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ASSESSMENT OF RC HOLLOW-PIERS FOR SEISMIC LIMIT STATE OF DAMAGE - DIRECT REPAIR COSTS

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Abstract

Due to the vulnerability of reinforced concrete hollow piers subjected to seismic actions, it becomes urgent to assess the expected shear damage and its evolution with the increase of the intensity level. Additionally, the focus of the scientific research dedicated to seismic behaviour of these elements is still reduced, in particular with regard to the limit states of damage and 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.

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 behaviour. It also intends to discuss adequate strengthening strategies and their direct costs, associated with each seismic physical limit state of damage. An extensive review of numerous cyclic experimental works on RC hollow piers will be performed, and in liaise with specialized construction companies, the direct repair costs will be estimated.

Keywords: Repair cost; Shear limit state damage, RC hollow-piers, Non-linear cyclic behavior.

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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].

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.

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] and Figure 1 illustrate the reinforcement details. An axial load of 250 kN was considered, that corresponds to a normalized axial force of 0.08.

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.

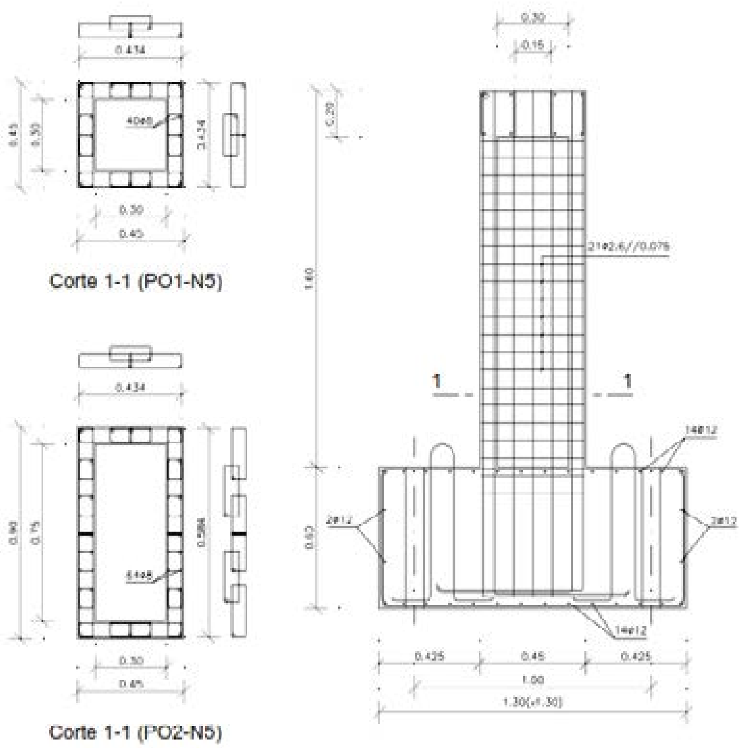

Figure 1: Piers PO1-N5 and PO2-N5 reinforcement details [1].

2. LIMIT STATES OF SEISMIC DAMAGE

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 2 illustrates the evolution of damage, in the various limit states of damage.

a) b) c) d)

Figure 2: 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. Table 2 translates the drift limit values associated with each physical damage state.

Limit State	*Drift* (%)
Slight	0.6
Moderate	1.3
Extensive	2.0
Collapse	3.0

Table 2 :Limit states and corresponding drift value.

3. SEISMIC REHABILITATION TECHNIQUES

Currently, there are several techniques for the repair and strengthening of structures, with the aim to ensure the replacement or improving of seismic behaviour and capacity. 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. In this study, the costs of the access to the pier to be repaired and other works, were considered.

3.1. Slight Damage

This limit state is characterized by minor or irrelevant, and almost imperceptible visualized damages, with 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].

3.2. Moderate Damage

The state of moderate damage is characterized by small cracks in the abutment faces, corresponding to an opening between 0.5mm and 1.0mm. Structural stability is not compromised, and any type of structural intervention is unnecessary. To repair crack openings, the most appropriate repair technique is the injection of epoxy resin, which must comply with EN 1504-5 [9], regarding injections in reinforced concrete structures

3.3. Extensive Damage

In the limit state of extensive damages the crack width is, approximately, between 2mm 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].

One of the most used strengthening techniques is the jacketing with carbon fibre blankets (CFRP). This technique has the advantage of causing a minimal increase of the section and greatly increasing the strength. This technique consists of bonding carbon fibre blankets using epoxy resins and then finishing with a self-adhesive mortar. In this type of strengthening, it is necessary to ensure that the ends are well bonded. Figure 3 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 3: Pier reinforced with CFRP.

3.4. Collapse

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.

