Analysis of the influence of cladding panels in the seismic behaviour of a PRC Industrial Building

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Abstract

Recent reports on the latest earthquakes in Italy and Turkey have highlighted some critical problems in the connections of cladding panels on industrial precast reinforced concrete (PRC) structures. The panel connections did not perform as expected, causing non-structural damages and, in most cases, leading to the panels overturning. The damage and collapse of these elements may result in significant losses of human lives and large socio-economic impacts due to business interruption. Despite being demonstrated that cladding panels can have a significant contribution on seismic response, these elements are often considered as non-structural, ignoring the interaction with the RC frame, and considering that they do not influence the seismic behaviour. Making use of a simplified macro element, this study assesses the seismic capacity of commonly employed claddings-to-structure connections, as well as the interaction of the cladding panels with the PRC industrial buildings. The analyses were carried out considering a PRC building representative of the Portuguese industrial park, studied with and without cladding panels. The seismic behaviour of the structure are assess considering both non-linear static and dynamic procedures

Keywords: *PRC buildings, cladding panels, connections, seismic behaviour.*

1. Introduction

In Europe, precast reinforced concrete (PRC) industrial buildings represent a significant part of the industrial building stock (Batalha et al., 2019; Fischinger et al., 2012). PRC buildings have exposed their vulnerability on recent earthquakes, highlighting structural and non-structural damages most related to deficient transferring of horizontal forces at the connections between elements (Batalha et al., 2019).

According to Del Monte et al. (2019), the recent Italian earthquakes, such as L'Aquila 2009 and Emilia 2012, highlighted some critical issues associated with in the behaviour of cladding-to-structure devices utilized in the past. Cladding-to-structure fastenings play a key role in the safety, performance, and economy of both the cladding system and the main structure itself.

The cladding panels end up accommodating the lateral displacements to which the structure is subjected through relative displacements and rotations of the connections. The undesired behaviour and contribution of the cladding panels on the seismic response of the buildings occurs due to the high stiffness of the panels when compared with the stiffness of the connections between the panels and the main structure and because those connections are not ductile enough to accommodate the displacements demand imposed by the structure (Belleri et al., 2015).

Several authors reported heavy damages related to cladding panels (Dal Lago et al., 2018; Liberatore et al., 2013; Magliulo et al., 2014; Savoia et al., 2017). In particular, Bournas et al. (2014) reported that approximately 75% of PRC industrial buildings designed without seismic provisions exhibited damage and detachment of the exterior claddings panels. According to Scalbi et al. (2018) the current design approach (e.g. Eurocode 2 part 1-1 and Eurocode 8 part 3) considers the cladding panels as non-structural elements, ignoring the interaction with the frame and considering that they do not contribute to the seismic behaviour, while many authors have demonstrated that cladding panels can have a significant contribution on seismic response (Arnold, 1989; Batalha et al., 2019; Colombo et al., 2014; Dal Lago et al., 2018; Magliulo et al., 2015; Scalbi et al., 2018; Toniolo and Colombo, 2012).

The current design practice for PRC industrial buildings is based on bare frame models and the cladding panels stiffness is generally neglected. The connection to the main structure is ensured through mechanical connections designed to support forces orthogonal to the plane of the panels. No interaction between panels and structure is considered. This approach leads the panels to became part of the resistance system resulting in much higher forces than those calculated from the frame model, causing the fastening elements to fail (Batalha et al., 2019; Colombo et al., 2014; Magliulo et al., 2015). It is important to say that the inadequate design of these connections may cause the cladding panels (with weight up to 10 tons) to collapse, representing potential risk for humans, even during the evacuation procedures (Belleri et al., 2016), and huge economic losses (Dal Lago et al., 2018).

Considering that the connection between the cladding panels and the main structure was one of the least investigated issues in PRC (Zoubek et al. (2016)) the project Safecladding, emerged to give answers to the problems previously mentioned between cladding panels and PRC buildings, aiming to improve the conception and design of new fastening systems to guarantee the good seismic performance of the structure (Scalbi et al., 2018). Nonetheless, the deficient connection of the existent panels is not sufficiently covered in the existing literature nor by the industry (Belleri et al., 2016).

