Physical vulnerability characterization of CFRP retrofitted RC buildings to support seismic risk mitigation policies

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ABSTRACT

Seismic risk mitigation policies are a crucial step in the risk management of countries, such as those located in southern Europe. For this reason, the risk reduction measures associated to structural strengthening and retrofitting should be based on cost-benefit analysis of regional building stocks. This requires a full characterization of the seismic vulnerability of building classes before and after retrofitting.

Past research studies mainly focused on the characterization of the physical vulnerability of existing reinforced concrete buildings. However, further investigation is needed concerning the evaluation of the vulnerability of retrofitted buildings. This paper reports on the characterization of the vulnerability of classes of reinforced concrete buildings, representative of the building stock found in Portugal, before and after retrofitting. The characterization of the selected building cases was performed through a computational framework developed at the University of Porto, which is based on simulated design and accounts for multiples sources of uncertainty, such as building-to-building variability and other parameters (year of construction, structural layout, number of storeys, etc). The framework also models the building structures in OpenSees, which allowed the conduction of nonlinear static analysis needed to evaluate and design the strengthening solution, as recommended in Part 3 of Eurocode 8. The results indicate that strengthening solutions using carbon fibre reinforced polymers (CFRP) satisfy the code requirements, although they do not limit the global structure deformation neither change the global mechanism expected to occur.

Keywords: retrofitted RC buildings, CFRP, building classes characterization, strengthening solutions

INTRODUCTION

Past research studies mainly focused on the characterization of the physical vulnerability of existing reinforced concrete buildings (Simões et al., 2014; Masi & Vona, 2012; Silva, 2013). However further investigation is needed concerning the seismic design and performance assessment of retrofitted buildings, such as design methodologies, and modelling approaches that accurately account the enhancement of the selected retrofitting solution and, more importantly, the characterization of the physical vulnerability of the retrofitted buildings.

The study presented herein focused on the characterization of vulnerability of reinforced concrete buildings classes, representative of the building stock found in Portugal, before and after the retrofitting.

The definition of the building set for a given building class is carried out through a computational framework developed at the University of Porto (Romão et al., 2019) which is based on simulated design and accounts for multiples sources of uncertainty, including building-to-building variability and the consideration of other different parameters such as the number of storeys, structural layout, year of construction and structural characteristics (reinforcement detailing and ratios, the presence of infills, etc.). This framework automatically generates and designs buildings with different geometric and material properties complying with different seismic design criteria.

The framework also models the buildings in Opensees (McKenna et al., 2007), which allows performing nonlinear static analysis of the building classes that are used for the seismic assessment and eventual strengthening of the structures, as recommended in Part 3 of Eurocode 8 (CEN, 2005).

This paper describes the methodology implemented in the framework that extends its features to the development of new classes of retrofitted buildings based on the application of carbon fibre reinforced polymers (CFRP).

DESIGN AND ASSESSMENT METHODOLOGY OF STRENGTHENING SOLUTIONS

The design and assessment methodology proposed in this study follows the recommendations of EC8-3 (CEN, 2005) and is applied specifically for elements retrofitted with carbon fibre reinforced polymers (CFRP). The selection of this type of strengthening solution is related with the fact that it is a less intrusive and effective solution when a global intervention is not applicable.

The methodology consists of the following steps:

Step 1. Evaluation of the capacity of the original building structure
For each building of the selected class a nonlinear static analysis is performed.

Step 2. Calculation of the performance point

Calculation of the performance point using the N2 method or the extended N2 method (Dolšek & Fajfar, 2005), depending on the type of pushover curve obtained. If the pushover curve has a bilinear elasto-plastic form, it is recommended the application of the N2 method. Otherwise, if the pushover curve has a multilinear elastic-plastic form with residual strength, as commonly observed in framed structures with unreinforced masonry infills, the use of the Extended N2 is recommended (D'Ayala et al., 2014).

Step 3. Seismic safety assessment of the original building structure

Seismic safety assessment for all structural elements according to EC8-3, i.e., calculation of the demand/capacity ratio of the members to identify the ductile and brittle mechanisms. The chord rotation is employed for the ductile mechanism, as indicated in section §A.3.2.2 of EC8-3 (Equation (1)) and the shear strength for the brittle mechanism, as detailed in section §A.3.3.1 of EC8-3 (Equation (2). The EC8-3 conditions must be verified in both directions. If the demand/capacity ratio is greater than unity, the elements do not comply with safety and hence need to be strengthened. Simplifications regarding the evaluation of the demand and capacity were made as suggested by (Romão X., 2010).

