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SEISMIC SAFETY ASSESSMENT OF CURVED BRIDGES USING PUSHOVER ANALYSIS

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Abstract. *The seismic safety assessment of bridges using nonlinear static analysis methods is not straightforward. Not only an accurate modelling of the structural frames inelastic behaviour is required, but also a correct definition of the force distribution patterns, analysis directions, reference points and target displacements that best represents its seismic structural performance. This difficulty on the pushover parameters definition increases when irregular-in-plan bridges are considered, namely curved bridges. Hence, the aim of this study is to assess the seismic safety of a set of curved bridges using the eurocode's pushover analysis method. Particular attention is paid to the RC columns biaxial behaviour modelling. The bridge structural response is evaluated in terms of global and local capacities. Comparative evaluation of the calculated response of the bridges illustrates the applicability of the N2 pushover method and the influence of the different directions of analysis in its local and global capacity demands definition.*

1 INTRODUCTION

Since the early 1960s, irregular-in-plan curved bridges have gained high popularity, particularly in the highway interchanges and urban expressways, as a result of geometric constraints, limitations of space and high density of urban traffic [1].

However, due to the relative particularity of its forms, curved bridges present an apparently different dynamic response when compared to common straight bridges, which may naturally affect its seismic behaviour. Indeed, in view of the collapse of some curved bridges during the 1971 San Fernando earthquake, United States of America, D. Williams and W. Godden [2] conducted a shaking table test study of a scaled microconcrete curved bridge model, which main objective was to evaluate the effects of both linear and nonlinear dynamic behaviour and the influence of the expansion joints to its resistance capacity. W. Tseng and J. Penzien [3] have also studied the nonlinear seismic response of long, multiple-span, reinforced concrete curved and straight bridges, and concluded, alike [2], that the ductility requirements at the column bases of curved bridges are not so critical and important compared to the levels observed in long straight bridges.

Likewise, N. Burdette and A. Elnashai [4] observed that, in the transverse direction, the curved decks provide greater stiffness to the structure through arch or catenary action, while the straight decks resists transverse forces in flexure, which allows more of the pseudostatic displacements to be absorbed by the bridge deck. However, when the longitudinal direction was analysed, the opposite was observed, that is to say, curved bridges resists inertial forces by a combination of flexural and axial stiffness of the deck, while the straight bridge deck resists these forces efficiently in pure tension and compression, giving the structure a greater stiffness longitudinally.

Therefore, the seismic response of curved bridges usually should be considered in both longitudinal and transverse directions, having the direction of the input seismic action, the planar irregularity and the two-axis related bending a great role on the maximum values of the response [5-8].

The use of nonlinear dynamic time-history analysis (THA) is, by far, the most reliable method to assess the seismic behaviour of structures, particularly the irregular ones. However, it requires a high effort of computational capacity and time, which increases when multi-directional seismic actions are considered. Thus, nonlinear static pushover analysis (PA) appears as an interesting alternative, more simple and expeditious.

The applicability of PA method to bridges has been extensively studied recently and numerous variants of the traditional method, with increasing accuracy and complexity, are available today [9-11]. However, a limited number of studies focused the use of pushover analysis in curved bridges [5, 12-14].

The seismic assessment of bridges using PA methods is not straightforward. Not only an accurate modelling of the structural frames inelastic behaviour is required, but also a correct definition of the force distribution patterns, analysis directions, reference points and target displacements that best represents its seismic structural performance. This difficulty increases when irregular-in-plan bridges are considered, since the columns tend to present biaxial behaviour and the critical input angle of the seismic action, as well as the respective direction of analysis, vary with the type and curvature of the structure.

In view of the previous considerations, the present study attempts to assess the seismic response of a set of curved bridges using the Eurocode's [15, 16] pushover method. Some practical procedures that take into account the different directions of analysis are presented and the results obtained compared to those obtained using THA. Special attention is paid to the evaluation of the seismic action critical input angle and to local and global capacities.

2 PUSHOVER ANALYSIS PROCEDURE

The PA method proposed by the Eurocode 8 is the well known N2 method, firstly developed by P. Fajfar and M. Fishinger [17] to assess the seismic behaviour of regular buildings. The Eurocode 8 presents the PA procedure for bridges in both Parts 1 [15] and 2 [16], defining, in the first, the method to determine the target displacement from the structures capacity curve and, in the second, the parameters that allow the capacity curve definition, such as the directions of analysis, reference points and load distributions.

As mentioned above, with the increasing of the curved bridges radius of curvature, the dynamic response tends to change significantly. In these cases, the principal direction of analysis is no longer the transversal one and a set of different oriented directions of analysis should be considered, in order to obtain the critical response direction. According to Eurocode 8, only two horizontal directions of analysis should be considered: a longitudinal X-direction, defined by the centres of the two end-sections of the deck; and a transverse Y-direction, that should be assumed to be orthogonal to the first.

Additionally to these directions of analysis, the Caltrans SDC [18] recommends the application of the ground motion along the principal axes of individual components. The ground motion must be applied at a sufficient number of angles to capture the maximum deformation of all critical components.

Therefore, having both normative recommendations in consideration, the steps of the PA adopted procedure are summarized in the following:

- Once defined the geometry and the structural models of all analysed bridges (Figure 2 (A)), the first step consists on the selection of the PA load distribution patterns (Figure 2 (B)). According to Eurocode 8 the pushover curves must be obtained by pushing the entire bridge structure with two load distributions patterns: a constant along the deck pattern (PAc) and a proportional to the first mode shape pattern (PAm). In spite of not being mentioned by the European Standard, it is recommended [12, 13] to carry out the pushover analysis in both positive and negative transverse direction when irregular-in-plan structures are not symmetric. Since the importance of the longitudinal response of curved bridges increases with the radius of curvature, a third pushover pattern (proportional to the mode with higher mass participation factor in the X-direction) is also proposed by some researchers [12,13] (PAxm). Finally, with the objective of capture the critical direction of the curved bridges response, a constant along the deck pattern with a variable local axis orientation (PAvoc) will be adopted as well. It should be noted that the global X-Y axis is defined by the Eurocode’s directions of analysis and the local X’-Y’ axis by the principal axes of individual columns elements and abutments, as presented in Figure 1.

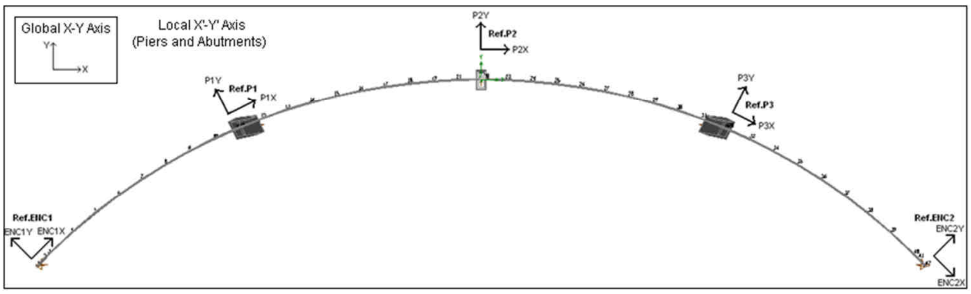


Figure 1: Local and Global axes.

- The second step concerns the construction of the total base shear vs displacement of reference point pushover curve for each considered load distribution pattern (the reference point, according to Eurocode 8, should be the centre of mass of the deformed deck) and for the various directions of analysis. The local X´-Y´ axis capacity curves are obtained from converted deck displacements and shear forces, as it is represented in Figure 2 (C).
- The last step of the presented PA procedure refers to the determination of the earthquake displacement demand associated with each pushover curve obtained previously (Figure 2 (C)). For such, the multi-degree-of-freedom (MDOF) system pushover curves must be transformed into equivalent single-degree-of freedom (SDOF) system pushover curves through a transformation factor, Γ, as it is proposed in [15]. This transformation factor depends on the normalized displacements, which should be taken as local axis converted normalized displacements depending on the direction of analysis. Once determined the target displacement for the SDOF system, d_t*, using an idealized elasto-perfectly plastic force-displacement relationship, the final MDOF system target displacement of the control node, d_t, is given by Γd_t* (Figure 2 (C)).

Previous studies [9-11] have shown that traditional PA methods generally works reasonably well when applied to bridges of regular configuration. However, T.S. Paraskeva *et al* [12] concluded that a single mode-based load pattern should not be used in bridges with strong curvature in plan, even when they qualify as regular. Hence, the results obtained using the presented PA procedures should be evaluated by comparisons with those obtained using a more accurate THA (Figure 2 (D)).

3 STRUCTURAL MODELING AND DYNAMIC CHARACTERISTICS OF THE ANALYSED CURVED BRIDGES

This study considered six different curved bridges, defined from the well-known P232 PREC8 regular bridge [19], with infinite, 1000m, 700m, 420m, 240m and 130m radius of curvature of the deck, as represented in Figures 2 (A).

The bridges were modelled using the SAP2000 analysis program considering concentrated plasticity at the columns base (Figure 3), so as to represent the Eurocode’s idealized local ductility cantilever model. SAP2000 allows the definition of lumped inelastic rotational hinges through backbone uncoupled or interaction MM models and fiber models [20]. Although the use of backbone models, with Takeda’s hysteretic model, ensures a lower effort of time and processing capacity, they fail to perform a 3-dimensional dynamic analysis. Thus, knowing the importance of the columns biaxial behaviour in curved bridges, a more accurate fiber hinge model was adopted. The fiber hinge computes a moment-curvature relation in any bending direction for varying levels of axial load by assigning particular material stress-strain relationships to individual discretized fibers in the cross section. The longitudinal column reinforcement stress-strain relationship was defined by a bilinear model with kinematic hysteretic behaviour, while the confined and unconfined concrete stress-strain relationships were defined by the J. Mander *et al* [21] model with Takeda’s hysteretic behaviour. The lumped plasticity is assumed to occur over a plastic hinge length and is specified at the middle of the plastic hinge. The plastic hinge length was defined by the Eurocode’s Annex E [16] expression. The remaining elements of the structure were taken as linear-elastic and the masses were lumped at the top of the columns and midspans (Figure 3).