Most of those PRC facades are constituted by precast cladding panels that can be arranged in the vertical or horizontal direction. In the Portuguese industrial park, the most current arrangement of cladding panels observed is the horizontal ones (Rodrigues et al., 2020), recognized as the most vulnerable ones (Belleri et al., 2014; Ercolino et al., 2014; Zoubek et al., 2016). According to the damage observed in recent earthquakes in the Italian territory, the seismic vulnerability of precast horizontal panels was greater compared to the vertical panels, which behaved slightly better. It was verified that the anchor channels were not adequate to allow for large seismic displacement demands, consequently, their plasticization induced the expulsion of the retaining bolts by prying action, mainly in the upper panels. (Belleri et al., 2014)

Furthermore, during the research and the buildings survey, it was observed that the cladding panels, both in the old and recent buildings are not considered in the design, not even with simplified procedures, and therefore no specific details are generally provided.

Taking into consideration the previous issues, this study analyses the importance of the cladding panels in the seismic response of PRC considering a building representative of the Portuguese industrial park. The seismic performance, assessed with nonlinear static and dynamic analyses, is analysed considering models with and without cladding panels, simulated through a simplified macro element representative of cladding-to-structure connections commonly used.

2. Numerical modelling

Precast reinforced concrete industrial buildings are structures that present a greater flexibility when compared with traditional RC building structures, due to the higher story height (in Portugal usually between 6 and 8 m (Rodrigues et al., 2020) and to the horizontal stiffness of the structure, usually constituted by cantilever columns fixed at the base, prestressed beams and hinged connections between those two elements.

The way to model the contribution of the cladding panels in the PRC building has suffered several improvements in the last years (Ercolino et al., 2014), from elastic elements mixed with rigid bars to include the initial stiffness, to multiple struts and springs to include the mass and the non-linear behaviour of the connections (Babič and Dolšek, 2016), among other strategies.

For the nonlinear analysis of large and complex structures under severe loads, such as those induced by earthquakes, in many cases it is not appropriate to adopt refined models. Thus, many authors in the last decades have proposed and used simplified nonlinear models for these structures, considering the behaviour and its interaction with the main structure (Rodrigues et al., 2010).

2.1. Simplified macro element

The present work proposes a modelling strategy inspired in the simplified model developed for infill masonry walls (Rodrigues et al., 2010), composed of a simplified macro-element that aims to describe the main global contribution of conventional connections of horizontal cladding panels to the main PRC structure.

In this PRC cladding panel model, the contribution of the panels are concentrated in one macro element defined at the centre of the frame and connected to the column edges through four diagonal truss elements, with rigid behaviour (Fig. 1). With the arrangement, the non-linear hysteretic behaviour resulting from the contribution of all the panels and associated connections is concentrated in the central element, whose behaviour reflect the lateral resisting force as a function of the relative horizontal displacement measured between the top and the bottom of the columns. The hysteretic assumed for this central element was calibrated based on the behaviour nonlinear central element, characterized by the response curve inspired by the "Standard" connection model by Del Monte et al. (2019) for horizontal panels.

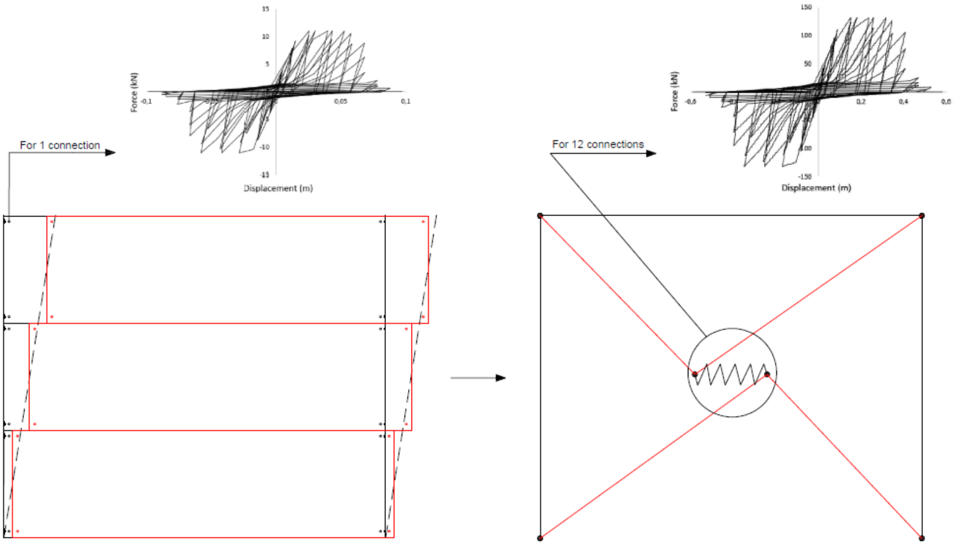


Figure 1 - Simplified Macro element for the simulation of cladding panels.