$$\theta_{um} = \frac{1}{\gamma_{el}} 0.016(0.3^{\nu}) \left[\frac{\max(0.01;\omega')}{\max(0.01;\omega)} f_c\right]^{0.225} \left(min\left(9;\frac{L_V}{h}\right)\right)^{0.35} 25^{\left(\alpha\rho_{sx}\frac{f_{yw}}{f_c}\right)} (1.25^{100\rho_d}) \tag{1}$$

$$V_R = \frac{1}{\gamma_{el}}\left[\frac{h-x}{2L_V} min(N;0.55A_c f_c) + \left(1-0.05min\left(5;\mu_\Delta^{pl}\right)\right) \cdot \left[0.16max(0.5;100\rho_{tot})\left(1-0.16min\left(5;\frac{L_V}{h}\right)\right)\sqrt{f_c}A_c + V_w\right]\right] \tag{2}$$

$$V_{w,f} = \rho_w b_w z f_{yw} \tag{3}$$

where θ_{um} is the ultimate chord rotation capacity; γ_{el} is the safety factor, ν is the axial load ratio;, ω' and ω are the compression and tension longitudinal reinforcement, respectively; f_c is the concrete strength; L_V is shear span; h is the section hight; α is the confinement effectiveness factor; ρ_{sx} and f_{yw} are the transversal steel reinforcement ratio and strength, respectively; ρ_d is the steel ratio of diagonal reinforcement (if any); $V_R$is the shear strength capacity; x is the compression zone depth; N is the axial load; $A_c$is the cross section area; μ_Δ^{pl} is the displacement ductility; $\rho_{tot}$is the total longitudinal reinforcement ratio; V_w is the contribution of shear reinforcement to shear resistance, b_w is the web width and z is the length of the internal lever arm.

4. Design of the CFRP strengthening solution

For the elements that need to be retrofitted, the number of layers of CFRP is determined according to deformation and shear capacities requirements, according to clauses §A.4.4.3 and §A.4.4.2 of EC8-3, respectively. Equation (4) illustrates the CFRP contribution to the rotation capacity (§A.4.4.3(6)), expressed by $\alpha\rho_f \frac{f_{f,e}}{f_c}$, whilst Equation (5) shows the shear enhancement that the carbon fibres provide through the inclusion of the term $V_{w,f}$ (§A.4.4.2(9)), which is given by Equation (6).

$$\theta_{um} = \frac{1}{\gamma_{el}} 0.016(0.3^{\nu}) \left[\frac{\max(0.01;\omega')}{\max(0.01;\omega')} f_c\right]^{0.225} \left(min\left(9;\frac{L_V}{h}\right)\right)^{0.35} 25^{\left(\alpha\rho_{sx}\frac{f_{yw}}{f_c}+\alpha\rho_f\frac{f_{f,e}}{f_c}\right)}(1.25^{100\rho_d}) \quad (4)$$

$$V_R = \frac{1}{\gamma_{el}}\left[\frac{h-x}{2L_V} min(N; 0.55A_c f_c) + \left(1 - 0.05min\left(5;\mu_\Delta^{pl}\right)\right) \cdot \left[0.16max(0.5;100\rho_{tot})\left(1-0.16min\left(5;\frac{L_V}{h}\right)\right)\sqrt{f_c}A_c + V_w\right]\right] + V_{w,f} \quad (5)$$

$$V_{w,f} = 0.5\rho_f b_w z f_{u,fd} \quad (6)$$

The variables ρ_f, $f_{f,e}$, $f_{u,fd}$ are, respectively, the CFRP geometric ratio, the effective CFRP stress and the design value of CFRP ultimate strength.

5. Evaluation of the capacity of the retrofitted building structure

Evaluation of the retrofitted building structure's capacity through the performance of nonlinear static analysis on a modified model that takes into consideration the retrofitting intervention with CFRP. The modelling approach used to simulate the behaviour of the elements strengthened with CFRP is the one proposed by Sousa et al. (2022), developed for lumped plasticity models. This proposal follows the moment-rotation trilinear relationship, with peak (θ_{peak}) and post-capping (θ_{pc}) rotation capacities including the contribution of the CFRP. The relationship between the maximum moment (M_{max}) and the yield moment (M_y) is taken equal to 1.19. The shear enhancement due to CFRP was not incorporated into the lumped plasticity model.

6. Seismic safety assessment of the retrofitted building structure

Seismic safety assessment of the retrofitted elements as recommended in clauses §A.4.4.3 and §A.4.4.2 of EC8-3 and described in Step 4. If the demand/capacity ratio of the retrofitted members is greater than unity, the number of CFRP layers needs to be increased. The design and assessment of efficiency of the CFRP solution is, therefore, an iterative process.

APPLICATION OF THE METHOLOGY TO A RC BUILDING CLASS

Description of the selected buildings

This section describes the buildings generated by the framework. The framework performs the generation and design of multiple buildings, considering several parameters such as the number of storeys, the layout, year of construction, reinforcement detailing, among others. This framework serves the purpose of assessing the seismic safety of several structures from different building classes and, after that, conducts the modelling and evaluation of the retrofitted structures.

