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COMPARISON OF CYCLIC RESPONSE OF REINFORCED CONCRETE INFILLED FRAMES WITH EXPERIMENTAL RESULTS

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ABSTRACT :

This paper intends to estimate the numerical cyclic response of RC frames with and without masonry infill through a simplified nonlinear analysis using a commercial FEM package. The numerical model is based on the experiments carried out in the National Laboratory of Civil Engineering (LNEC) and the numerical and experimental results are compared to assess the accuracy of the simplified analysis based on the inelastic hinge method either for the bare frame and the infill frame.

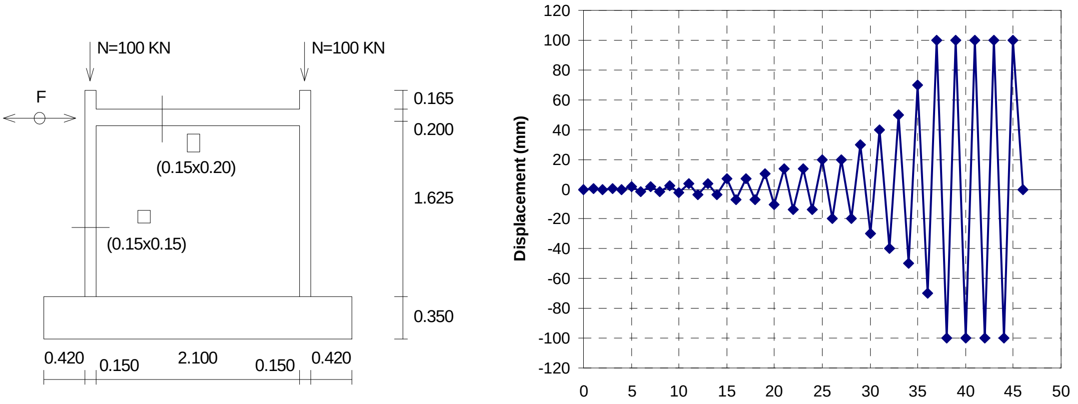
KEYWORDS: Cyclic response, nonlinear analysis, plastic hinge models, fiber model, RC structures

1. INTRODUCTION

The more common structural solution for regular buildings is based upon the spatial repetition of masonry infill frames. The damage and collapse of structures of this type as a result of a significant lateral floors deformation induced by a moderate seismic event are nowadays two of the main concerns of the structural designers.
Although the classical methodologies are based on the capacity of the structural elements to accommodate plastic deformations without compromise the structure stability, the new analysis and design methodologies allow defining the criteria that manage the structural response for some levels of structural performance. The main purpose of this paper is to validate some simplified nonlinear models used to carry out a material nonlinear analysis. To validate the nonlinear model available experimental information carried out in the National Laboratory of Civil Engineering was used.

2. EXPERIMENTAL RESPONSE

In the scope of an experimental research program developed in the National Laboratory of Civil Engineering (LNEC) [1], to study the influence of brick masonry panels on cyclic response of RC frames, a bare frame and several infill frames were tested (Figure 1).



a) b)

Figure 1 – Experimental frame: a) general description; b) lateral displacement law

A constant vertical load (P=100 kN) at the top of each column and a lateral increasing cyclical load/displacement pattern at the beam level were applied.

