# PUSHOVER ANALYSIS OF RC BUILDINGS WITH DIFFERENT NONLINEAR MODELS

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**ABSTRACT :**

The use of non-linear static procedures on seismic analysis of structures, mainly pushover-based ones, has recently known considerable developments. On that matter, studies that have been carried out focus mainly on issues that are related to the computation of an equivalent SDOF structure and consequent conversion of the pushover curve. However, equally relevant are the modeling aspects of the original structure, which influence the MDOF unchanged pushover curve. It is commonly accepted that two major modeling possibilities are considered when non-linearity is on steak: either a fibre-based model, with non-linear models for steel and concrete or non-linearity concentrated on plastic hinges located at elements' extremities.

The present paper aims to go through different modeling possibilities, using a set of different building frames, discussing its application and their relative effects on final results, obtained by assessment on the basis of non-linear static analysis. Therefore, using both possibilities, a direct comparison of the achieved pushover curves is performed. Conclusions are set towards the establishment of relative advantages and/or limitations, if relevant, coming from the choice for each of the modeling possibilities.

**KEYWORDS:** Fibre-based model, Plastic hinge model, RC buildings, Pushover analysis

## 1. INTRODUCTION

The importance of seismic effects on structures has been widely discussed, especially in what concerns to its design criterias and concepts.

An important issue that cannot be neglect is related to the capacity of materials to dissipate energy. This is the aim of actual seismic design strategies, diverging from the general design methodologies, where the structure's behaviour during such kind of action is admitted to lead materials to surpass their elastic limits, reaching stresses over their yield strength but with a simultaneous displacement's degree control. This strategy is presented and accounted for by the main seismic codes and legal guidelines.

Nonlinear dynamic analyses are consensually recognized as the most accurate tool to perform seismic evaluations and to predict the structural damages, though its inherent complexity and time constrains conduct to the study of simple, but also truthful methods. Herein, the Nonlinear Static Procedures (NSP) emerge, being widely developed and suggested among the engineering society in the last decade, particularly when applying to buildings, assuring similar results to the dynamic analyses. Pushover techniques constitute as reliable and practical instruments, mainly for design-office applications, taking into consideration the nonlinear material behaviour.

Modeling the nonlinear material behaviour is possible to attain pursuing two different paths: considering the distribution of plasticity along elements, representing the material nonlinearities in terms of inelastic deformations through the elements length – fibre-based models; or considering the plasticity concentrated in the elements extremities – plastic hinge models.

Thus, the current endeavour aims at verifying the effectiveness, validity and adequacy of employing the two introduced alternative nonlinear models – fibre and hinge models. Following a commonly used nonlinear static procedure, the study focuses on the limitations of the nonlinear models and proposes specific modeling aspects to each consideration.

To accomplish those objectives two commercial softwares were considered: one based on a fibre modeling – SeismoStruct (2006), and a plastic hinge based – SAP2000 (1999). A plastic hinge based software, developed in Porto's University – PNL – is also considered in the analysis, (Varum, H., 1995).

Finally, two existing frame buildings configurations are assessed and scrutinized, concerning a role of structural parameters, representing the structures response to a seismic input, measuring the unlikeness between modelings.

## 2. NONLINEAR MODELS

As mentioned above two alternative nonlinear modelings were adopted in the present study, embracing conceptual differences which are traduced on the structural response to seismic actions. The distributed nonlinearity model is recognized as the most accurate one nevertheless, its complexity requires a sensitive and rigorous analysis on results information and a higher numerical instability. In contrast, the concentrated nonlinearity model presented in elements extremities represents a simpler structural nonlinear definition that can provide significant reduced time calculations to the fibre-based model, but with less truthful produced results.

### *2.1. Distributed Nonlinearity Model*

The bar elements formulation according to a distributed nonlinearity approach is defined through a fibre modeling method, representing a more accurate characterization of the structural damage presented in each frame planar bar, figure 1.