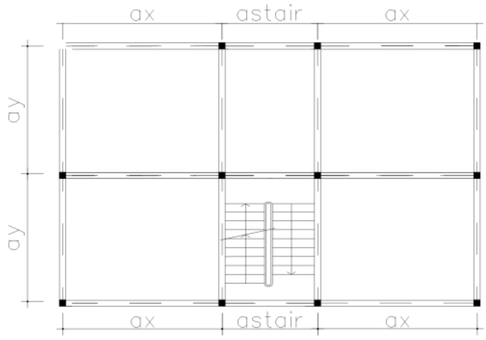


Figure 1. *Layout of the generated buildings*

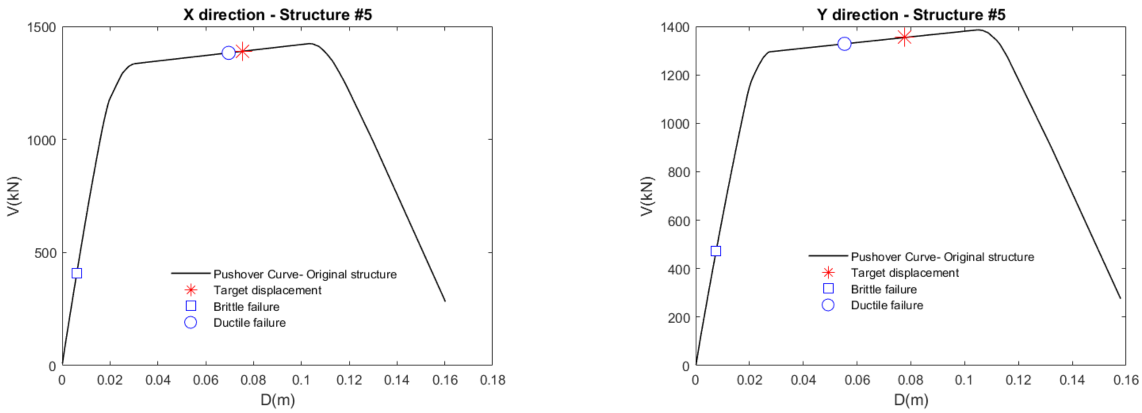
In this study, 20 buildings were generated, complying with the first Portuguese seismic standards (RSCCS, 1958), considering a seismic coefficient of 0.1 for structures located in *Zone A* (south and southeast of Portugal, including Lisbon). These structures have four storeys with variable floor heights and the layout shown in Figure 1. The buildings have masonry infills along the height except for the first story, a characteristic of the buildings located in the Alvalade and Benfica areas of Lisbon.

Seismic performance assessment (before and after strengthening intervention)

As mentioned previously, the design and modelling of the buildings was conducted with the framework. The details about the framework development can be found in (Romão et al., 2019). This study refers only to the implementation and description of the methodology applied to design, model and evaluate the CFRP strengthening solutions in the framework.

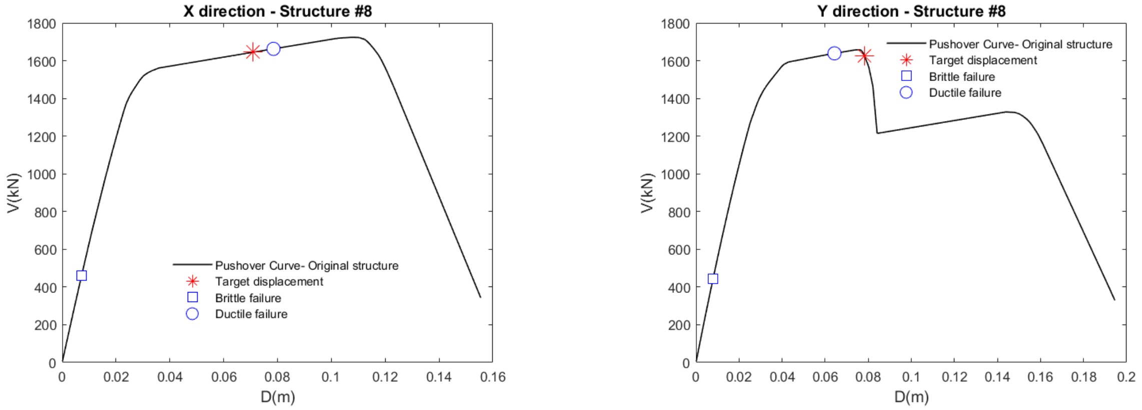
Figures 2, 3 and 4 show the application of Step 1 (evaluation of the capacity of the original building structure), Step 2 (calculation of the target displacement) and Step 3 (Seismic safety assessment of the original building structure) for three structures, namely structures 5, 8 and 14. The figure's circle and square points indicate, respectively, the occurrence of the first column ductile and brittle failure mechanisms.

The seismic evaluation was performed for Type 1 seismic action, for an a_{gR} equal to 2 m^2/s (Faro, Zone 1.2) and a type D soil. The target displacement was calculated using the N2 method or the extended N2 method, as recommend by (D'Ayala et al., 2014). For each structural element, the chord rotation and shear demand were compared with the capacity values of chord rotation and shear strength. According to the Portuguese Annex of EC8-3 (CEN, 2005), for existing residential buildings only the Significant Damage (SD) limit state needs to be verified.