The numerical modelling of the cladding panels was focuses on commercial connections in use in Portugal, referring to the Isostatic Sliding-Frame system for horizontal panels consisting of anchor channel pre-installed and hammer-head screws. An experimental campaign carried out by Del Monte et al. (2019) in this type of system, allowed to demonstrate the hysteretic behaviour of a connection, through the force-displacement curve and the backbone curve. Based on these experimental results, the behaviour for four connections was admitted through equations (1) and (2):

$$F_{macro} = F_1 \times N_p \times N_c \tag{1}$$

$$\delta_{macro} = \delta_1 \times N_p \times 2 \tag{2}$$

In the previous equations, F_1 refers to the strength of each point of the backbone curve for one connection, δ_1 is the displacement of each point of the backbone curve for one connection, N_P the number of panels and N_c the number of connections per panel. In Figure 1, it is possible to observe the force-displacement relation for a single connection (left) and for the entire set of panels in the span, represented in the macro-model (right).

The nonlinear behaviour of the macro-element is controlled through a modified hysteretic procedure, based on the Pinched model, which is shown to be the most adequate and similar to represent the behaviour of the conventional connection, described in work from Del Monte et al. (2019). This model represents the response displacement-force evolution of the PRC section to cyclic actions and contemplates mechanical behaviour effects such as non-linear stiffness, strength deterioration, and pinching effects.

Therefore, the chosen model more accurately represents the overall response and energy dissipation during the structural response.

2.2. Description of the case study

The case study used to access the importance of the cladding panels refers to an existing PRC industrial building built in Portugal. The building under study is a framed structure (Fig. 2) constituted by one floor with a height of 6.26 m and an area of 39.32 x 44.8 m^2. The structure has 2 spans in the X direction with 18.12 m and 21.2 m in length and 6 spans in the Y direction with 7.4 m in length at the ends and 7.5 m in the inner ones. The columns, assumed fix to the foundation, have a height of 6.26 m and two types of rectangular section, namely a 0.4 x 0.4 m^2 section at the central columns and 0.5 x 0.4 m^2 in the remaining ones (Fig. 3). The concrete used was C40/50 and steel S500 NR-SD.

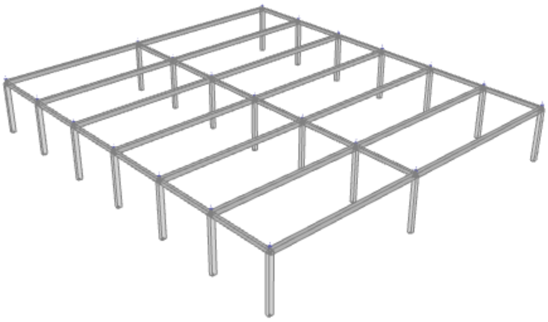
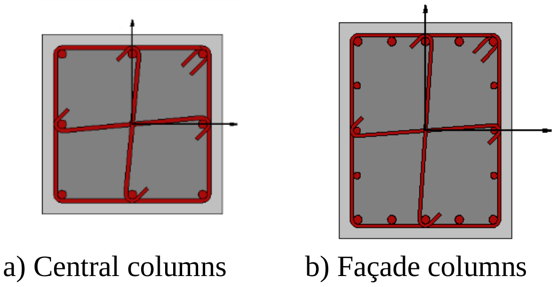


Figure 2 - 3D overview of the building under study.



a) Central columns b) Façade columns

Figure 3 - Transversal sections of the elements considered in the numerical model.