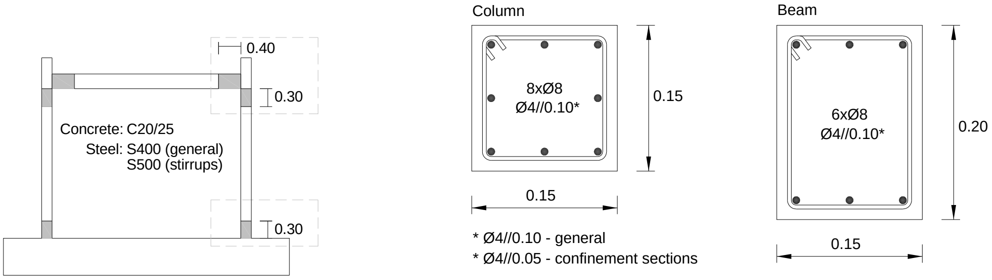
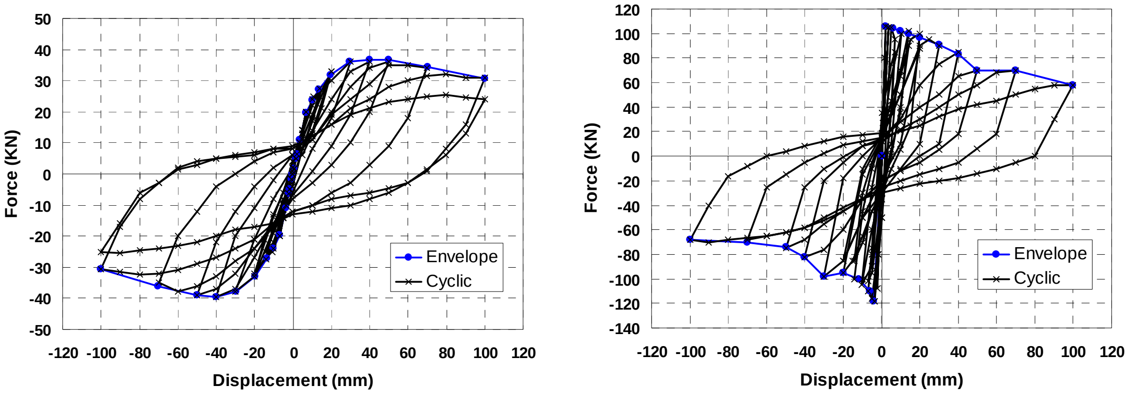


Figure 2 – RC frame: confinement sections and cross sections

The materials used in the RC bare frame were: C20/25 concrete; S400 for longitudinal reinforcement and S500 for the stirrups. To guarantee a good concrete confinement at the critical sections at the near end of each element a narrow stirrup spacing was used (Ø4//0.05 instead of general Ø4//0.10) as shown in Figure 2. For the infill frames regular hollow brick masonry (30x20x15) was used.
As shown in Figure 3, the bare frame shows a smooth evolution with a maximum obtained just before the complete concrete cracking at the top and bottom columns ends. After this point a soft stiffness decrease occur without collapse but with significant columns damage and inelastic hinge spread. The infill frame exhibits a well-known behavior for this type of erection solution: an upward linear branch in which the RC frame and the infill masonry work as one building block until the masonry cracking starts; an upward nonlinear branch related with the masonry cracking and a decreasing nonlinear branch related with the damage of the infill panel [1].



a) Bare frame b) Infill frame

Figure 3 – Experimental cyclic response

3. NUMERICAL ANALYSIS

Framed structures, when subjected to cyclic loads, usually present a structural behavior characterized by the development of plastic hinges at the extremities of the elements, see figure 4. As it would be expected, the experimental results to be modeled here show clearly this behavior. The goal is to access the performance of different available nonlinear constitutive laws.
The typical formation of plastic hinges in specific zones has promoted the development of several methodologies that allow accomplishing nonlinear analyses of framed structures (both static and dynamic) in a non-complex fashion. These methodologies are founded on the simplification associated to the concentration of the nonlinear behavior in zones in correspondence with the development of plastic hinges.