The individual capacity curves of each column of the P232 Bridge, defined in terms of moment-displacement and force-displacement relationships, for both longitudinal and transverse directions, are presented in Figure 4.

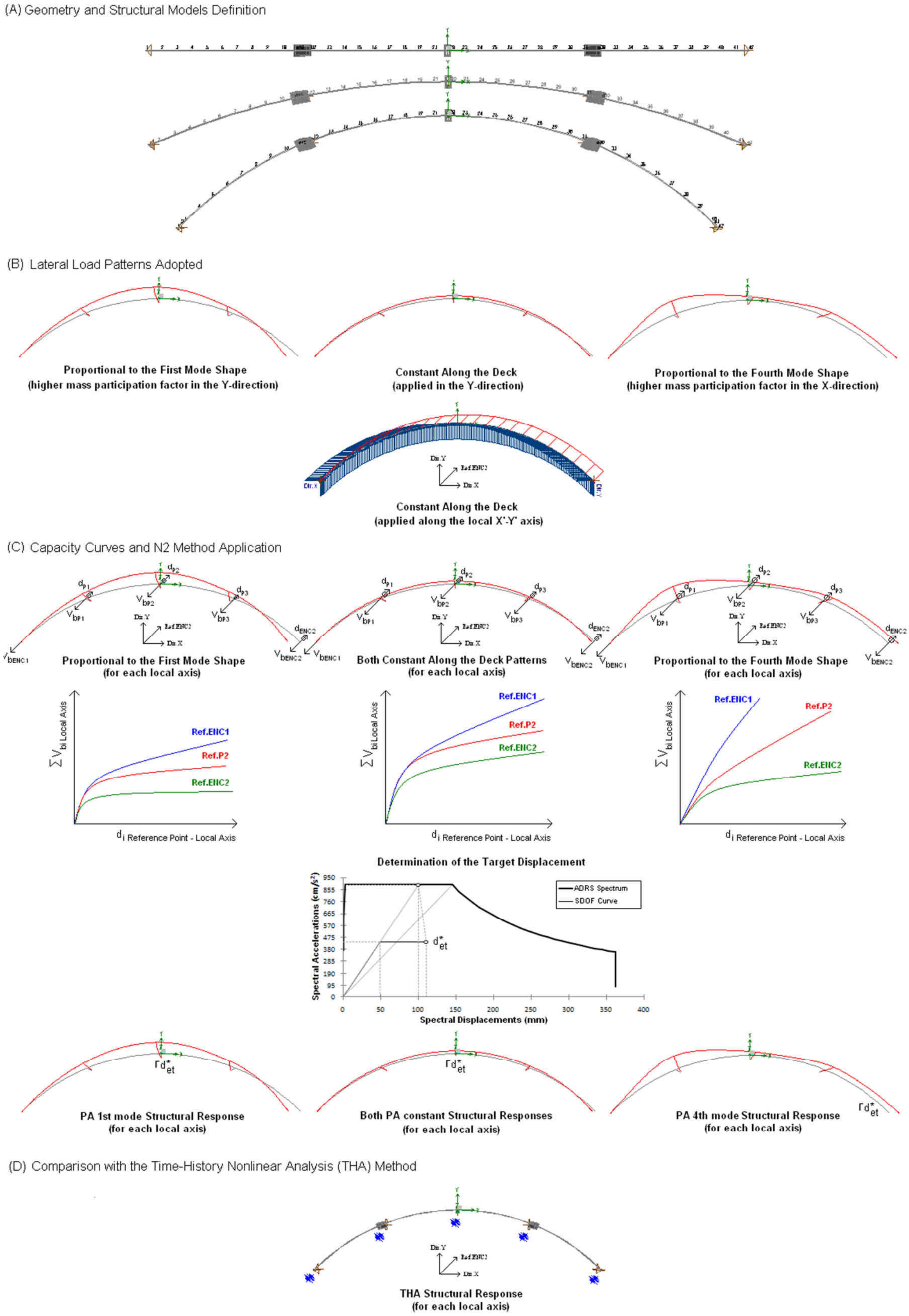


Figure 2: Analysis procedure adopted.

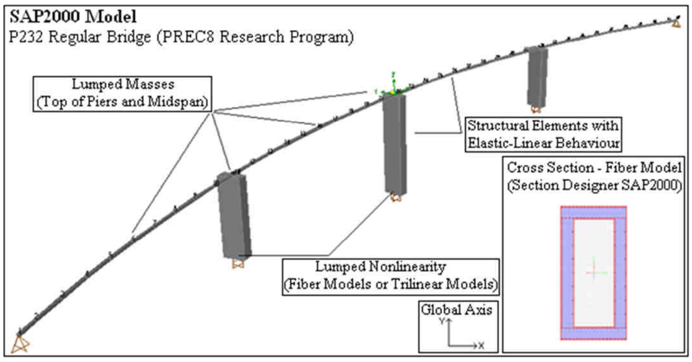


Figure 3: Structural model with concentrated plasticity at the columns base.

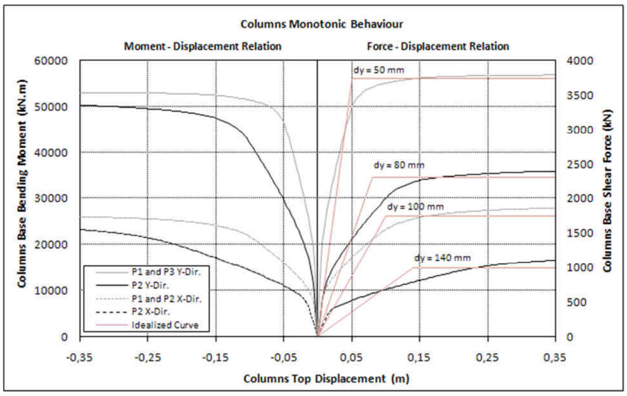


Figure 4: Capacity curves of each column in both longitudinal and transverse directions.

It is also presented in Figure 4 the yield displacements values of the RC columns in both directions, evaluated by idealising the actual F-d diagram by a bilinear diagram of equal area beyond the first yield of reinforcement, as it is proposed in [16].

With regard to the dynamic characteristics of the analysed curved bridges, it can be seen from Figure 5 a significant and expected variation on the modal eigenvalue properties with the increase of the radius of curvature. Likewise, Table 1 exhibits the evolution of the modal mass participation ratios of the 1^{st} and 4^{th} modes of vibration (which represents, respectively, the bridges responses on the transverse and longitudinal directions) with the curvature of the deck, being evident a counterbalanced decrease of the 1^{st} mode importance with the increase of the 4^{th} mode importance in the Y-direction, and the opposite in the X-direction.

Modal Mass Participation Ratios (%)				
Bridges	1^{st} Mode of Vibration		4^{th} Mode of Vibration	
	Y-Direction	X-Direction	Y-Direction	X-Direction
Straight Bridge	91	0	0	90
Radius = 1000m	89	1	0	64
Radius = 700m	89	2	0	58
Radius = 420m	85	5	13	40
Radius = 240m	76	14	20	42
Radius = 130m	54	34	36	23

Table 1: Evolution of the modal mass participation ratios with the curvature of the deck.

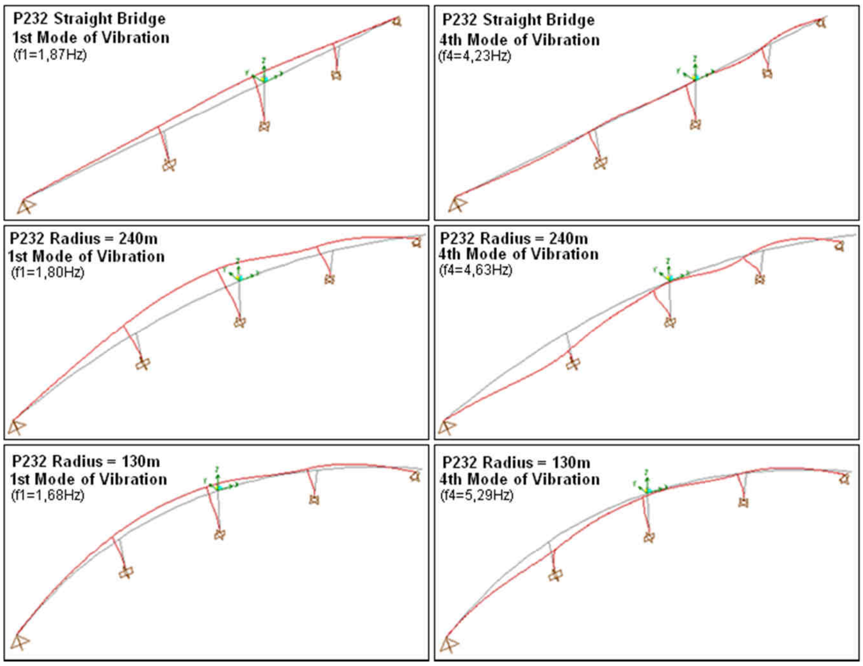


Figure 5: Transverse and longitudinal mode shapes and respective frequencies of vibration.

Before presenting the main results obtained through the adoption of the previously exposed PA procedures, some preliminary values, in terms of target displacements, are displayed in Figure 6. An evident divergence between the PAm, PAc and PAxm results is observed, particularly in the case of the PAxm results, which are well below the expected. Hence, as the PAxm results are not representative, from now on they will not be considered.