The building features two types of beams: the longitudinal “I” beams, with a cross section of 0.5 x 0.4 m^2, and the transversal beams with a cross section of 0.4 x 0.3 m^2. The weight of the roof girders with a maximum height of 1.3 m, together with a light roof cladding system, were assumed in the numerical model through concentrated loads applied end nodes of the beams. Therefore, for the numerical analyses, the constant vertical loads concentrated were considered to simulate the dead load of the self-weight of roof. In the model developed, the columns were modelled with fibre-based nonlinear force-based elements whilst an elastic behaviour was assumed for both longitudinal and transverse beams, as they are expected to remain essentially undamaged. Although recognizing the importance of the beam-to-column connections in the seismic performance of these buildings (Sousa et al., 2020), in this study it was decided to consider a simple pinned connection in order to better understand the influence of the cladding panels with a minimum modelling bias in the other structural elements. The structural behaviour of the precast building was simulated along the two main directions with a 3D model using the computer program SeismoStruct (Seismosoft, 2020).

2.3. Numerical analyses

The aim of the numerical analyses is to assess the seismic capacity of the reference building presented in the previous section, determining its vulnerability with and without cladding panels. The building is located in a central area of Portugal in seismic zone 1.5, according with the seismic zonation defined in the Portuguese version of the Eurocode 8, Part-1 (CEN, 2010), characterized by a reference peak ground acceleration of 0.061g, for a return period of 475 years and a soil type B. The analyses were carried out following a nonlinear static approach as well as the nonlinear dynamic counterpart. In addition to the general conclusions associated with the presence of the panels, the building was also assessed based on the ultimate chord rotation and shear capacity defined in the Eurocode 8, Part-3 (CEN, 2017).

2.3.1. Static Pushover Analysis

The pushover analysis was performed according to Eurocode 8 (CEN, 2010), considering the two conventional load distributions, the uniform distribution proportional to the buildings mass, and the modal one proportional to the first mode along the X and Y directions. In order to assess the performance for the expected hazard level, the target displacement was determined following the N2 method, also adopted in Eurocode 8, Part-1. The results presented hereafter represents the analyses carried out along the two main directions with and without the consideration of the cladding panels.

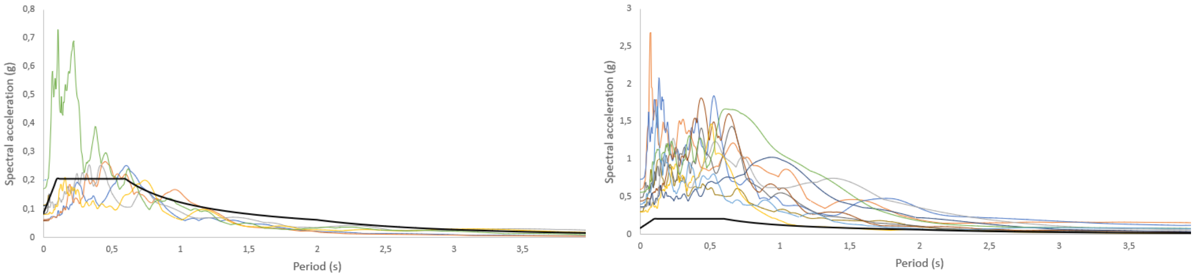
2.3.2. Nonlinear Dynamic Analysis

The dispersion in the structural response resulting from the specific properties associated with each accelerogram implies that it is necessary to consider several registers, in order to obtain a wide and reliable set of results (Sousa et al., 2011)

The records used in this study were selected from suit of nearly 3500 records (including two horizontal and a vertical component) from a database of ground motions recorded in the Mediterranean region. The selection and scaling follow generically the strategy presented in (FEMA P-58-1, 2018). Given the average building period and the geometric mean spectrum of each calculated ground motion, the 10 ground motions are selected whose arithmetic mean along the period interval defined. Ground motions were considered in 2 groups of 5 records to be used in the present study.

The first group of records was selected based on the seismic action characteristic of the place where the building is located, and whose response spectrum is presented in Fig. 4a). In order to assess the behaviour of the panels' influence for higher levels of seismic action, a group of records was also selected considering spectral accelerations five times higher than those considered in the first group (Fig. 4b).