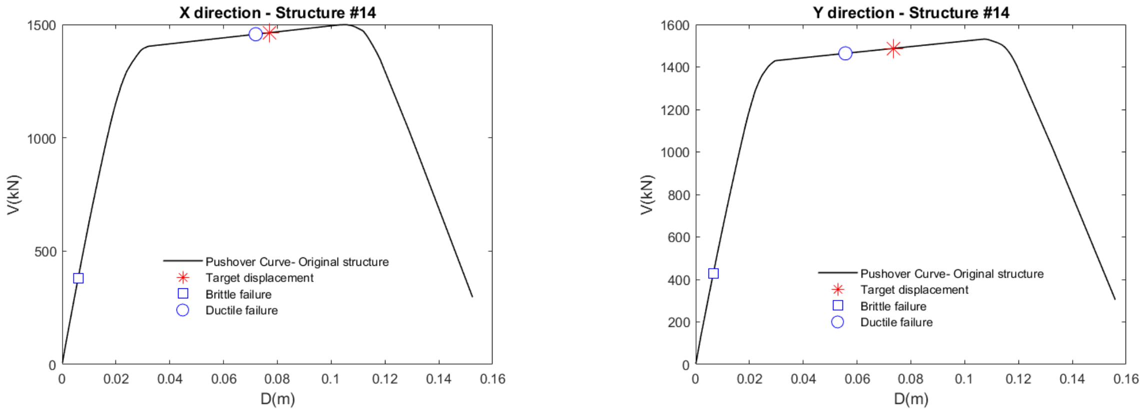
a) b)

Figure 2. Pushover curves of the original structure #5 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms



a) ***b)***

Figure 3. Pushover curves of the original structure #8 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms



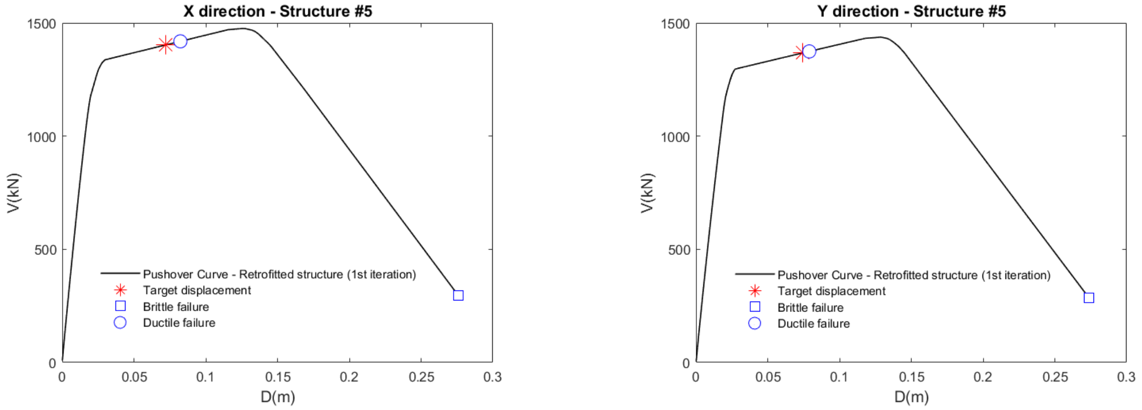
a) ***b)***

Figure 4. Pushover curves of the original structure #14 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms

The outcome of the analysis of these three structures is representative of the behaviour response observed for the group of twenty structures. In all structures' columns brittle and ductile failures occur before the target displacement is reached, indicating the need of strengthening for flexural and shear resistance. Additionally, it is observed that the brittle mechanisms occur for early stages of lateral deformation, being the governing mechanism in both directions.

Figures 5, 6 and 7 illustrate the capacity curves of the retrofitted structures (structures 5,8 and 14) using CFRP as the strengthening solution, as well as the indication of target displacement and failure (brittle and ductile) mechanisms.