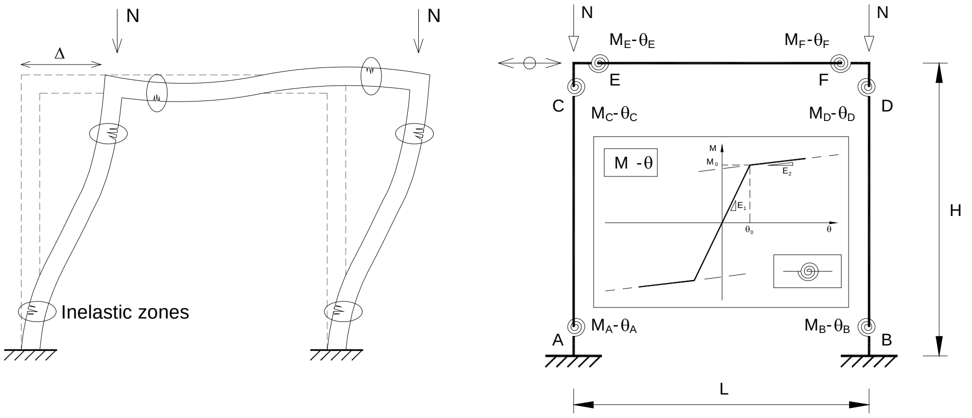


Figure 4 – Typical critical zones in framed structures and idealized plastic hinges

The following step corresponds to the definition of the constitutive law that rules the formation and further development of the plastic hinges.

3.1. Simplified procedures for nonlinear analysis of bare frames

The software employed in this work [2] makes use of two different procedures to define the nonlinear behavior of framed structures, namely: Plastic hinge model (PHM) and Fiber model (FM). The main difference between the two models lies in the way the constitutive laws are defined and used [3]; three different models for plastic hinges were considered: Clough's model (bilinear); tri-linear Takeda's model and tetra-linear Takeda's model.

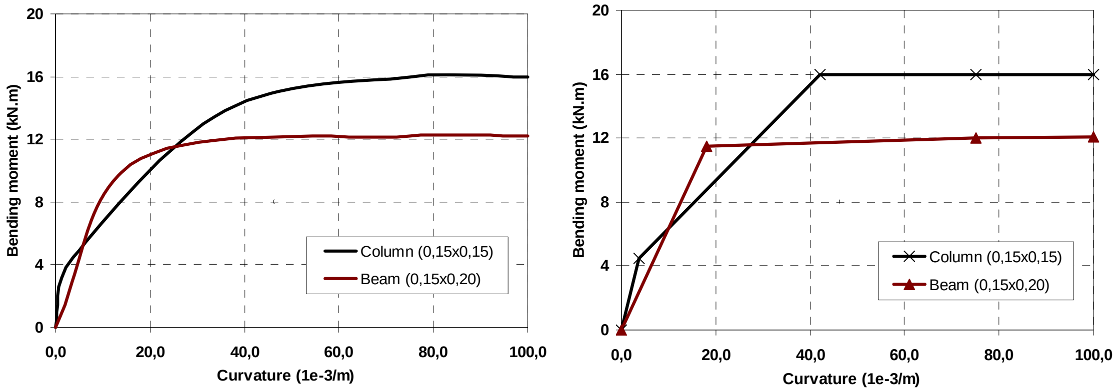


Figure 5 – Numerical and Idealized bending moment-curvature diagrams

A good numerical model must carry out: stiffness decrease due to deformation; stiffness decrease in the unload path; resistance decrease; P-Δ effect; influence of shear force effect (pinching), bond deterioration and reinforcement slipping. For the computation of the constitutive M-θ laws the BIAX algorithm was used [4], which allows obtaining the capacity curve in terms of bending moment of a reinforced concrete cross section.