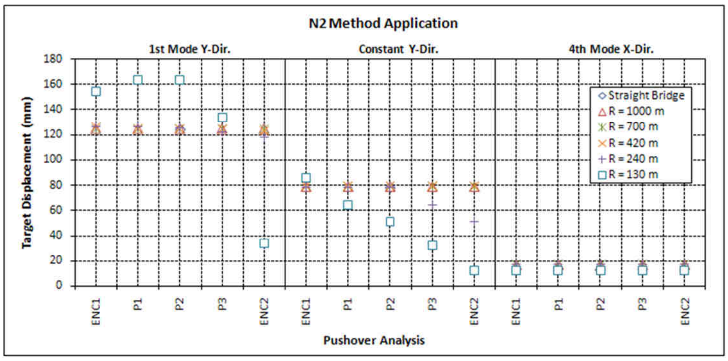


Figure 6: N2 Method application: target displacement values.

4 PUSHOVER CAPACITY CURVES

The pushover capacity curve definition step is one of the most important in the PA procedure, since it is the step that defines the structures characteristics through their total base shear vs displacements of the control node curves. As mentioned above, in order to represent the behaviour of the bridges in several directions of analysis, the construction of the capacity curves will be conducted from local axis converted deck displacements and shear forces, being the chosen local axis systems defined by the principal axes of the individual columns elements and the abutments (Figure 1). These local axis systems were obtained from the rotation of the generic global X-Y axis, with the rotation angles presented in Table 1 for each analysed curved bridge.

Local Axis Rotation (º)					
Bridges	ENC1	P1	P2	P3	ENC2
Straight Bridge	0	0	0	0	0
Radius = 1000m	5,5	3,0	0	-3,0	-5,5
Radius = 700m	8,0	4,3	0	-4,3	-8,0
Radius = 420m	13,4	7,2	0	-7,2	-13,4
Radius = 240m	23,9	12,6	0	-12,6	-23,9
Radius = 130m	44,9	23,8	0	-23,8	-44,9

Table 1: Global to local axis rotation.

Therefore, the PAm, PAc and PAvoc capacity curves, for each local axis systems and both X' and Y' directions, are plotted in Figures 7 to 12. Two major conclusions can be drawn by the analysis of these figures, concerning the influence of the local axis and the curvature of the deck.

Firstly, and as aforementioned above, it is easy to verify a significant variation in the curved bridges structural response with the increase of radius of curvature. If one only considers the local P2 axis results, which are identical to the global axis results, an important divergence in the Y'-direction pushover curves can be noted in the case of the PAc and PAvoc (Figures 9 and 11). For instance, under these circumstances, a similar 0,1m displacement demand at the top of the P2 central pier leads to a 25000 kN base shear in the stronger curved-in-plan bridge, while in the straight bridge it only leads to a 15000 kN base shear, representing a 40% variation. On the other hand, the X'-direction capacity curves revealed a higher divergence in the PAm (Figure 8), as expected with the evolution of the modal mass participation ratios. Thus, it can be seen that the longitudinal capacities of the analysed bridges increased, from zero (straight bridge), with the increase of the first mode X'-direction participation ratios.

The second major conclusion concerns the influence of the local axis systems in the definition of the analysed bridges pushover curves, and, consequently, on their structural capacities along the various directions of analysis. Not only can be observed from Figure 12 that bridges with stronger deck curvature tend to be more affected by different directions of analysis, but also that the direction of analysis defined by the ENC2 local axis seems to lead to lower capacity curves, while the ENC1 local axis direction of analysis lead to higher capacity curves, which is due to the higher longitudinal displacements of the ENC2 roller support.

The sequence of plastic hinge formation was also derived for both straight and higher curved bridges, as presented in Figure 13, which allows us to understand the latter conclusions. It can be noted that the sequence of plastic hinge formation is much closer to being simultaneous in the transverse direction of the straight bridge, behaving practically like an SDOF system, than in the transverse direction of the bridges with higher deck curvature for each local Y' axis, wherein hinging is also affected by higher modes, like the longitudinal mode, and takes place at differently stages of the response. Furthermore, as also displayed in Figure 13, the hinging formation inverts its sequence with the various directions of analysis, in agreement with the respective local axis converted first mode shapes. Thus, the P3 column reaches the yielding point (at a 0,5m displacement, Figure 4) earlier in the ENC1, P1 and P2 directions, while the P2 column is the one to first yield in the P3 and ENC2 directions, wherein the bridge response has rotated from its transverse response to its longitudinal response.

Interesting results were also observed through the application of the alternative constant along the deck patterns, PAc and PAvoc, whereby the forces acting at each node are proportional to the nodal mass in the considered directions of analysis. These patterns are mainly used as a mean of identifying critical combinations of shear and flexure in each vertical element of bridge structures. The PAc and PAvoc capacity curves bring forward a higher overall strength of the system when compared to the PAm capacity curves, which may be explained by the fact that, while the first mode shape tends to present a single column with a significantly larger displacement, and so with a higher modal force, the constant patterns tends to equally distribute the inertial force at all columns, if the masses at each one are similar. As a result, for the same displacement demand, higher forces are developed in the PAc and PAvoc cases.

In terms of PAc and PAvoc capacity curves comparison, it can be verified that, as the curvature of the bridges increase, the capacity curves tend to diverge, particularly in the case of the P3 and ENC2 local axis.

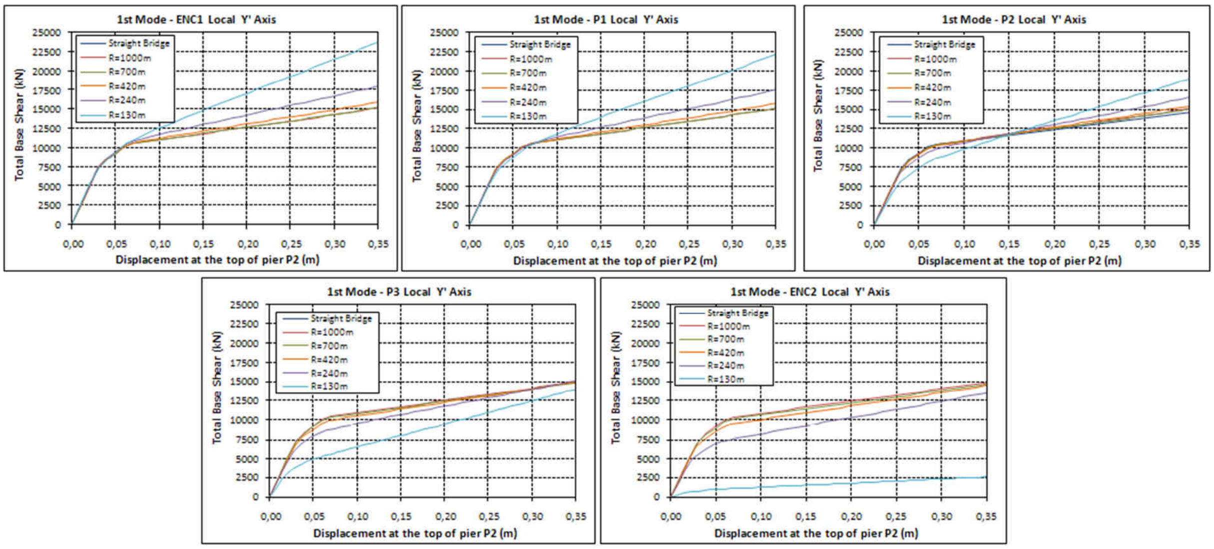


Figure 7: PAm capacity curves for each local Y' axis.

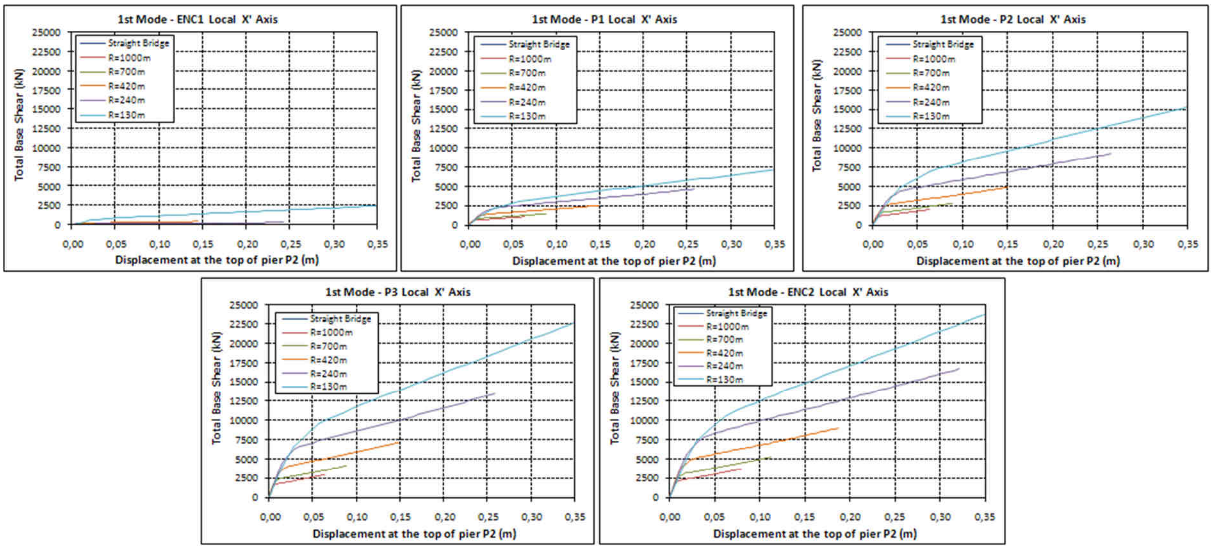


Figure 8: PAm capacity curves for each local X' axis.