4. DIRECT REPAIR COSTS ESTIMATION

After identifying the unit costs associated with the tasks and resources required for each rehabilitation and strengthening technique of the piers, the evolution of the cost according to the response of the structural element was quantified. The pier behavior develops according to its material and geometric characteristics, and the level of seismic action. The drift was considered as the response parameter, thus allowing to estimate the cost of piers rehabilitation for each seismic damage limit state [7]. The quality of the cost estimate for repair or strengthening is very important in the identification of the technique to be adopted. In the case of rehabilitation works, construction presents several sources of uncertainty, due, for example, to the difficulty in performing some of the tasks, making it difficult to quantify the necessary resources, such as man cost and equipment needed in the intervention. However, in this work an estimate of the average costs of the pier rehabilitation was carried out according to its damage limit state and separating the cost by type of work to be carried out, that is, the cost of materials, the cost of labor and cost of access to the pier area to be repaired and other additional works.

4.1. Slight Damage

For the limit state of slight damage, if the cracks have openings less than 0.5mm, the cracked surface must be repaired, corresponding to the pier bottom, in this case approximately equal to the dimension of the cross section. Table 3 illustrates the separation of repair costs according to the type of work to be carried out.

	Average Cost (€)
Material	77
Labors	49
Accessibility and other works	21
Total	154

Table 3 :Pier repair costs for limit state of slight damage.

4.2. Moderate Damage

For the limit state of moderate damage with cracks between 0.5mm and 1mm, the injection of epoxy resin should be used. In this case, about 2/3 of the pier surface is cracked, including the repair costs associated with each task in Table 4.

	Average Cost (€)
Material	112
Labors	98
Accessibility and other works	49
Total	259

Table 4 :Pier repair costs for limit state of moderate damage.

4.3. Extensive Damage

The limit state of extensive damage is characterized by the deteriorating of the state of the structure, with the appearance of large cracks, with openings that can vary between 1 mm and 3 mm, distributed on all sides of the pier, and it is also possible to verify the spalling of the concrete cover. When the pier reaches this state of damage, the surface treatment is not sufficient to guarantee the necessary minimum requirements, thus it is necessary to proceed with a structural reinforcement of the element. Table 5 represents the different costs by type for repair, taking into account an average estimate of the three structural reinforcement techniques namely: increase in section with reinforced concrete, reinforcement with the addition of metallic profiles and reinforcement with carbon fiber blankets (CFRP).

	Average Cost (€)
Material	245
Labors	252
Accessibility and other works	105
Total	602

Table 5 :Pier repair costs for limit state of extensive damage.

4.4. Collapse

Finally, for the limit state of collapse, which is characterized by a large detachment of the covering concrete, its repair is economically unfeasible. Thus, the demolition and construction of a new pier corresponds to the work to be applied in this case. The total cost will reflect all the demolition work on the pier, involving the recycling of all materials, loading, transport and unloading, as well as the auxiliary tasks necessary for cleaning the site. The cost of building a new pier includes the execution of an identical reinforced concrete pier, including the supply, placement, compaction and curing of the concrete. The total price for demolition and construction of this reinforced concrete pier is around € 699. Table 6 shows the costs separated according to the type of work to be carried out. Unit costs were estimated and validated through contact with specialized construction companies.

	Average Cost (€)
Material	209
Labors	280
Accessibility and other works	210
Total	699

Table 6 :Pier repair costs for limit state of collapse.

4.5. Evolution of structural intervention costs

After analysing the costs of each structural repair and strengthening 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 strengthening of the piers.

In order to make this analysis more global, it was adopted to represent the evolution of the ratio between the cost of repair and the cost of replacing the pier as a function of the drift, as illustrated in Figure 4, for each Limit State of Damage (LSD). This transfer evolution of damage into costs, provides an important indicator for any cost estimate in hollow section reinforced concrete piers. Additionally, it also allows to assess the impact and efficiency of each repair or strengthening technique. Figure 4 reveals that the repair costs associated with the extensive and collapse damage levels mean that the repair of the structural element is not viable. However, even in the case of slight and moderate damages the respective costs are already quite significant.