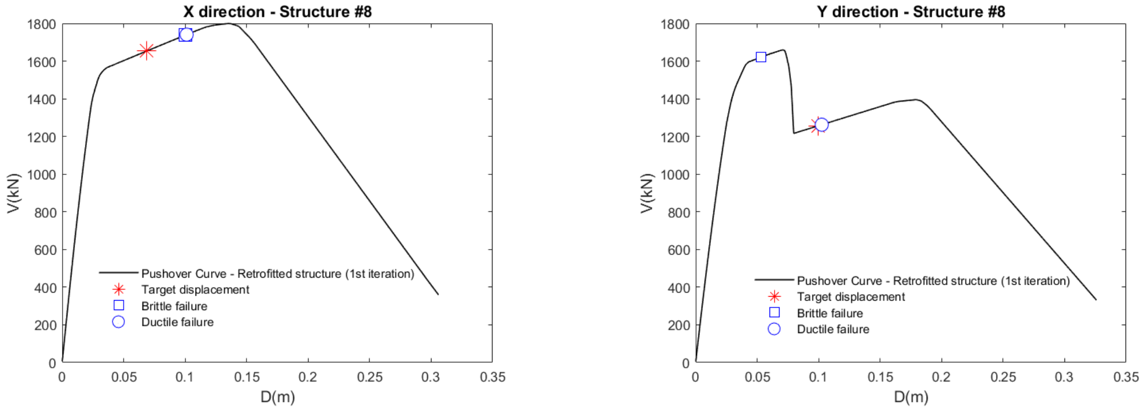
The initial seismic assessment indicated the need for improvement of some columns' flexural and shear capacities. As stated before, the retrofitting strategy selected consisted of applying CFRP to the elements that required enhancement. The design of the CFRP solution was based on increasing the chord rotation and shear capacities in order to satisfy the demand values obtained at the instant that the target displacement occurs. Following the selection of the CFRP, the number of layers was determined, as indicated in Step 4. Then, the numerical model is updated based on the strengthening solution, new pushover curves are generated, and a new assessment is performed (Step 5). If the new seismic assessment complies with the safety criteria, the process is finalized (Step 6). Otherwise, a new CFRP solution needs to be considered and the procedure is repeated. To improve the existing solution, the number of layers may be increased or the CFRP may be upgraded. This results in an iterative procedure.



a) *b)*

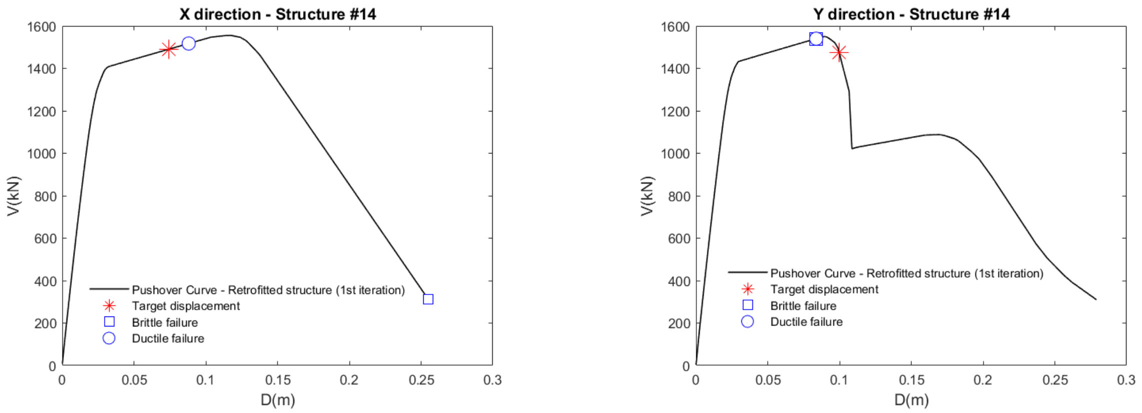
Figure 5. Pushover curves of the retrofitted structure #1 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms (1st iteration)

As it can be seen, the strengthening solution initially adopted for Structure 5 (Figure 5) was enough to address both shear and chord rotation demand requirements in both loading directions. This solution consisted of 2 layers of CFRP for all the ground floor columns, 1 layer in 1st and 2nd floor of the stair columns and 1 layer for the middle frame columns, in X direction, at 1st floor.



a) *b)*

Figure 6. Pushover curves of the retrofitted structure #8 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms (1st iteration)



a) *b)*

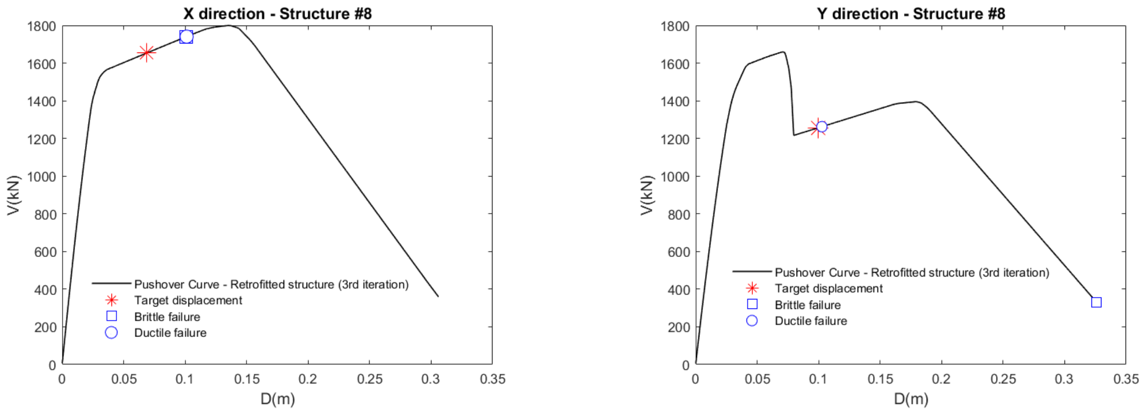
Figure 7. Pushover curves of the retrofitted structure #14 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms (1st iteration)

Regarding structures 8 and 14 (Figures 6 and 7), the initial strengthening solution also worked well in the X direction, satisfying both shear and chord rotation demands. Nevertheless, it was insufficient for the Y direction. The CFRP solution for Structure 8 (3 layers in all ground floor columns and 1 layer in all 1st floor columns) did not satisfy shear demands in the internal columns at the ground floor.