Figures 9 and 11 demonstrate that the overall strength of the bridges grows with the rotation of the local axis from ENC2 axis to ENC1 axis, namely in the case of the more curved bridges. As said before, this grow can be explained by the change in the type of the response, what, in other words, means that ENC1, P1 and P2 local axis seems to characterize the transverse response of the bridges, while P3 and ENC2 local axis seems to represent their stiffer longitudinal response. Unlike the PAc procedure, that considers converted local axis capacity curves from the global axis capacity curve, and so equally converted inertial forces, the PAvoc method admits that the same inertial forces are applied in each direction, proportionally to the lumped masses. For this reason, the PAvoc capacity curves present a higher overall strength of the system comparatively to the PAc capacity curves. This may suggest that the PAc procedure loses feasibility when applied to bridges with strong curvature in plan.

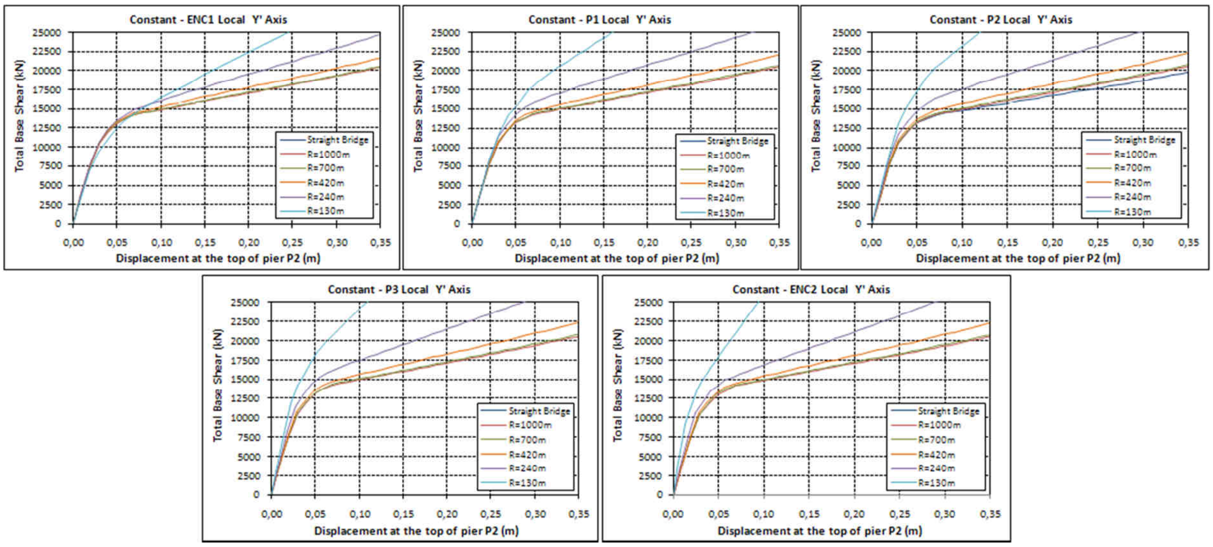


Figure 9: PAc capacity curves for each local Y’ axis.

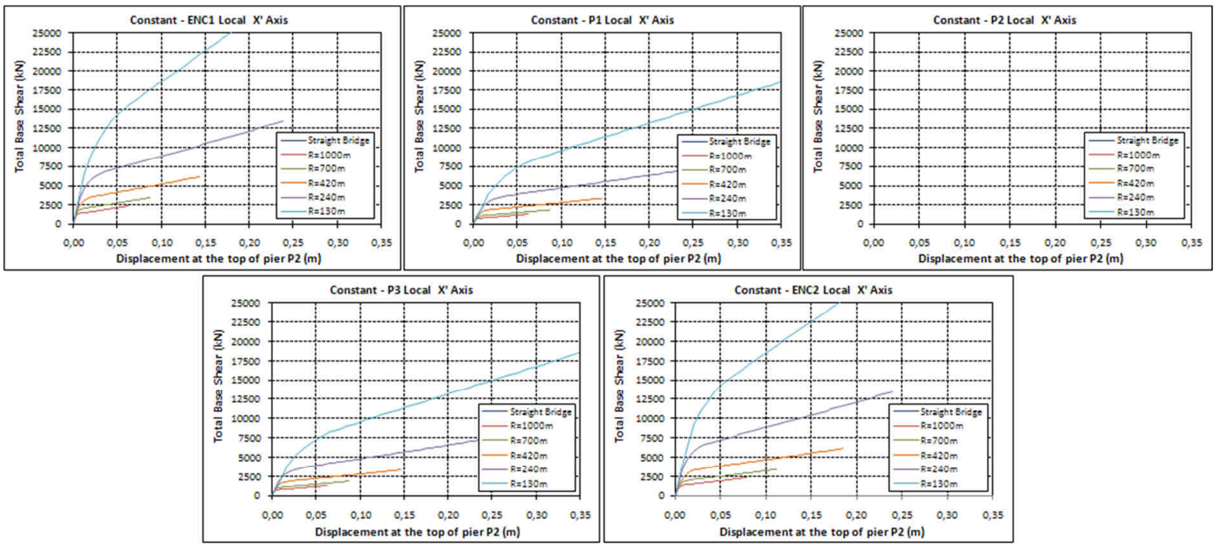


Figure 10: PAc capacity curves for each local X’ axis.

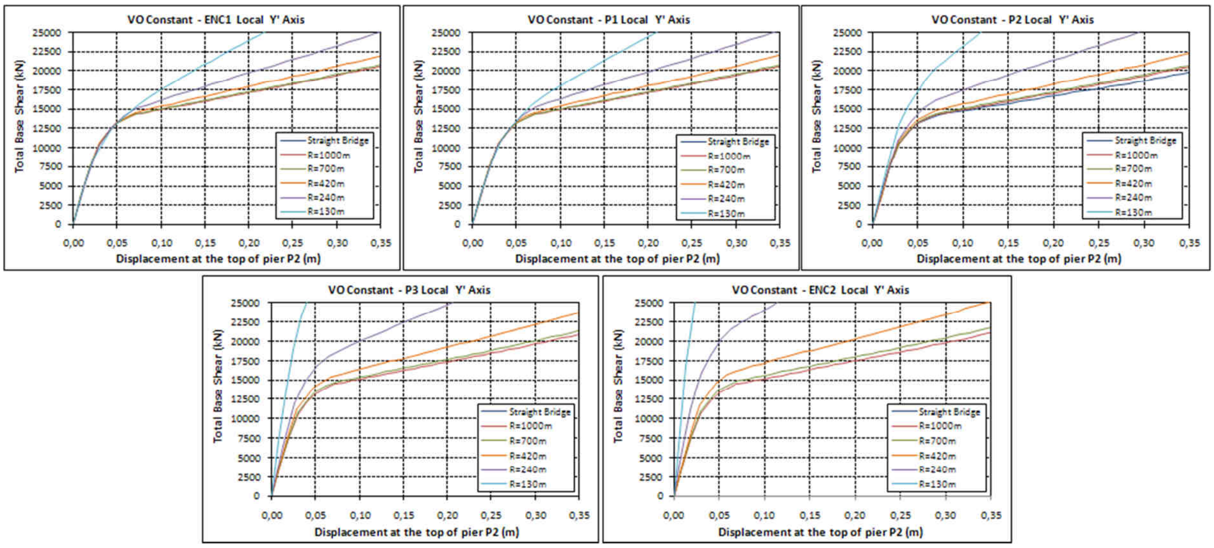


Figure 11: PAvoc capacity curves for each local Y' axis.

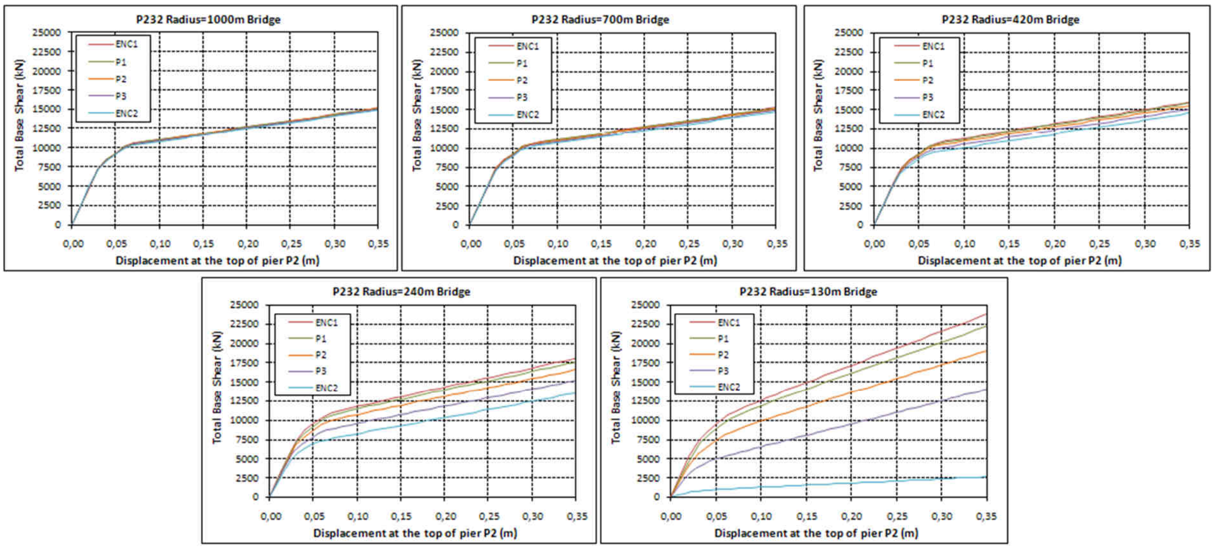


Figure 12: PAm capacity curves for each analysed curved bridges in local Y' axis.