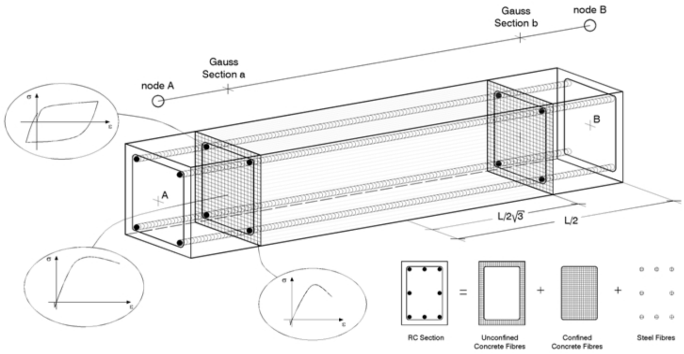


Figure 1 Bar element fibre-based modeling

The discretisation of an element cross-section is constituted by a sufficient number of subdivisions, extended throughout the element's length. From the uniaxial nonlinear stress-state response of each individual filament it is possible to obtain, through integration of the entire number of fibres, the sectional stress-strain state. Consequently, the main requirement to accurately model the cross-section material nonlinearity consists in the number of considered fibres. A sufficient number, around 200 to 400, can lead to good estimatives also in the case of high inelasticity.

Two control nodes – integration Gauss points – per structural element and distributed alongside its longitudinal axis (covering the entire fibres) are used for the numerical integration, with a cubic inelastic formulation, suggested by Izzudin, B.A. (1991). The interaction between axial and transversal deformations (the beam-column effect) is implicitly introduced in the Izzudin's cubic formulation, wherein the internal deformation state is completely traduced by means of the axial deformation and the generalised curvature along the local element axis. This cubic equation allows calculating the transversal displacement (v) as a function of the extremity rotation ($\vartheta$), at a position $x$ of the element's length, Eqn. 2.1.

$$v(x) = \left(\frac{\vartheta_1 + \vartheta_2}{L^2}\right)\cdot x^3 - \left(\frac{2\vartheta_1 + \vartheta_2}{L}\cdot L\right)\cdot x^2 + \vartheta_1 x \qquad (2.1)$$

Previous equation is particularly adopted to short concrete elements, where the axial force assume a constant value over its length. Therefore, a precise inelastic structural modeling requires a minimum number of sub-elements per structural bar.

This nonlinear modeling is implemented in the well-known commercial software SeismoStruct (SS), which has been used in this work.

### *2.2. Concentrated Nonlinearity Model*

In opposition to the previous methodology, the concentrated nonlinearity model considers the entire structural material inelasticity located only at specific points of each element – the hinges. These plastic hinges represent points where the nonlinear material deformation occurs, being situated through elements' extremities because of higher bending forces. The plastic hinges behaviour is traduced by a moment versus curvature relation, inherent to each element. The ultimate deformation capacity depends on the ultimate curvature and plastic hinge length.

Consequently, the first step consists of depict the bars' moment-curvatures function, that will traduce the correspondent nonlinear behaviour of that element. This law is obtained by a fibre model program, developed by Vaz, C.T. (1992) named BIAX, where for a specific bar element, loaded by a pre-defined and constant axial load, an increasing curvature is imposed being obtained the correspondent moments.

Following, it is necessary to define the correct positioning of the plastic hinges and their length. Herein, a sensitive study has been done, concluding that the ideal location for the hinges corresponds to a distance, relatively to the extremity, equal to half of the hinge length. It has also been revealed that calculating the hinge length using the most current equations (Park and Pauley, 1975, Priestley and Park, 1984, or Park et al., 1982) provided similar results, thus the plastic hinge length is obtained from half of the cross-section height.

The concentrated nonlinearity model is implemented in this work using the commercial software SAP2000 (SAP) and an academic program, PNL (PNL).

## 3. NONLINEAR STATIC PROCEDURE

In order to accomplish the seismic assessment of RC frame buildings with different nonlinear models was carried out a pushover analysis. The verification and employment of Nonlinear Static Procedures (NSP) have been extensively presented to the scientific community, and in continued advancement, due to its potentialities in what seismic analysis and simplicity concerns (Antoniou, S. and Pinho, R., 2004).

Within this study it is followed a force-based pushover technique proposed by Fajfar, P. and its co-workers (1988), the N2 method. This procedure is established in the European Code 8 (2005), featuring a pushover analysis of a multi-degree-of-freedom (MDOF) structure, with an inelastic response spectrum of its single-degree-of-freedom (SDOF) system. The capacity curve – a relation between the control node displacement and the base shear force – definition is dependent to the considered control node (usually a node at the roof top level) and to the load shape definition (herein an uniform and a modal shape were adopted). The performance point is obtained from the intersection of the initial period of vibration of the equivalent SDOF system and an inelastic spectrum, based on the ductility inherent to the structure.

## 4. PARAMETRIC STUDY

### *4.1. Structural and General Descriptions*

During the current work were analysed two existing RC frame buildings, representing the typically non-seismically designed structures (gravity-only designed), with geometric irregularities and different number of storeys, figure 2.