The initial strengthening solution for Structure 14 (2 layers in all ground floor columns, 1 layer in all 1st floor columns, except corner columns, and l layer in 2nd floor external stair columns) did not satisfy the chord rotation demand in the external stair columns at ground floor and shear demand in several columns at ground and 1st floors.

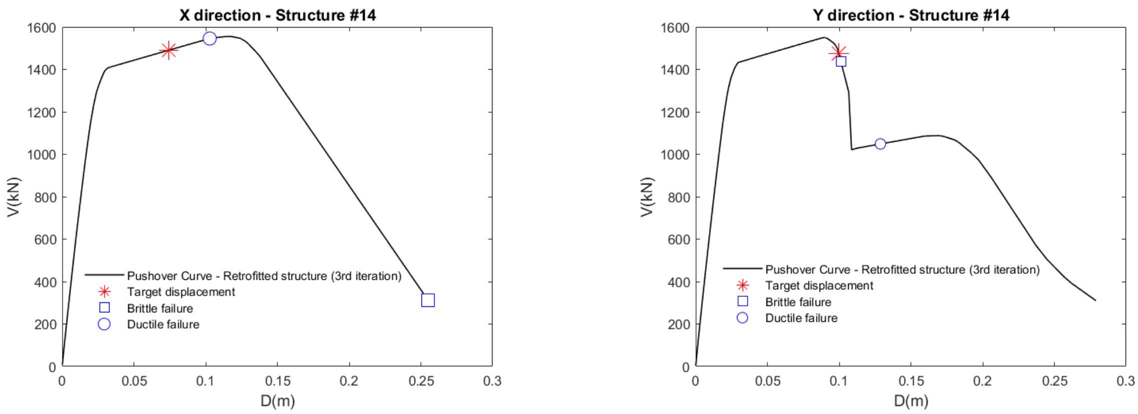
After the first assessment of the group of retrofitted structures, it was observed that, besides structures 8 and 14, structures 1, 4, 7, 12, 15, 19 and 20 still required strengthening. For these structures, the structural elements (columns) were identified and strengthened with more 1 or 2 layers of the selected CFRP. Afterwards, the modelling of these elements with CFRP was implemented in the OpenSees model, following the approach proposed by Sousa et al. (2022) and the safety checks were repeated. With exception of Structures 7, 8, 14 and 20, all structures satisfied their seismic demands after the 2nd iteration. Structures 8 and 14 needed 3 iterations (Figures 8 and 9) to satisfy the seismic safety checks, while for structures 7 and 20, the type of CFRP was upgraded.

The characteristics of the CFRP selected to improve all the structures, except structures 7 and 20, are: i) tensile strength of 3500MPa; ii) tensile modulus of 225GPa; iii) tensile elongation of 1.56% and iv) nominal ply thickness of 0.167mm. The radius of the corners of the confined section with CFRP is 0.04m.



a) ***b)***

Figure 8. Pushover curves of the retrofitted structure #8 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms (3rd iteration)



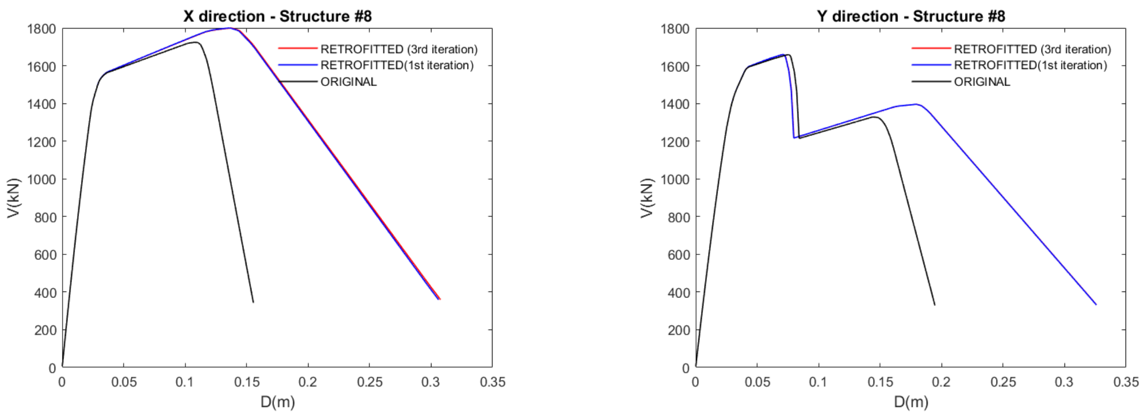
a) ***b)***

Figure 9. Pushover curves of the retrofitted structure #14 for: a) X and b) Y directions with the indication of the target displacement and failure mechanisms (3rd iteration)