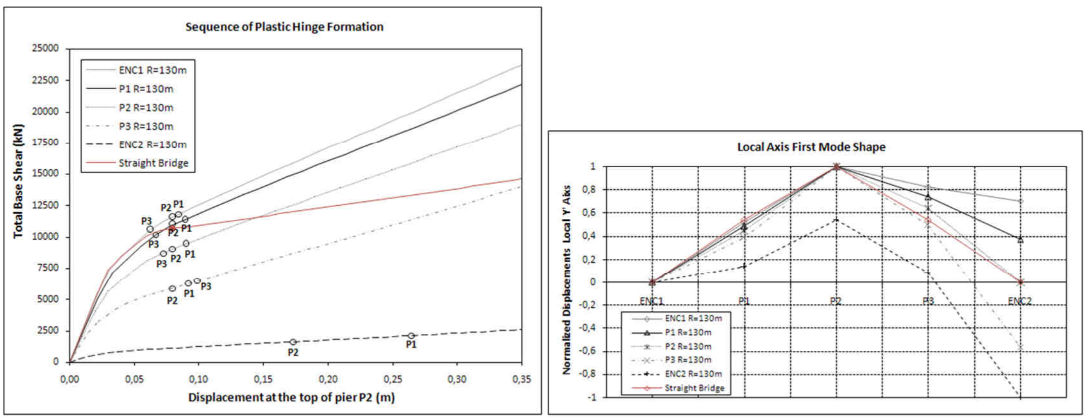


Figure 13: Sequence of plastic hinge formation and local axis converted first mode shapes.

5 APPLICABILITY OF N2 PUSHOVER METHOD

Previous studies [11, 12, 22] have shown that, for bridges with an effective modal mass of the fundamental mode equal or greater than 80% of its total mass, the N2 method in general works fine. Once, in short bridges the effective mass of the fundamental mode increases together with the seismic intensity, in this cases the accuracy of the N2 method also increases. Therefore, good results are expected with the application of the N2 method to bridges with high first mode modal mass participation ratios (Table 1).

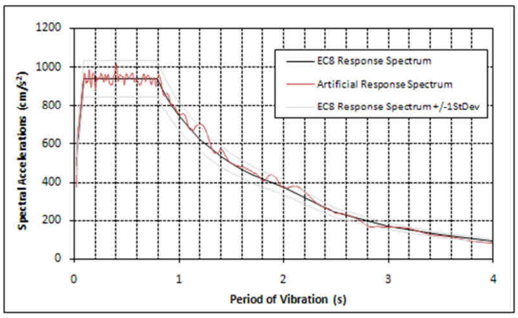
However, when this fundamental mode mass ratios decrease, the higher modes start to significantly influence the response, regardless of the seismic intensity. Hence, according to [12], simplified pushover procedures should not be used in bridges with high curvature in plan.

In line with the latter considerations, a most reliable analysis procedure must be used in order to correctly evaluate the applicability of the N2 method to all analysed bridges. Thus, the nonlinear dynamic time-history analysis (THA) will serve as a benchmark for this evaluation.

5.1 Nonlinear Time-History Analysis (THA)

Contrarily to the nonlinear static analysis methods, the THA accounts for strength degradation of different elements of the bridge, as well as the influence of all modes and the characteristics of the dynamic response, making it the more accurate method of analysis. The general approach for the solution of the dynamic response of structural systems is the direct numerical integration of the dynamic equilibrium equations at a discrete point in time. Several time-integration methods are available, such as the Newmark and Hilber-Hughes-Taylor (HHT) algorithms. According to [13], the latter is more beneficial under high input ground motions, because it can reduce the high short-duration peaks in the solution, therefore it will be employed in this study. It should be noted that, if convergence problems occur during nonlinear analysis, the HHT method should be used initially with an $\alpha = -1/3$ to get an approximate solution. The analysis should then be repeated with decreasing α values to obtain greater accuracy in the results [20]. Moreover, as the results are extremely sensitive to time-step size, a time step of 0,0001s is recommended to ensure a consistent convergence of displacements [22]. A uniform damping value of 5% was assumed for all modes of vibration, as proposed by [16] for reinforced concrete structures, through the use of the Rayleigh damping coefficients. The THA was conducted considering a set of artificial records compatible with the Portuguese EC8 elastic spectrum, as presented in Figure 14.

In spite of the SAP2000 fiber model ability to represent successfully the degradation and softening after yielding, it not includes the pinching and bond slip effects. Moreover, SAP2000 requires a high effort of processing time for a cross-section discretization number of 200 fibers and the referred time step size. Therefore, the THA analysis was conducted using the SeismoStruct analysis program, well known by the scientific community.



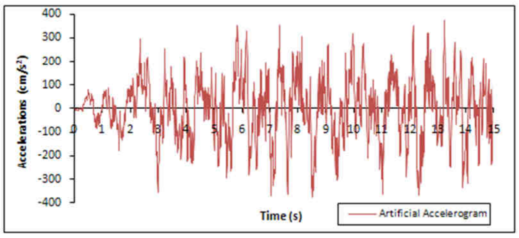


Figure 14: Seismic action adopted: EC8 response spectrum (Type 1 seismic action, Zone 1 and Ground Type D of the Portuguese National Annex) and respective generated artificial accelerogram and response spectrum.

Figures 15 and 16 depict the THA results, being evident the same conclusions drawn in the previous analysis of the pushover capacity curves. In agreement with the dynamic characteristics of the studied curved bridges, as the curvature in plan increases, the higher modes of the structure gain importance, namely the longitudinal mode of vibration. Thus, it may be seen from Figure 15 a reduction on the bridges Y-direction flexural bending moments and a contrary increase in the X-direction flexural bending moments, of approximately 40% in the P1 pier and 70% in the P3 pier, respectively. From Figure 16 it can also be observed the evolution of the longitudinal response of the various studied bridges.

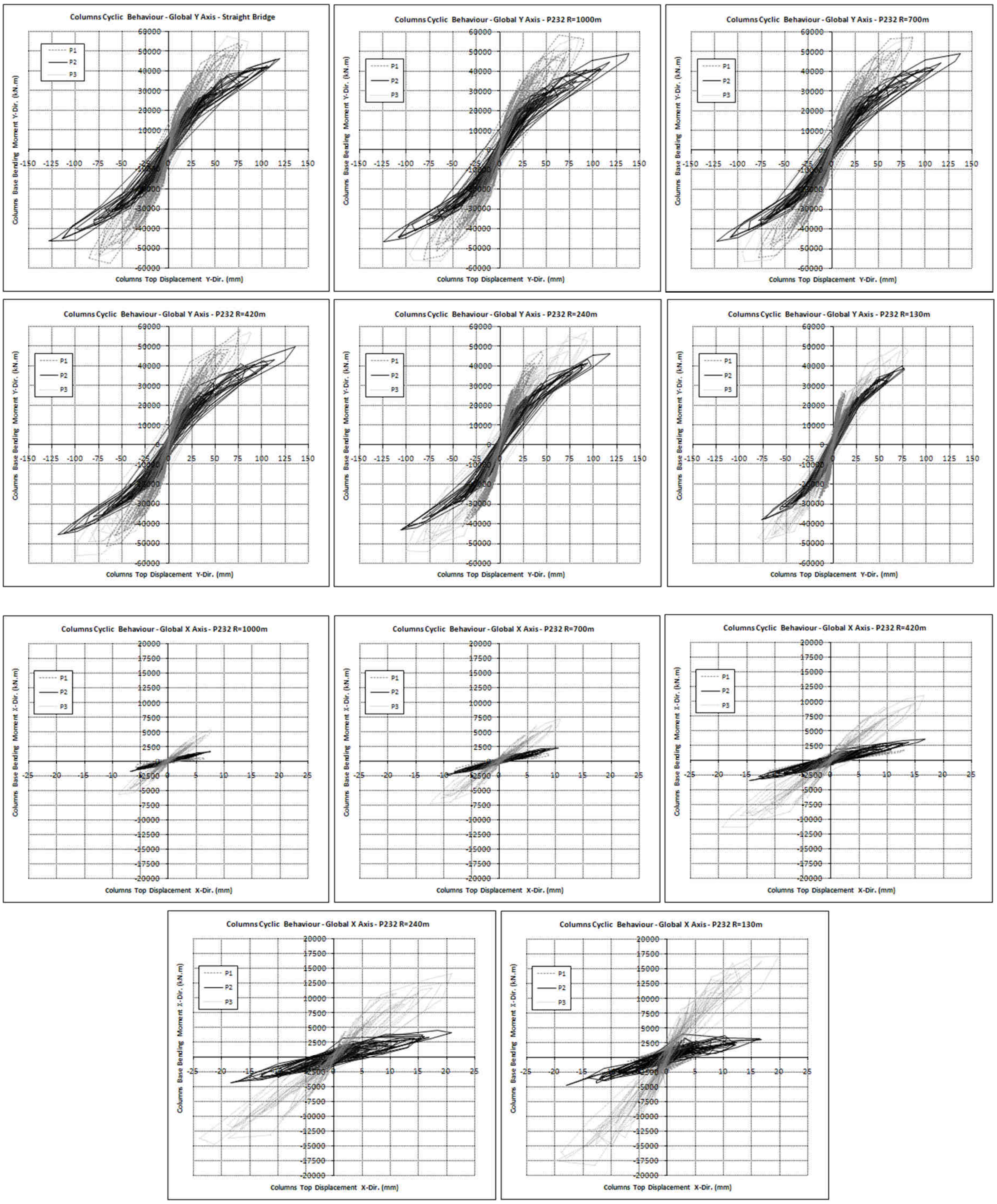


Figure 15: Columns cyclic behaviour for each analysed bridges using THA applied along the global Y axis.

