysis of a benefit-cost study for structural intervention in hollow reinforced concrete piers, and may be equally important for analyses of seismic risk at the structure level or at a regional scale (portfolio analysis).

7. ACKNOWLEDGMENTS

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