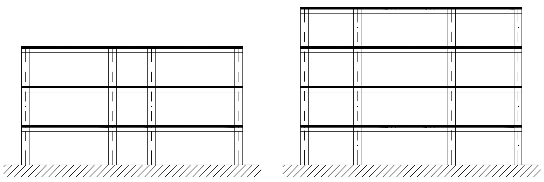

Figure 2 Considered frame buildings

The structure at left side, labelled as “mod4”, has 3 storeys with 2.75, 3.25 and 3.25 m height respectively, and 3 spans per storey level, with 4.05, 2.0 and 3.5 m. The remaining frame, labelled as “mod6”, has 4 storeys with 2.7 m each, and 3 spans per storey with 2.5, 5.0 and 5.0 m. The structural elements were subdivided into four bar elements to better traduce the structural response in the different inelasticity modelings. These buildings were involved under a seismic action assessment, by means of a nonlinear static pushover analysis and two different plasticity models, controlling the structural response by a maximum admissible interstorey drift of 4%.

The seismic action employed in the present work is defined by ten accelerograms, selected from a real-earthquake database in California, covering a range of magnitudes and epicentral distances. A significant duration between the build up of 5 to 95% Arias Intensity was considered in each record. These records were therefore scaled to match the NEHRP design spectrum (SAC joint venture, 1997), defined with a 10% probability of exceedance in 50 years (475 years return period) for Los Angeles; this represents the 1.0 intensity level. Furthermore, was introduced a proportional factor, to the seismic action, of 0.25, 0.5, 0.75, 1.25 and 1.75. The demand spectrum used in the Non-linear Static Procedure (NSP) corresponds to the median demand spectrum of ten accelerograms, shedding potential irregularities presented in single accelerogram spectra.

The seismic demand through the analysed structures is evaluated in terms of response parameters such as: Displacements (D), Interstorey Drifts (ID), Base Shear (V), Interstorey Shear (IV) and Ductility (Duct). Then, in order to appraise the accuracy of the different nonlinear models (and softwares), these factors are normalised with respect to the median of the corresponding response quantities obtained through the fibre plastic model – that is assumed as the most exact method, Eqn. 4.1. This normalisation provides also fairly "comparable" all response parameters, since the normalised quantities have the same unitary target value, thus appearing the definition of a building index. The building index (BI), Eqn. 4.2, is computed as the median of normalised results for the considered parameter, Δ, throughout all m locations; the standard deviation (STD), on the other hand, measures the associated dispersion with respect to the median.

$$\overline{\Delta}_i = \frac{\Delta_{i,hinge}}{\hat{\Delta}_{i,\,fibre}} \cdots \underset{ideally}{\rightarrow} 1 \tag{4.1}$$

$$BI_{\Delta} = median_{i=1,m}\left[\overline{\Delta}_i\right] \tag{4.2}$$

### *4.2. Structural Evaluation*

This global results overview is presented separately for both structures, initially are depicted the (i) correspondents capacity curves for the nonlinear model approaches, then the (ii) comparison between the different techniques, traduced by building indexes (BIs) by response parameter and finally the (iii) associated scatter – standard deviation (STD).

#### *4.2.1. mod4 – Results*

Figure 3 depicts the relation between the base shear force and the displacement of the control node at top roof level, using an uniform and a modal load shape force distribution. These forces are applied through each structural node. It is noticeably revealed that, notwithstanding a slightly maximum base shear force obtained through the fibre modelling, there are no major differences amongst the capacity curves.