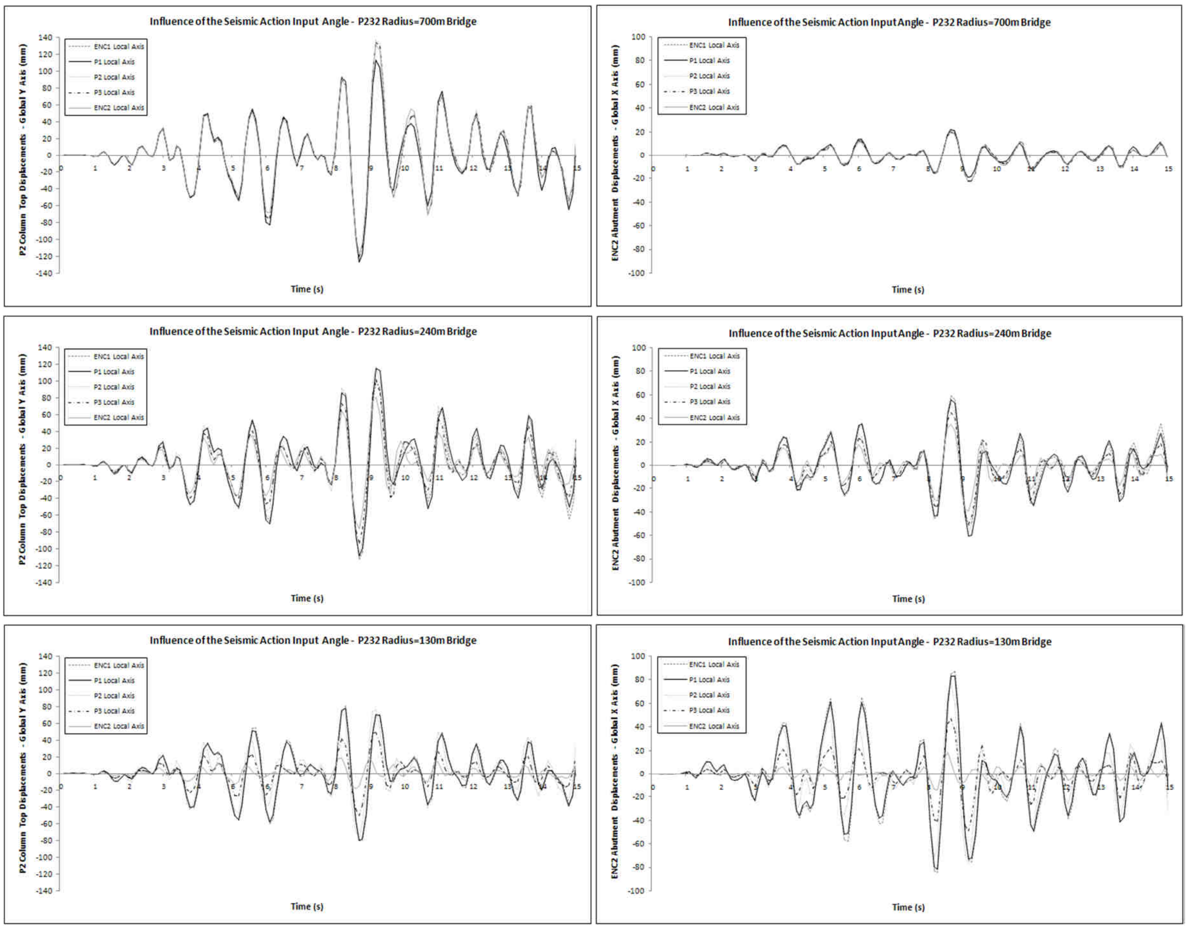


Figure 16: Influence of the seismic action input angle on the R=700m, R=240m and R=130m bridges response using the THA.

Notwithstanding, special attention should be given to the influence of the local axis systems on the bridges response. In this case, displacements variations of approximately 80%, 50% and 3% between ENC1 and ENC2 local axis systems can be observed for the Y-direction and for the bridges with radius of curvature of 130m, 240m and 700m, respectively.

5.2 Evaluation of the N2 Pushover Method by Comparisons with Time-History Analysis

During the feasibility assessment of the previously presented pushover procedures, two main comparison criteria should be taken into account: a first PA vs THA comparison criteria, which seeks the evaluation of the simplified pushover procedures by comparisons with a more refined method of nonlinear analysis; and a second PAc and PAvoc comparison criteria, which intents to evaluate the applicability of the deck displacements and shear forces conversion technique.

As mentioned above, it can be seen from Figure 17 that the PAm procedure worked very well in the case of the P232 straight viaduct, in accordance with the 91% value of the 1st mode mass participation ratio (Table 1). The bridges response is thus clearly governed by its transverse direction fundamental mode. On the contrary, the PAc procedure underestimated the deck displacements values, with an approximately 30% variation with regard to the THA result. This expected variation is due to the equal distribution of the inertial forces along the bridges piers, which allows the structure to develop a higher overall strength.

For its part, Figures 18, 19 and 20 present the response in terms of deck displacements of the bridges with a smaller curvature in plan and with a 1st mode mass participation ratio higher than 80%. In accordance with both comparison criteria, it can be firstly concluded that, in spite of the direction of analysis (seismic action input angle), the PAm procedure is the one that best fits the THA results; however a 16% variation in the Y'-direction P2 top displacements of the bridge with a radius of curvature of 420m can be observed between the use of the ENC1 and the ENC2 local axis systems, which was considered negligible. Once more, the PAc results are considerably below the THA results. Secondly, it can be observed that, not only the PAc results are identical to the PAvoc results, but also that the X'-direction displacements obtained using the PAm procedure fit quite well with the THA longitudinal displacements. Therefore, it can be concluded that the deck displacements and shear forces conversion technique leads to good results under these conditions.

Similar conclusions can be drawn from the analysis of Figure 23, where it can be seen that the differences between the PAm and the THA results are, in general, not higher than 20% (higher values are due to ENC2 local axis and to the slight stronger curvature of the R=420m bridge, which tend to increase the importance of the longitudinal response), and that the PAc vs THA displacements ratios overlap the PAvoc vs THA ratios.

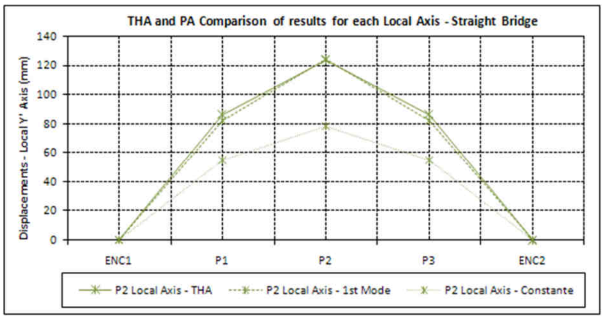


Figure 17: Response of viaduct P232, in terms of Y-direction deck displacements, calculated from PAm, PAc and THA.

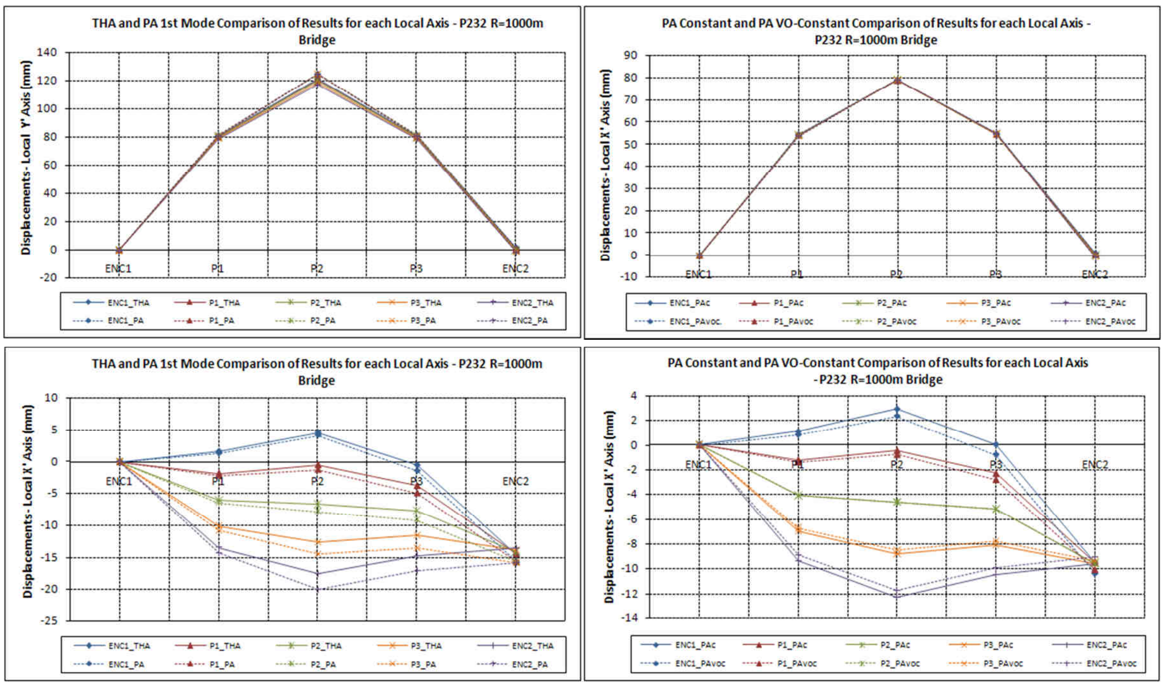


Figure 18: Response of viaduct P232 with a radius of curvature of 1000m, in terms of Y-direction and X-direction deck displacements, calculated from PAm, PAc, PAvoc and THA.