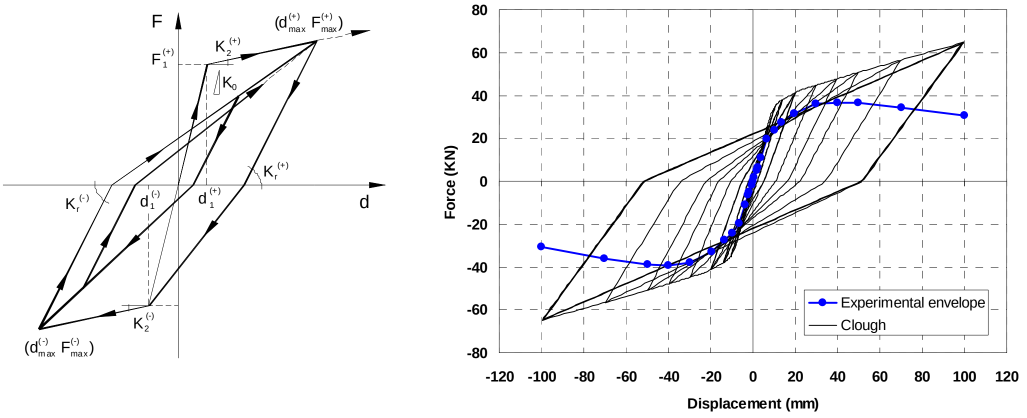
3.1.1 Clough's plastic hinge model

The first model (Clough's model) corresponds to a simplified constitutive relationship based on a bilinear variation of stiffness, with the properties indicated in Table 1, as shown in Figure 6(a).

Table 1 – Elastic and reduced stiffness (Clough´s model)

	Column	Beam
K_0	1380 kNm^2	610 kNm^2
K_1	6.9 (0.05%)	30.5 (20%)

Departing from the parameters shown in Table 1 and performing a fitting of the unloading stiffness, it was possible to reasonably obtain the structural load-displacement curve represented in Figure 6(b).



a) b)

Figure 6 – Clough's model: a) Idealized hinge model; b) Load-displacement curve

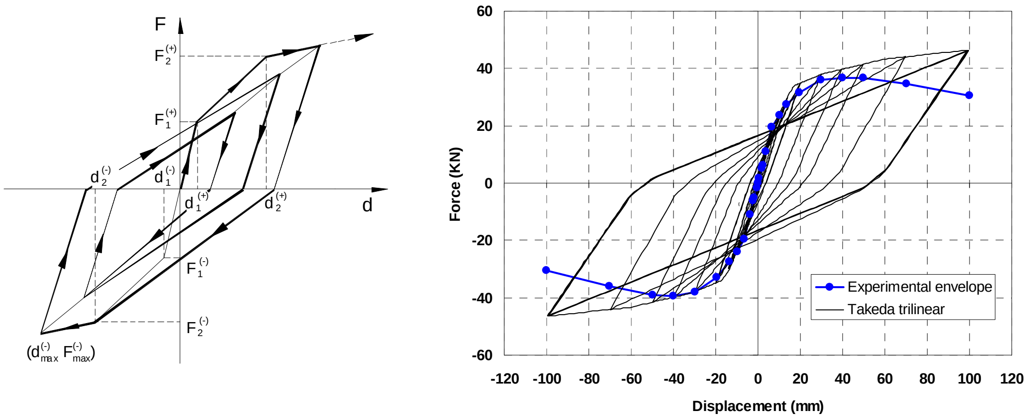
Comparing this curve against the experimental results, it is clear that the model does not represent adequately the real behavior of the structure, where a significant increase of the strength is visible.

3.1.2 Tri-linear Takeda's plastic hinge model

In this case the structure was modeled using a tri-linear envelope law, with the properties indicated in Table 2, which allows a more powerful representation of the structural behavior of the cross section (Figure 7).

Table 2 – Elastic and reduced stiffness (tri-linear Takeda's model)

	Column	Beam
K_0	1380 kNm^2	610 kNm^2
K_1	276 (20%)	30.5 (5%)
K_2	6.9 (0.5%)	-



a) b)

Figure 7 – Tri-linear Takeda's model: a) Idealized hinge model; b) Load-displacement curve