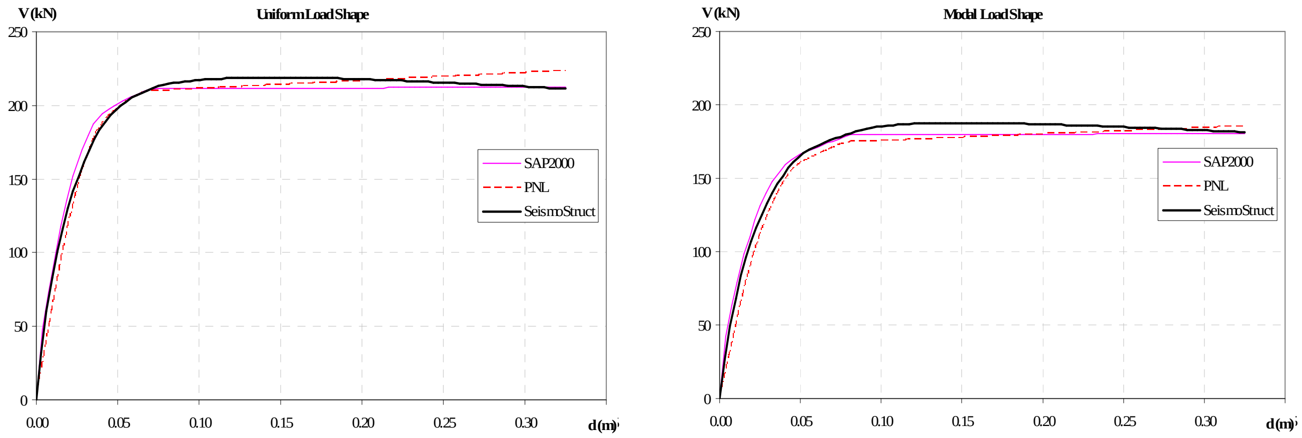


Figure 3 Capacity curves considering an uniform and a modal load shape

According to structural parameters, it has been compared the previously referred building indexes (BI) between the plastic hinge models and the fibre-based model, over the 6 intensity levels (I.Lv.), figure 4, for both uniform and modal load shapes.

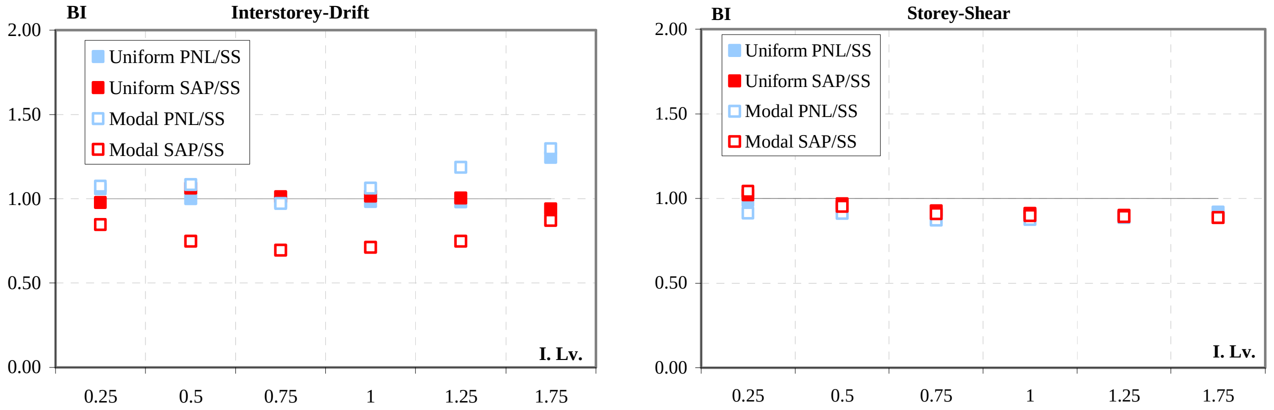


Figure 4 Building-Indexes over the entire intensity levels

An additional results overview consists on the computation of the median BI over all intensity levels, figure 5.