In order to optimize the time consumption of the analyses, every record was trimmed based on the 5% maximum peak ground acceleration following the work by (Bommer & Pereira, 1999). 20 dynamic time-history analyses are performed, varying the two horizontal direction components. Stiffness-proportional damping was considered, in accordance to 1st mode, with mean period of 0.7 s and damping ratio of 1%, proportional to the tangent stiffness. Considering the number of records analysed alternatively along the two main directions, with and without panels, totalises 40 dynamic analysis.



a) 1º group b) 2º group

Figure 4 - Response spectra of the two groups of earthquakes in relation to the building under study.

3. Comparative study

In this section, the results obtained with and without cladding panels are presented and analysed. The main objective is to assess the seismic capacity, as well as the interaction of the cladding panels with the building under study. In addition to understand the results of the two types of nonlinear analysis explored, in a first step a non-linear static analysis is performed in each independent and in a second step are performed 3D non-linear dynamic analysis.

3.1. Frequency and vibration modes

Table 1 shows the properties of the main modes of vibration with their frequencies and associated directions. The first mode of vibration refers to the Y direction, for both types of analyses, although it has a difference in frequency, due to the fact that the horizontal stiffness of structure increase in the presence of the cladding panels in the facade. In the second mode of vibration referring to the X direction, this difference is less pronounced due to the fact that the building is more elongated and does not behave like a rigid diaphragm. When considered as a rigid diaphragm, a greater difference in frequencies is evident, mainly in the Y direction and with presence of the cladding panels.

Table 1- Frequency and vibration modes of analyses.

	Frequency with panels		Frequency without panels	
Direction	W/ diaphragm (Hz)	W/out diaphragm (Hz)	W/ rigid diaphragm (Hz)	W/out diaphragm (Hz)
Y	2,477	1,485	1,428	1,339
X	2,083	1,692	1,724	1,686
Torsion	3,018	1,759	1,906	1,816

3.2. Non-linear static analysis

Follow the recommendations of Eurocode 8 (CEN, 2010), different load distributions were applied in the pushover analysis, a uniform and modal distribution. The capacity curves obtained for the two main directions are presented in Figure 5 and 6.

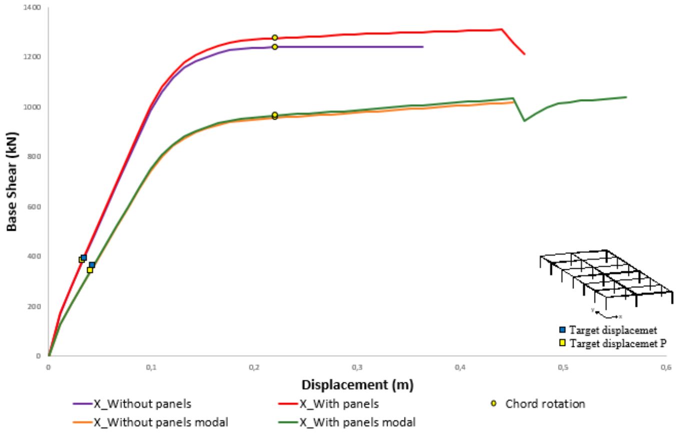


Figure 5 - Non-linear static analysis with and without cladding panels in the X direction.

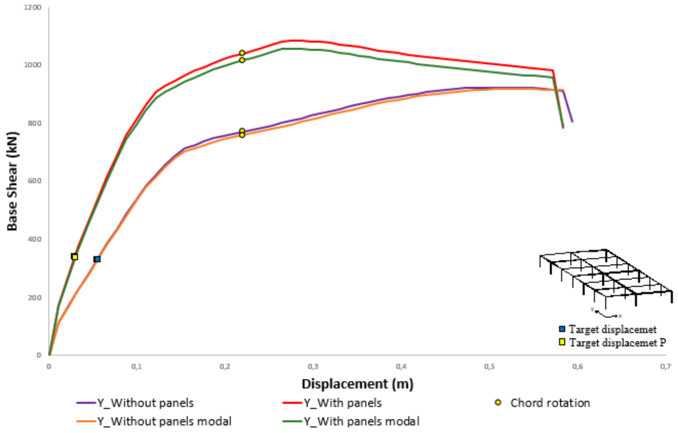


Figure 6 - Non-linear static analysis with and without cladding panels in the Y direction.