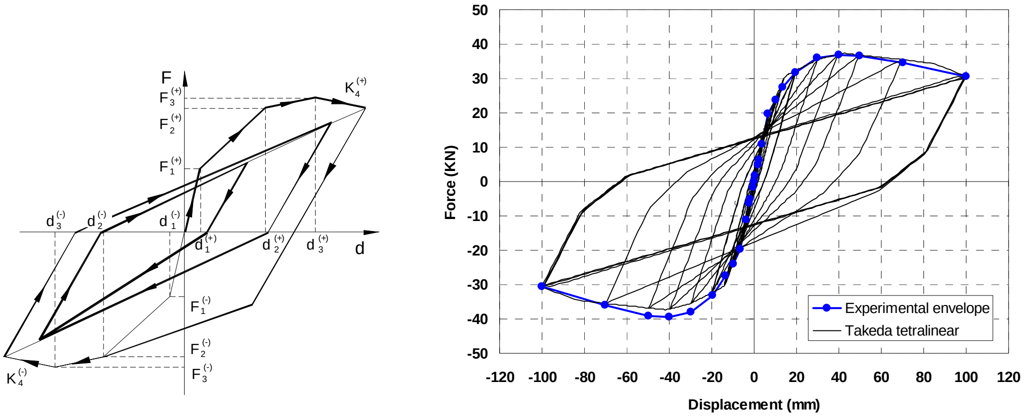
After performing a fitting of the unloading stiffness parameters, the obtained load-displacement curve is illustrated in Figure 7(b). When compared with the model of Clough, this second model represents the experimental behavior of the structure in a better way.

3.1.3 Tetra-linear Takeda's plastic hinge model

The tetra-linear Takeda's model originated by a modification of the tri-linear Takeda's model, through the inclusion of a fourth descending branch, allowing surpassing the aforementioned problem (Figure 8).

Table 3 – Elastic and reduced stiffness (tetra-linear Takeda's model)

	Column	Beam
K_0	1380 kNm^2	610 kNm^2
K_1	276 (20%)	30.5 (5%)
K_2	6.9 (0.5%)	-
K_3	-6.9 (-0.5%)	-



a) b)

Figure 8 – Tetra-linear Takeda's model: a) Idealized hinge model; b) Load-displacement curve

Figure 8 (a) illustrates the typical hysteric curves (both external and internal ones) of the tetra-linear model. From the analysis of Figure 8(b), it is clear that the tetra-linear model is the one that simulates the experimental results in the best way [5].

3.1.4 Fiber plastic hinge model

The fiber model is another methodology that can be used to analyze nonlinear behavior and is based on the discretization of a section in elements or fibers that are associated to each material with axial deformation only (Figure 9). The material constitutive laws have to rigorously reproduce the real behavior in order to get a reasonable section envelope that is intended to study. In this context, the Magenotto-Pinto steel model [6] and the Kent and Park concrete model [7] were used in this study, as explained earlier [5].

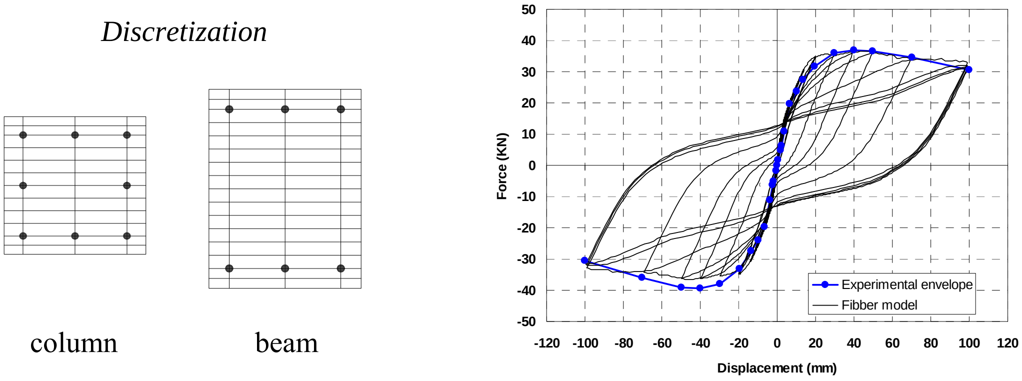


Figure 9 – Discretization and load-displacement curve for the fiber model

From Figure 9 it is verified that the envelope obtained through this methodology presents a good approach to the experimental model, also in the development of the hysteretic curves that present a more real evolution with gradual variations of the load-discharge cycles.

A comparison of the cumulative deformation energy stored in the structure is shown in Figure 10, to better understand the performance of each model [5]. The energy curve of the experimental procedure was scanned in accordance with the LNEC publication [1].