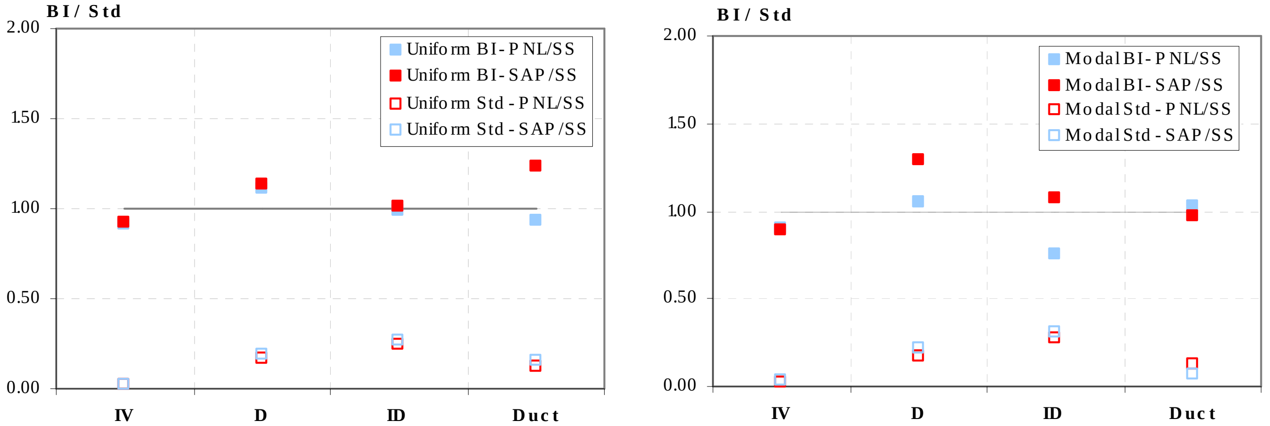


Figure 5 Median Building-Indexes and Standard-Deviations over all entire intensity levels

Due to space constrains it is not possible to represent the entire role of analysed response parameters, although, similar conclusions can be attained. Generally, quantities based on displacements produce higher differences between the two types of nonlinear models, and between the two plastic hinges softwares, particularly in what concerns to the modal load shape (traduced by a greater scatter level). On the other hand, shear parameters assume an almost perfect comparison between different inelastic modelings, and at the same time lower dispersion values, for both load patterns. When it is evaluated the BI involving the whole intensity levels, a closest to unit index is revealed for both plastic hinge based programs, with enhanced results when performing an uniform pattern pushover analysis. The assessed response parameters are characterized by lower dispersion levels.

Major divergences between the two nonlinear models are linked with the appearance of tension forces through beam elements, when it is performed a pushover analysis applying the lateral loads in each node in contrast of applying the forces distribution over the first piers' alignment. This fact is accounted for by SeismoStruct considering a linear tensile strength relationship, in opposition SAP2000 and PNL assume non tensile strength and that axial loads do not influence the nonlinear behaviour of each section.

In general, the study of *mod4* building has indicated relatively good approximations from nonlinear concentrated to nonlinear distributed modelings, with better accuracy for shear quantities, and also specifically to an uniform load shape. It is not possible to point out a plastic hinge program from the considered ones, with only diverged values for the modal pattern.

*4.2.2. mod6 – Results*

*Mod6* frame building revealed a slightly different behaviour between nonlinear models, comparing to *mod4*. Herein, it has been detected a less ductile structure, traduced by an abrupt decay of the maximum strength given by the fibre-based model, figure 6. This can be explained by the impossibility to traduce through plastic-hinges softwares the moment-curvatures functions from which, each section reaches its maximum moment. The fact that SeismoStruct is the only to consider P-delta effects can explains in part the global structural post-yielding behaviour, in agreement with the statement that the third alignment (from the left) governs the overall performance due to its higher lateral stiffness, thus a degradation of this piers will conduct the structure to a global mechanism that follows a different path to the other models.

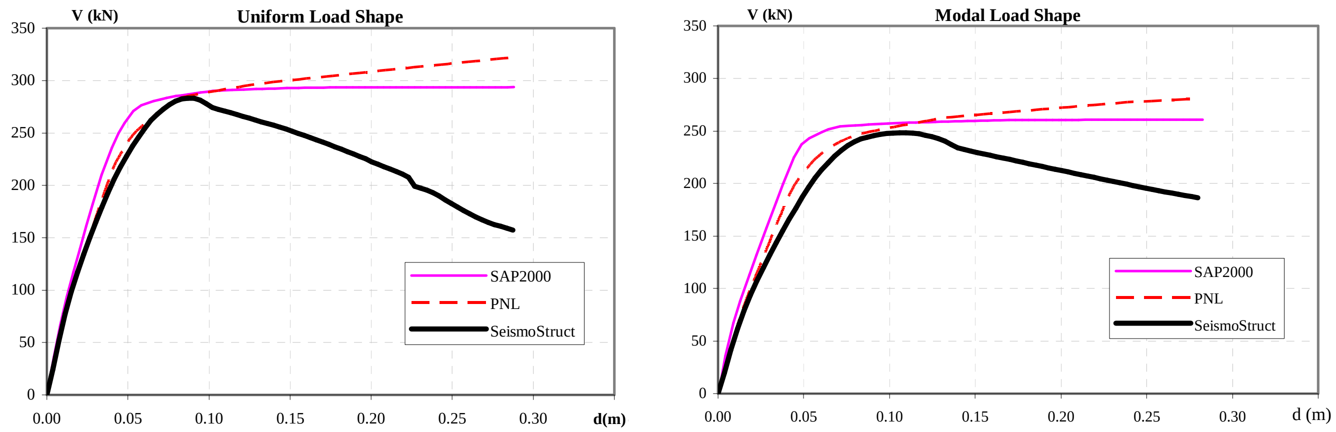


Figure 6 Capacity curves considering an uniform and a modal load shape

According to structural parameters, figure 7 evidences similar results between both plastic-hinges softwares, and also with the fibre-based model. Nevertheless, major differences in median BI values (and consequently, higher dispersion, Std) can be explained by the distinct post yielding behaviour, depicted in the capacity curves. The beginning of these differences corresponds to an intensity level equal to 0.75.