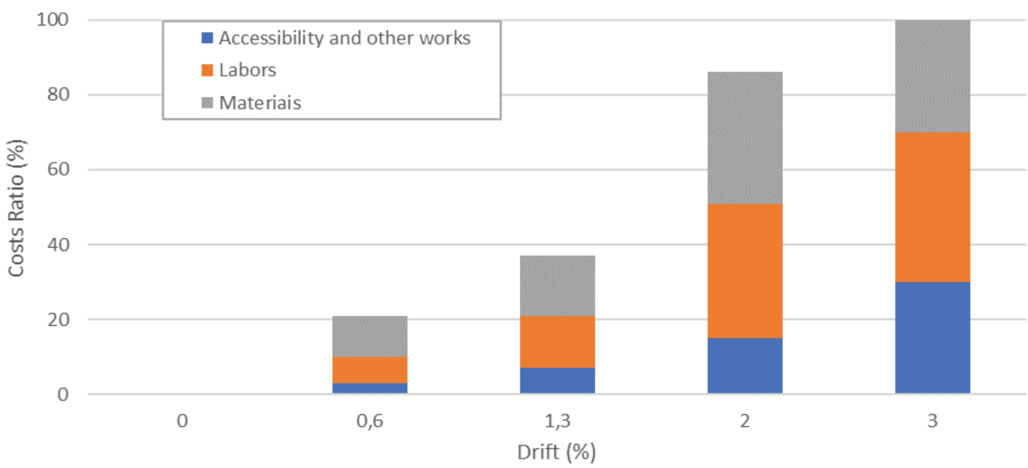

Figure 4: Evolution of the repair cost ratio (%) for each LSD/drift.

In the case of this study, for structures that suffered from the impact of an earthquake and therefore in need of rehabilitation, factors such as the type, size of the bridge and how it will be made accessible must be taken into account. The places where structures are found that are damaged by earthquakes are usually difficult to access, and the debris on the site and the size of the structure contribute to a considerable increase in the budget. The piers previously studied are usually implemented in different types of bridges, with different dimensions and which, in terms of accessibility, can vary between easy access, moderately difficult access and difficult access.

5. 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 (LSD), is based on a previous study of the authors of this study Delgado *et al.* [4]. This information was associated with repair and strengthening techniques, which are commonly applied in Portugal. Finally, the respective costs were estimated, which allowed to characterize the evolution of the costs of piers repair and strengthening as a function of the structural response. This work uses the construction techniques and their unit costs established under the PRISE project.

In this study, it was intended to obtain a methodology that is capable of predicting an assessment of the damage to the different piers, and the cost estimation of piers repair and strengthening, allowing to assess, in a simplified way, the cost estimate of the piers rehabilitation with insufficient shear capacity for each limit state of seismic damage. The proposed methodology allows to conclude that the repair of hollow reinforced concrete piers has significant costs even for moderate damage, and the replacement costs for collapse and extensive damage are practically identical. Thus, both from the point of view of costs and seismic safety, this study identifies the urgency of verifying the shear capacity of bridge piers and, in case it is insufficient, proceed to strengthening it in order to avoid the most severe LSD or collapse.

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REFERENCES

[1] Delgado, R., Delgado, P., Vila Pouca, N., Arêde, A., Rocha, P., Costa, A. Shear effects on hollow section piers under seismic actions: experimental and numerical analysis, *Bulletin of Earthquake Engineering,* **7**, 377-389, 2009. (DOI: 10.1007/s10518-008-9098-x).

[2] Delgado, P., Monteiro, A., Arêde, A., Vila Pouca, N., Delgado R., & Costa, A. Numerical Simulations of RC Hollow Piers Under Horizontal Cyclic Loading. Journal of Earthquake Engineering, 15:6, 833-849, 2011.

[3] Delgado, P., Arêde, A., Vila Pouca, N., Rocha, P., Costa, A., Delgado, R. Retrofit of RC Hollow Piers with CFRP Sheets, *Composite Structures,* **94**, 1280–1287, doi:10.1016/j.compstruct.2011.11.032, 2012.

[4] Delgado, P., Sá, N., Marques, M. & Arêde, A., Methodology for the characterization of seismic limit states of damage in RC hollow piers experiment. 16WCEE – *16th Conference on Earthquake,* Chile, 9-13 January, 2017.

[5] Rodrigues, H., Arêde, A., Varum, H. & Costa, A., Damage evolution in reinforced concrete columns subjected to biaxial loading. *Bull Earthquake Eng*, pp. 1517-1540, 2013.

[6] FEMA, HAZUS MR4. Washington DC: National Institute of Building Sciences, 2003.

[7] PRISE, "Avaliação de Perdas e Risco Sísmico dos Edifícios em Portugal", projeto financiado pela Fundação para a Ciência e a Tecnologia, 2013-2015 (http://prise.fe.up.pt)

[8] CEN, NP EN 1504-2. Produtos e sistemas para a protecção e reparação de estruturas de betão - Definições, requisitos, controlo da qualidade e avaliação da conformidade. Parte 2: Sistemas de proteção superficial do betão. Brussels: European Standard, 2006.

[9] CEN, NP EN 1504-5. Produtos e sistemas para a protecção e reparação de estruturas de betão - Definições, requisitos, controlo da qualidade e avaliação da conformidade. Parte 5: Injeção do betão. Brussels: European Standard, 2006.

[10] CEN, NP EN 1504-4. Produtos e sistemas para a protecção e reparação de estruturas de betão - Definições, requisitos, controlo da qualidade e avaliação da conformidade. Parte 4: Colagem estrutural. Brussels: European Standard, 2006.