Concerning Structures 8 and 14, the final strengthening solution consisted of the following:

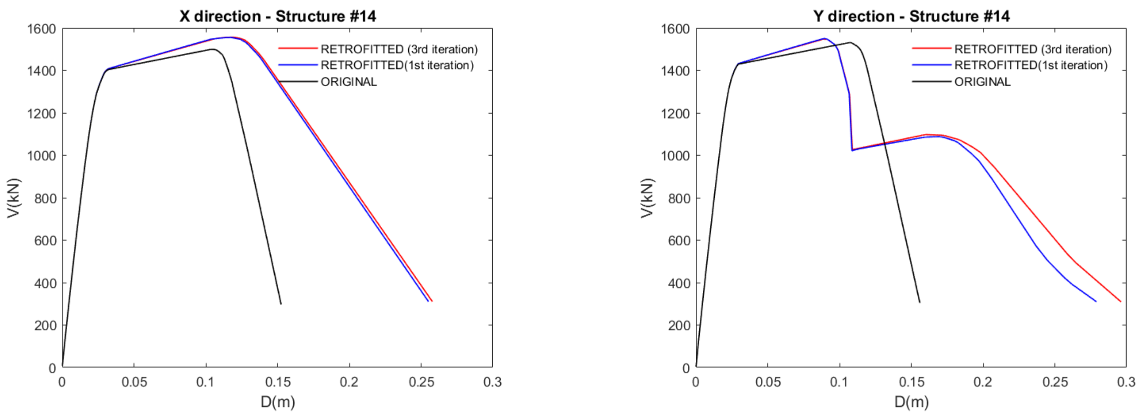
- Structure 8- 3 layers in all ground floor columns, except for internal stair columns that need 4 layers; 1 layer in all columns at 1st ground floor and 1 layer for internal stair columns at 2nd floor.
- Structure 14- 2 layers in all ground floor columns, except for internal stair columns and 2 corner columns that need 3 layers, 1 layer in all 1st floor columns, except 2 corner columns.

Figures 10 and 11 show the pushover curves comparison before and after retrofitting with the first and third CFRP strengthening solutions (1st and 3rd iterations) obtained for Structures 8 and 14. An increase of deformation and resistance provided by the CFRP solutions is clearly observed in the two structures for the two directions. It can also be seen that the strengthening solution adopted for Structure 14 changes the overall response of the structure in the Y direction, showing the loss of resistance of the infills walls located at 1st, 2nd and 3rd floor levels and loss of global capacity for a drift higher than 0.78%. Comparing the pushover curves of the first and third strengthening solutions, it can be observed that the intervention in Structure 14 provided more resistance and deformation capacity than the intervention in Structure 8, particularly in the Y direction. In fact, for structure 8 (Fig. 10) the increment in the capacity provided by the 3rd iteration, which corresponds to the addition of one more CFRP layer in the two internal stair columns at ground and 2nd floors, is only visible in X direction. This means that small increases in the number of CFRP layers or elements to be strengthened do not affect the structure's global strength and deformation capacity.



a) ***b)***

Figure 10. Pushover curves comparison before and after retrofitting for structure #8 in: a) X and b) Y directions



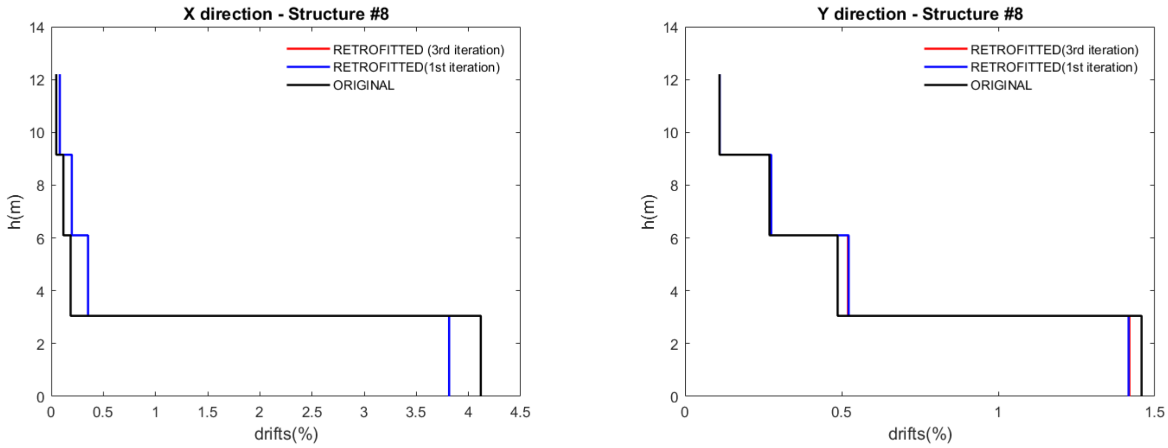
a) ***b)***

Figure 11. Pushover curves before and after retrofitting for structure #14 - in: a) X and b) Y direction

The interstorey drift distributions of the original and retrofitted structures, obtained at the instant that the pushover curves start to indicate loss of resistance for the retrofitted Structures 8 and 14, are shown in Figures 12 and 13, respectively.