Regarding the importance of the infill panels, the results obtained revealed a distinct behaviour along the two directions. In the X direction it is apparent that the presence of the cladding panels has a minor contribution to the horizontal strength and stiffness, given that the panels were considered only in the facades and there is no rigid diaphragm. In this case, the lateral deformation of the building is mainly concentrated in the middle frames. Only in the presence of a very large in-plane stiffness of the roof it would be possible to mobilize the panels that are at the extremity. On the other hand, given that in the orthogonal direction only one of the three frames does not include the panels, the horizontal the strength and stiffness increases significantly, even in the absence of a rigid diaphragm.

It is also important to note that, for the analysis along the X direction, the uniform distribution differs significantly form the modal one, highlighting the natural tendency for a larger deformability in the frames near the middle of the building.

Regarding the building performance for the seismic hazard level considered, it was observed that the building is safe, given that the lateral deformation for which the ultimate chord rotation is first reached, occurs for a top displacement of 0.22 m, much higher than the target displacement of the building that occurs for a top displacement approximately equal to 0.05m.

3.3. Non-linear dynamic analysis

In the dynamic analyses, the two groups of earthquakes presented previously were explored. The results of the nonlinear dynamic analyses presented in the following figures represent the combination of the maximum top displacement observed with the maximum base shear experienced during each record. It is important to perceive that these points are fictitious, as do not necessarily occur in the same instant. Figure 7 shows the results along the X direction and Figure 8 represents the ones corresponding to the Y direction.

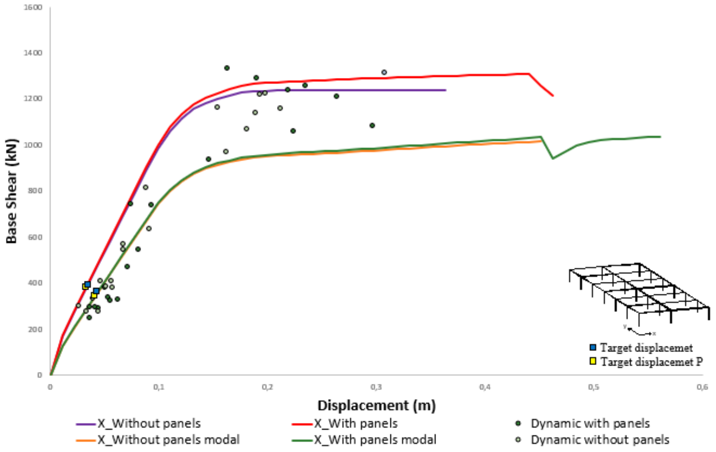


Figure 7 - Comparative analyses with and without cladding panels in the X direction.

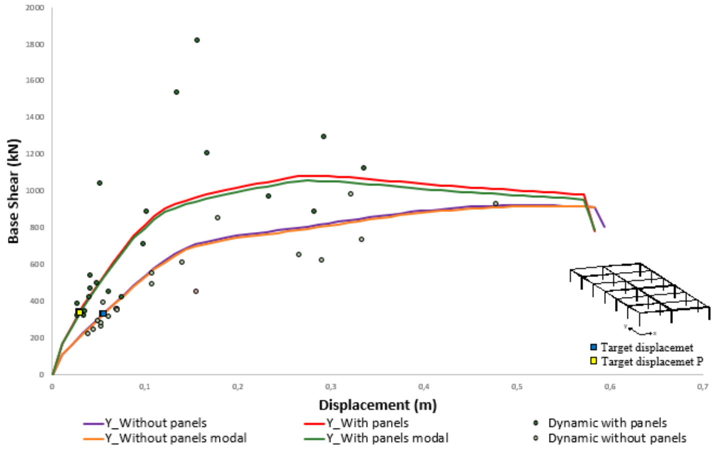


Figure 8 - Comparative analyses with and without cladding panels in the Y direction.