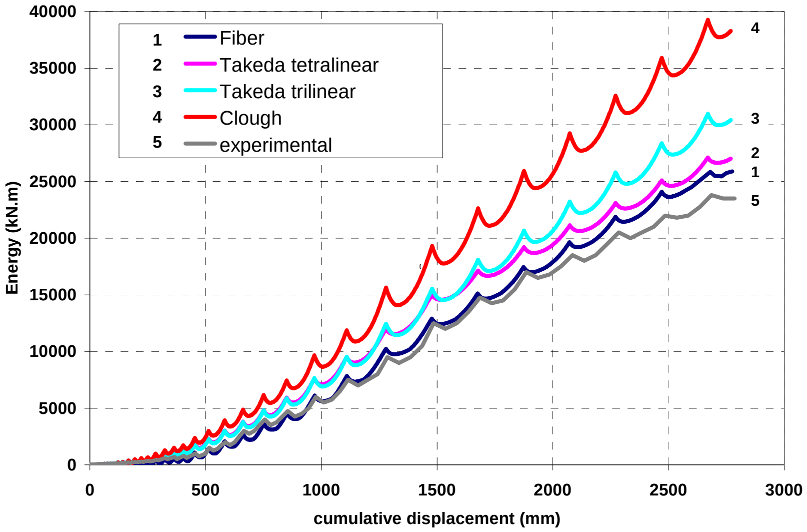
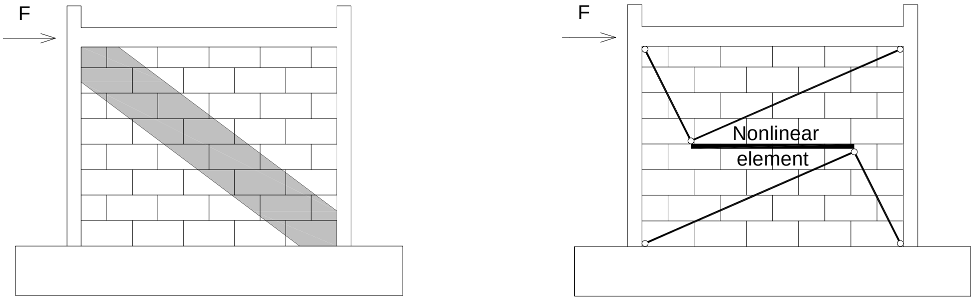


Figure 10 – Cumulative energy comparisons

It is evident that all the models have higher values compared to the experimental model. It is verified that the Clough's model is the worst approach (higher cumulated energy) compared to the experimental model, situation expected since this model does not conveniently represent the frame elements behavior. The remaining models are very close to the experimental model being the fiber and the tetra-linear Takeda models those that better represent the structure behavior. The fiber model is the more elaborated model and the obtained results allow evidencing a good approach to the experimental model.

3.2. Simplified procedures for nonlinear analysis of infill frames

In this chapter it will be revealed a simplified model to analyze an infill masonry frame, based also on a computed example of a previous bare frame geometry that was tested at the LNEC facilities. A regular brick wall was constructed into the bare frame and then the same experimental analysis was carried out.



a) Equivalent diagonal strut

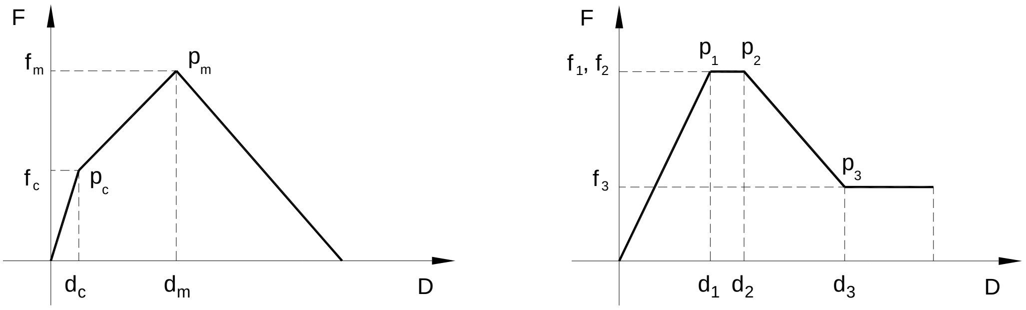
b) Interaction model

Figure 11 – Idealized force-displacement relationship

One of the more important aspects related with the infill frame resistance is the bond between the brick wall and the frame. Basically, the infill structure behavior can be compared with a frame filled with diagonal struts that simulate the walls [8, 9, 10] as represented in Figure 11 (a).