It should be noted that the outliers X'-direction ratios observed in the bridges with radius of curvature of 1000m and 700m are owing to the ratio of values that are close to zero, and so have no significance.

On the other hand, it is interesting to observe from Figure 21 that, in the case of the bridge with the radius of curvature equal to 240m, nor the application of the PAm, or the application of the PAc, leaded to perfectly good results, being evident the influence of both curvature of the deck and local axis systems in the bridge response.

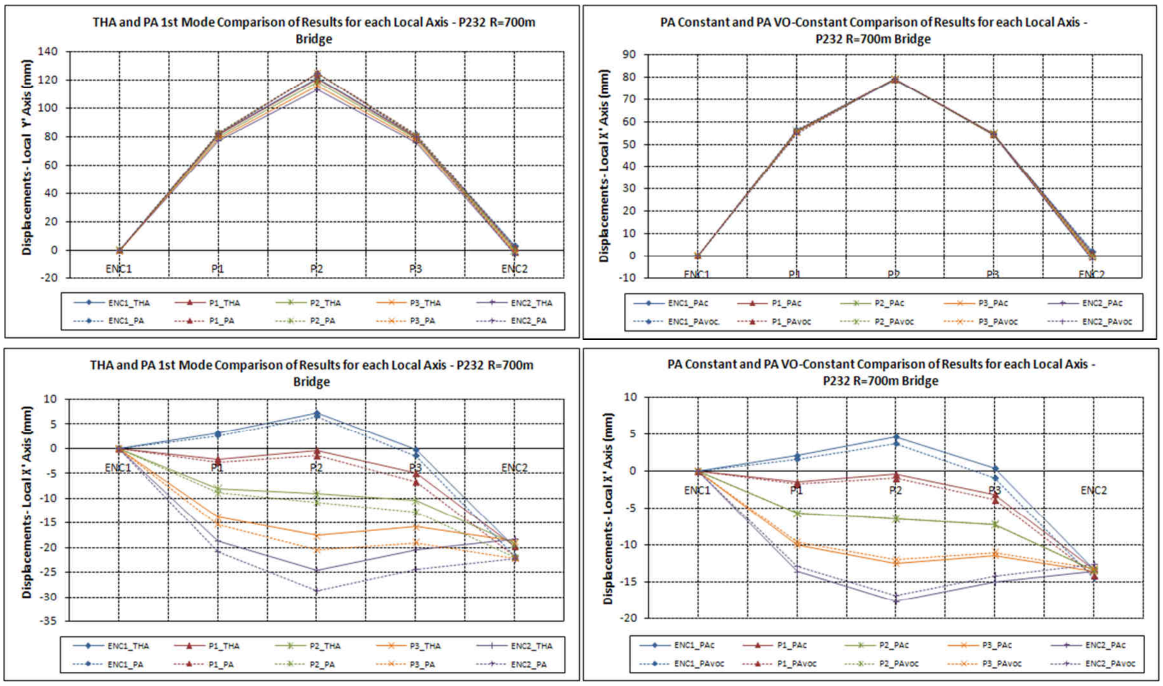


Figure 19: Response of viaduct P232 with a radius of curvature of 700m, in terms of Y-direction and X-direction deck displacements, calculated from PAm, PAc, PAvoc and THA.

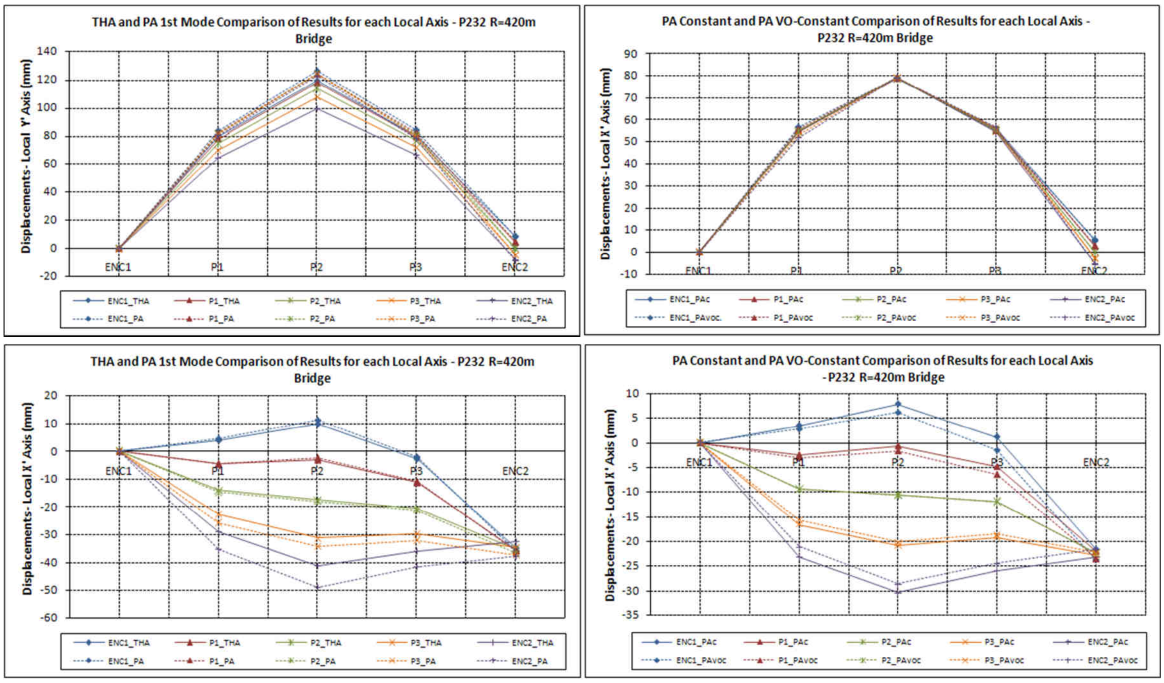


Figure 20: Response of viaduct P232 with a radius of curvature of 420m, in terms of Y-direction and X-direction deck displacements, calculated from PAm, PAc, PAvoc and THA.

Thus, while the PAm drove to relatively good results for ENC1, P1 and P2 local axis systems in both transverse and longitudinal displacements, for P3 and ENC2 local axis systems the PAm significantly overestimated the displacement demands, with a variation of 50% from the THA results in the latter case. The PAm procedure proved to be incapable of correctly reproducing the effect of the various directions of analysis in bridges with stronger curvature in plan. Although the PAc and the PAvoc procedures still to underestimate the response of the bridge, it may be noted that the results are getting closer to the THA results (Figure 23).

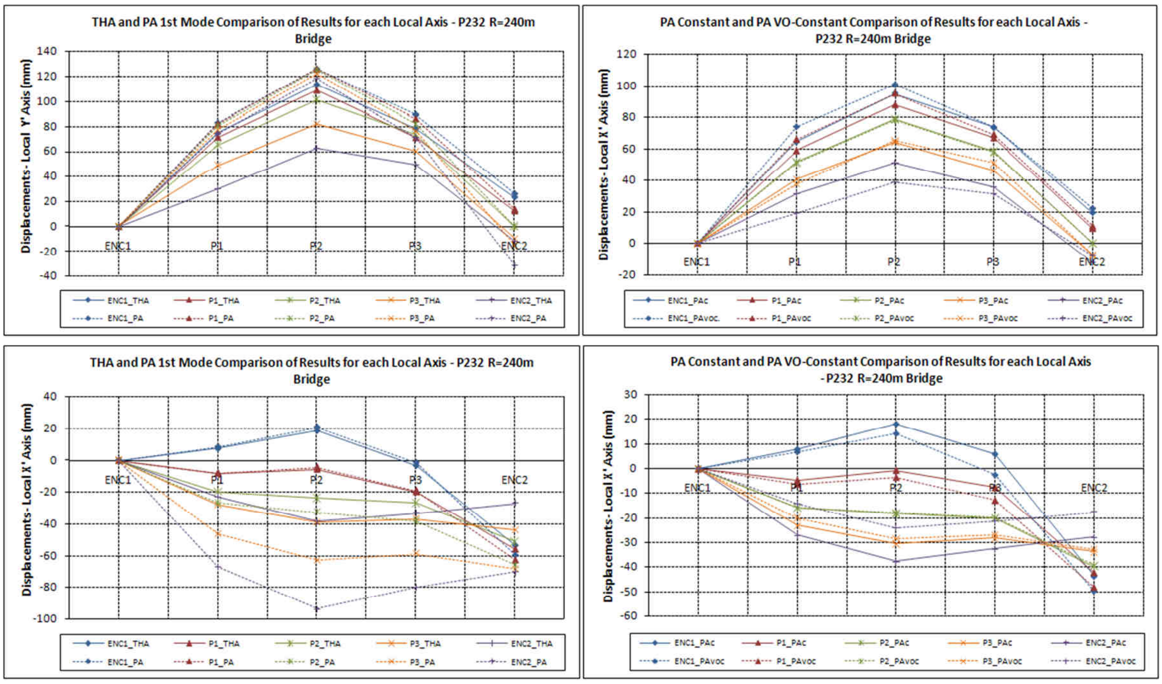


Figure 21: Response of viaduct P232 with a radius of curvature of 240m, in terms of Y-direction and X-direction deck displacements, calculated from PAm, PAc, PAvoc and THA.