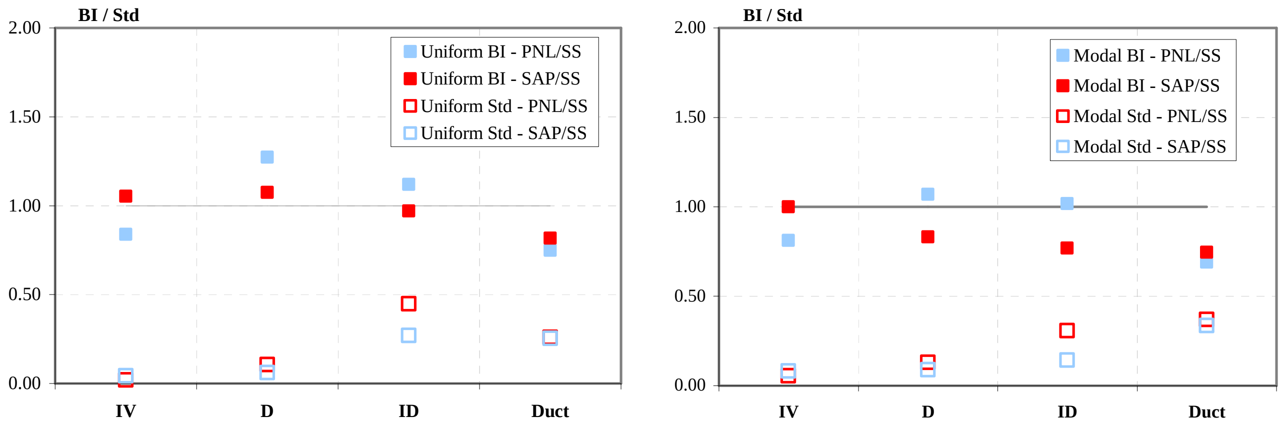


Figure 7 Median Building-Indexes and Standard-Deviations over all entire intensity levels

## 5. CONCLUSIONS AND CONCLUDING REMARKS

The present endeavour aims at validating the effectiveness of employing different nonlinear models in the seismic assessment of RC frame buildings using a pushover analysis, through comparison with results of both techniques for three different softwares. The study revealed a globally good response estimates between a plastic-hinge modeling and a fibre-based modeling, represented by a building index value, BI, inherent to a specific structural response parameter. These results evidenced an intrinsically dependence to the analysed frame building being necessary a rigorous interpretation of the structural behaviour to the applied loading and a complementary study involving both, upgrades to the plastic-hinges based softwares and a higher set of frame buildings, covering seismic dimensioning and regular and irregular structures.

To assure an improved comparison, the plastic-hinges definition in terms of moment-curvatures function should well characterize this relation. Characterizing this relation from the point that is mobilized the maximum admissible moment. This fact is not implemented in the SAP2000 and PNL softwares, its influence can be easily seen in *mod6* structure, evidenced by figures 6 and 7. Geometric nonlinearities in both plastic-hinges programs should also be assumed.

Another diverging issue may be linked with the fact that SeismoStruct considers the stiffness degrading on tensioned elements, represented by a linear tension strength relation, however the other involved softwares do not account for this reduction of stiffness what explains some differences between these two models. Subsequently, it should be implemented when it is performed a comparison between nonlinear models.

Finally, as future developments, this study should also be developed following different pushover modalities, for instance the Adaptive Capacity Spectrum Method, Modal Pushover Analysis or Capacity Spectrum Method and these results compared also with the dynamic nonlinear analysis, in order to establish a complete comparison.

## ACKNOWLEDGMENTS

Financial support to the first and third authors was provided by the Portuguese Science and Technology Foundation (FCT – Fundação para a Ciência e a Tecnologia). This study was partially performed with the financial support of the FCT through the Project PTDC/ECM/72596/2006, “Seismic Safety Assessment and Retrofitting of Bridges”.

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