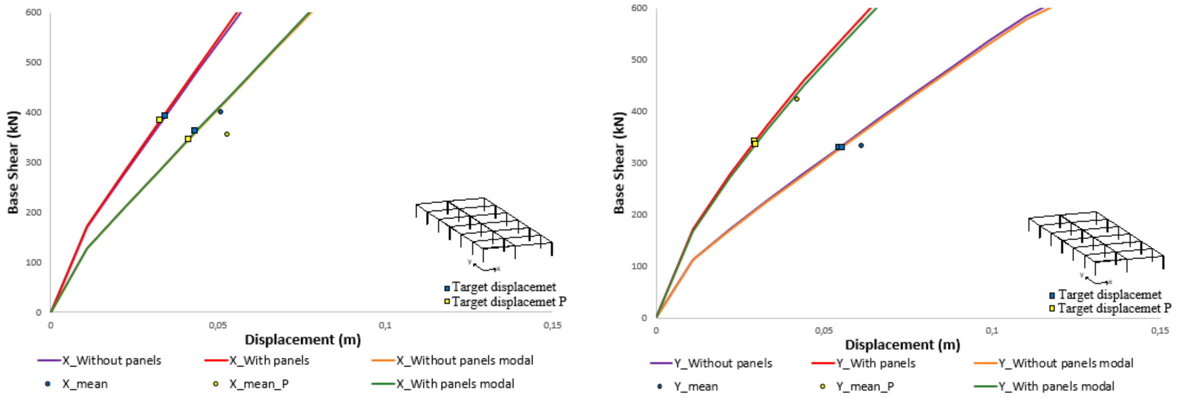
In general, the pushover curves obtained for each direction are in good agreement with the set of records used to perform the dynamic analysis. Nevertheless some analyses diverge significantly in terms of maximum base shear which appear to be related with the contribution of higher modes and the consideration of the seismic loads along the two direction simultaneously.

Regarding the consideration of the panels, the results of the non-linear dynamic analyses are similar to the pushover ones, mainly in the first group of earthquakes that is located more in the elastic part. In the X direction it is possible to observe that the results of maximum displacements and forces of the nonlinear dynamic analyses are closer to the elastic region of the modal capacity curve, and approaches the uniform one for increasing seismic actions.

On the other hand, along the Y direction, several of the dynamic analyses of the second group present a low base shear for large horizontal displacement, indicating that some cyclic degradation occur in the panels.

Regarding the safety of the building under study, for the first group of earthquakes in terms of its actual location, the building is safe, without any flexure or shear failure. For the second group of records that assess the building for higher intensities, the building reached the ultimate chord rotation for the determined spectra.

According to Eurocode 8 (CEN, 2010) if the dynamic response is obtained through 7 nonlinear analyses, the mean of the values obtained in all these analyses can be used in the verifications. Therefore, the mean dynamic points obtained through the analysis of the models with and without cladding panels of the first group of records is compared with the target displacement determined for each capacity curve (Fig. 9).



a) X direction

b) Y direction

Figure 9 - Comparative of nonlinear static analyses with the mean nonlinear dynamic analyses.

In general, the target displacements of pushover analyses indicate a good agreement with the mean of the maximum displacements and maximum shear base force, obtained with the dynamic analysis. Yet, it is apparent that, in the X direction the capacity curve associated with a modal distribution has a better approximation with the mean of the dynamic analysis. In the other direction such difference is not observed, as the modal and uniform curves are very similar.

4. Conclusions

In this study, the analysis of a RC precast building representative of the Portuguese industrial park was carried out, considering numerical analyses with and without the influence of the cladding panels.

The numerical models, considering the presence of cladding panels, make use of a simplified macro element that simulates the influence of the panels on the main structure. The model was calibrated to simulate the capacity of commonly employed cladding connections, as well as the interaction of cladding panels with RC precast industrial buildings.

The seismic behaviour of the structure was assessed considering both non-linear static and dynamic procedures. According to the results obtained through these analyses, when comparing the models with and without panels, it was concluded that the influence of the panels is notable in all analyses, expressing an increase in strength and stiffness. However, if the building is significantly elongated and does not have a rigid diaphragm, the contribution of the panels might be negligible.

In general, the structure response attained with non-linear static analyses is in good agreement with regard to non-linear dynamic analyses, indicating that these appears to be a reliable option, especially considering the relative simplicity of static analysis in comparison with the dynamic counterpart. Nonetheless, the models featuring cladding panels and subjected to large dynamic loads present a large dispersion, indicating that the consideration of the cyclic degradation effects of the panels might be important to determine the actual behaviour of the building. These conclusions are naturally conditioned to the type of connections considered, and generally find in Portugal, that features specific strength and stiffness and ensures some coupling level between the claddings and the main structure.

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