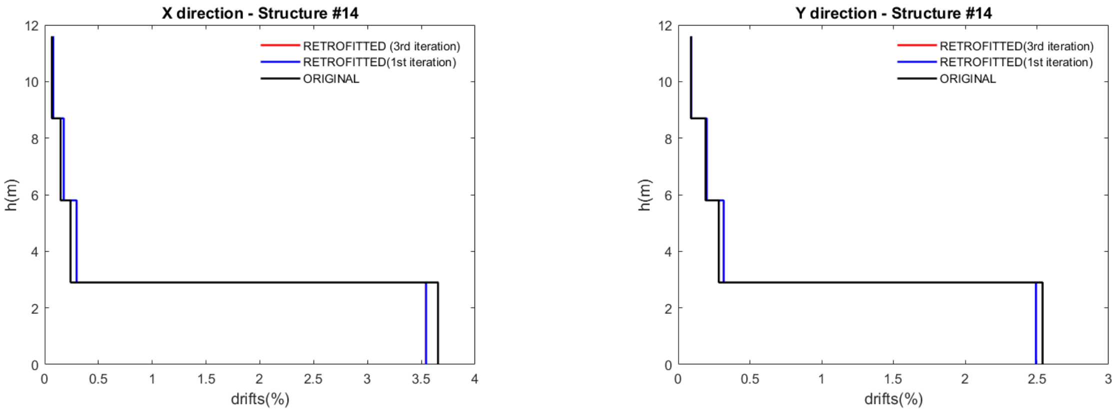
For structure 8, the instant at which the pushover curve indicates loss of resistance corresponds to a global drift of 1.10% in X direction and 0.58% in Y direction. It is observed in the X direction that, for these levels of deformation, the target displacement was already reached (Figure 8a) and a global soft-storey mechanism has developed (Figure 12a). In the Y direction, the target displacement occurs for higher levels of deformation than 0.58% of global drift (Figure 8b) and the levels of drift at ground floor columns are less than 1.5% (Figure 12b).

For Structure 14, the instant at which the pushover curve indicates loss of resistance corresponds to a global drift of 1.03% in X direction and 0.78% in Y direction. As in Structure 8, for these levels of deformation, the target was already reached in the X direction (Figure 8a) and a global soft-storey mechanism has formed (Figure 13a). In the Y direction, the target displacement is attained immediately after the loss of resistance of the pushover curve (Figure 8b). However, the interstorey drift distribution indicates that the structure behaviour is governed by the ground floor columns with drifts values of 2.5%.



a) ***b)***

Figure 12. Interstorey drift distributions before and after retrofitting for structure #8 - in: a) X direction for global drift of 1.10% and b) Y direction for a global drift of 0.58%



a) ***b)***

Figure 13. Interstorey drift distributions before and after retrofitting for structure #14 - in: a) X direction for a global drift of 1.03% and b) Y direction for a global drift of 0.78%

As indicated by Figures 8 and 9, the strengthening solutions with CFRP resulted in structures with enhanced performance that comply with the EC8-3 requirements, i.e., that satisfy both the shear and chord rotations demands at the instant at which the target displacement is reached. Nevertheless, the solutions adopted do not change the interstorey drift distributions, nor avoid the development of the global soft-storey mechanism that is expected for levels of deformations higher than the target displacement (Figures 12 and 13). The same conclusion can be drawn regarding the other structures of this group. This type of strengthening solution, although effective in terms of regulation, does not solve the problem of limiting the global deformation of the structures. Alternative retrofitting solutions could therefore be considered should a more improved performance of the buildings be targeted.

CONCLUSIONS

This paper reports on the characterization of the vulnerability of reinforced concrete buildings, representative of the building stock found in Portugal, before and after retrofitting. The building classes characterization was conducted through a computational framework developed at the University of Porto, which is based on simulated design and accounts for multiples sources of uncertainty, including building-to-building variability and the consideration of other different parameters such as the number of storeys, structural layout, year of construction and structural characteristics. For this study, a group of 20 buildings was generated complying with the first Portuguese seismic standards (RSCCS, 1958). Afterwards, the buildings were modelled in Opensees and nonlinear static analysis were performed to assess the seismic safety and eventual strengthening of the structure's members, as recommended in Part 3 of Eurocode 8 (CEN, 2005). The structural elements strengthening design and modelling approach, which was also implemented in the framework, is described in detail in this work. The retrofitting strategy consisted of the use of carbon fibre reinforced polymers (CFRP) for being a less intrusive solution. The main outcome of the application of this methodology is that the design and assessment of retrofitting solutions is an iterative process. Regarding the selection of CFRP, it can be concluded that this type of strengthening solution is effective in terms of regulation, however it does not solve the problem of limiting the global deformation of the structures.

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