A more sophisticated model based on the model of the double equivalent struts but with significant improvements relatively to the classic model can be used. In this case to represent the masonry panel four rigid struts with linear elastic behavior are used that give support to a fifth central element where the hysteretic nonlinear behavior of the panel is concentrated as shown in Figure 11 (b). This model was used in this study and it has the advantage of introducing the interaction between the two struts since in the classical approach the two struts act independently.

The global behavior of an infill RC frame can also be idealized as a multi-linear force-displacement relation that defines the envelope of the cyclic loading (Figure 12) or a pushover analysis [11, 12, 13].



a) Nonlinear equivalent element

b) Infilled RC frame envelope

Figure 12 – Idealized force-displacement relationship

In this approach the envelope is divided into four branches: an initial equivalent linear part that simulates the monolithic elastic and after cracking behavior of the infill RC frame; a second part normally small, due to lack of ductility of the infill frames, that represents yielding (between P1 and P2); a third part governed by the infill in which a degradation in observed until P3 is reached; the last part, after P3, is related with the infill collapse and when only the RC frame opposes the horizontal loads. The results of the numerical analysis (finished after setting the nonlinear equivalent strut parameters) are shown in Figure 13.

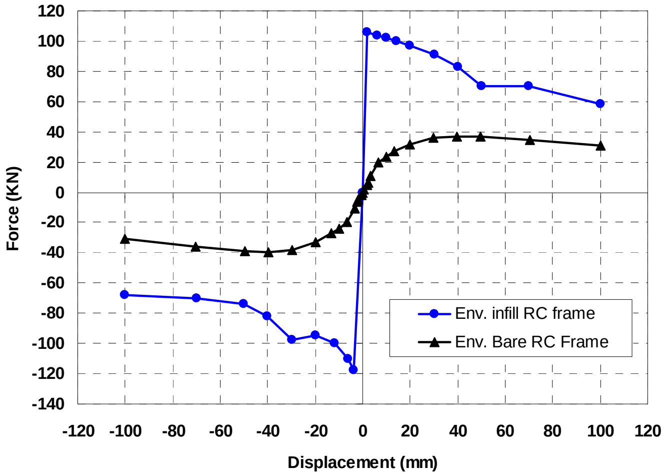


Figure 13 – Infill and bare RC frame envelopes

In this representation it is clear that the simplified model suits notably well the infill RC frame experimental envelope. At the last cycles there is some slight disparity between the numerical and the experimental results, explained by the large incursion into the nonlinear regime that is very difficult to simulate with these models.

Further studies are being undertaken to evaluate new simplified models in order to improve the presented numerical results, namely for hysteretic behavior. The conclusion about the envelope analysis allows and suggests developing a parametric study of infill RC frames through a pushover analysis, that will constitute part of the further developments of the present work.

4. CONCLUSIONS

In this paper the original structural member nonlinear section is modeled by a nonlinear hinge with an equivalent moment-curvature relationship. The mathematical models were validated by comparing the nonlinear simplified analyses results with the experimental results. The immediate conclusions, based on the obtained numerical results, permit to verify that increasing the complexity of the inelastic hinge constitutive law implies a better global nonlinear fitting of the analyzed frames behavior; so the numerical results show that it is possible to accurately reproduce the experimental results, if a correct computational model is selected. The use of more complex and more rigorous models cannot necessarily mean a significant increase of the quality of the obtained results. Another important visible aspect in this work is related with the numerical difficulty to represent large incursions in the nonlinear regime as observed in the experimental test. The simplified infill model can be used for envelope analysis but the hysteretic behavior needs a more accurate nonlinear model.

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