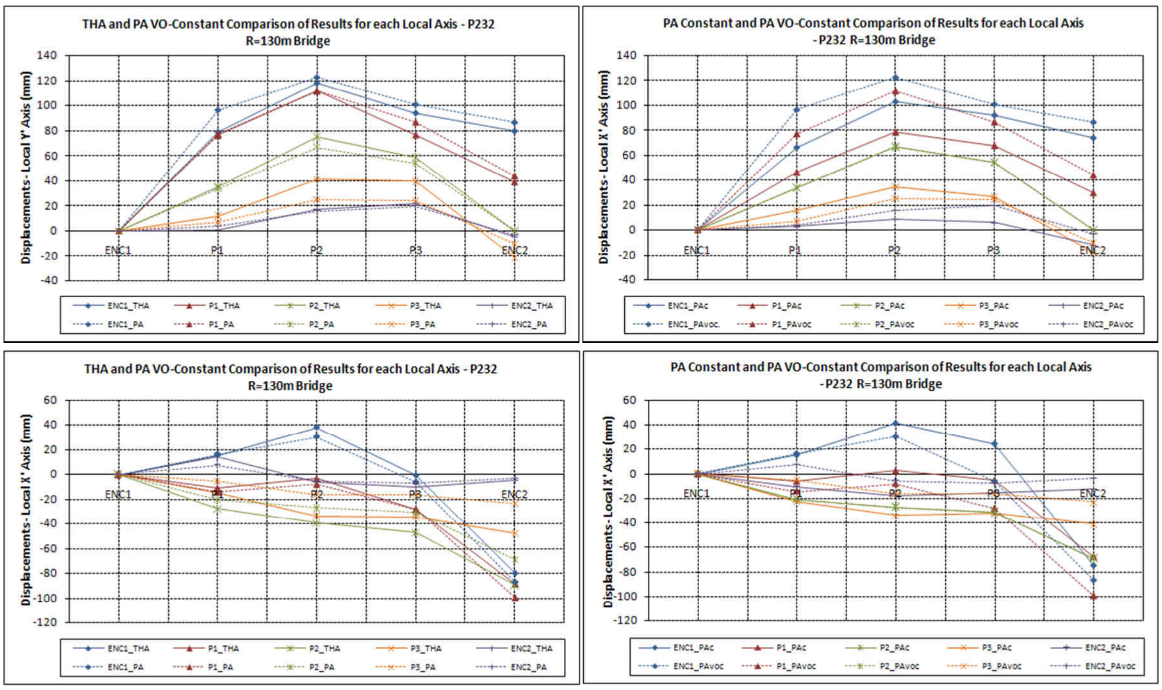


Figure 22: Response of viaduct P232 with a radius of curvature of 130m, in terms of Y-direction and X-direction deck displacements, calculated from PAc, PAvoc and THA.

It has been seen throughout this work that, for the geometric characteristics of the analysed bridges, the greater the inclination of the seismic action input angle in the direction of the left abutment, the more the curved deck will behave in flexure. Thus, the bridge response will be governed by its transverse response. On the contrary, when the seismic action is applied in the direction of the right abutment the bridge deck will behave in pure tension and the bridge response will be governed by its longitudinal response. Naturally, the validity of this statement increases with the curvature in plan of the bridge deck, such as the importance of the higher modes.

From Figures 22 and 23 it can easily be observed this influence of the local axis systems in the response of the bridge with the stronger curvature in plan, as well as the excellent approximation of the PAvoc results to the THA results and the contrary divergence of the PAm results, as already presented in Figure 6. Likewise, it can be noted that, in spite of the ability to predict the influence of the local axis systems, the PAc procedure loses accuracy when applied to bridges with a strong curvature in plan, being recommended the use of the PAvoc method in this circumstances.

A final remark regarding the third step of PA procedures, which refers to the determination of the earthquake displacement demand from the idealized SDOF system, should be taken. Not only the variation of the capacity curves with the directions of analysis (Figure 12) has an important role in the final target displacement values, but also the normalized displacements and the respective transformation factors. Thus, it was observed in stronger curved bridges that the transformation factors values decreased as the direction of the seismic action input angle rotated from the left to the right abutment, which leads to higher SDOF system idealized relationships and so to higher values of deformation energy up to the formation of the plastic mechanism, reducing the value of the target displacements. Moreover, as the final MDOF system target displacement of the control node is given by Γd_t*, smaller values of Γ conducts to smaller final displacement values. For instance, in the case of the bridge with the radius of curvature of 130m, its ENC2 local axis system transformation factor of 0,42 leaded to a higher SDOF capacity curve from a MDOF capacity curve that was significantly lower than the others (Figure 12) and to a similar SDOF target displacement comparatively to the other bridges and local axis systems. However, when the transformation factor multiplied the SDOF target displacement, it leaded to a lower final MDOF target displacement value, as displayed in Figure 6. On the contrary, bridges with not so stronger curvature in plan and identical transformation factors and capacity curves exhibit similar target displacements values.

5.3 Local and Global Capacity Demands

The modern structural design for earthquake resistance of bridges is based on the capacity design approach, which involves three main steps: (1) choose of the desirable mechanisms that best dissipate the most energy, in the present work, the plastic hinges were only considered at the columns base; (2) verification of deformation demands, the ductility demands, in terms of plastic hinge rotations or displacements, should be safely lower than the capacities of the plastic hinges; and, (3) verification of member against non-ductile failure modes, such as shear failure or joint failure. No reference will be made to step (3) in this work, however particular attention will be paid to the verification of the deformation demands of the bridge columns (step (2)) as a mean of identify the critical seismic action input angles. Therefore, Figure 24 presents the local ductility demands at the plastic hinges of the various analysed bridges, which is expressed in terms of displacement ductility factor, given by μ_d/μ_y, where μ_d is the displacement demand at each column and μ_y the yielding displacement of the same column (Figure 4).

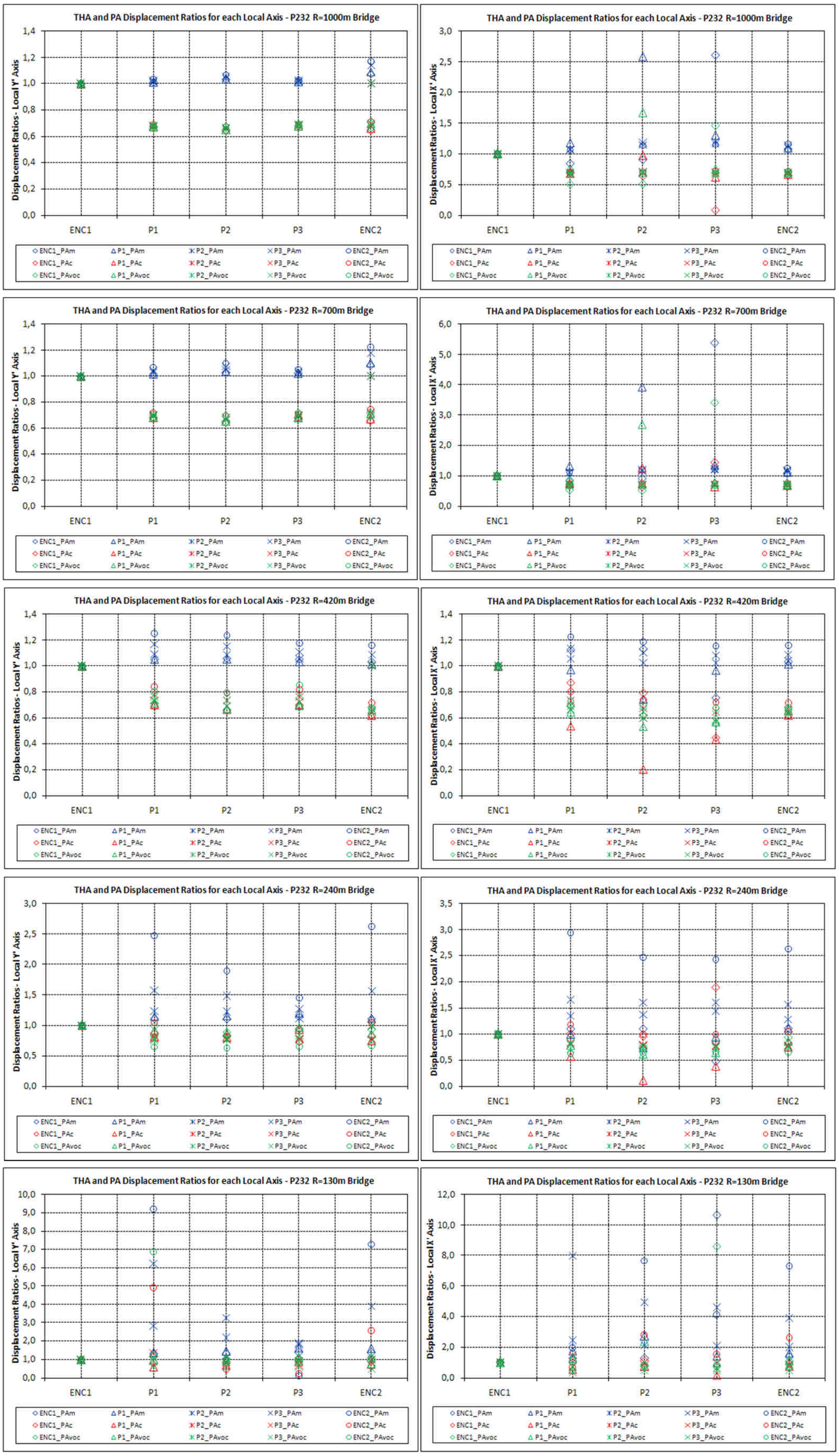


Figure 23: THA and PA displacement ratios for the various analysed bridges and for both local Y’-X’ axis.

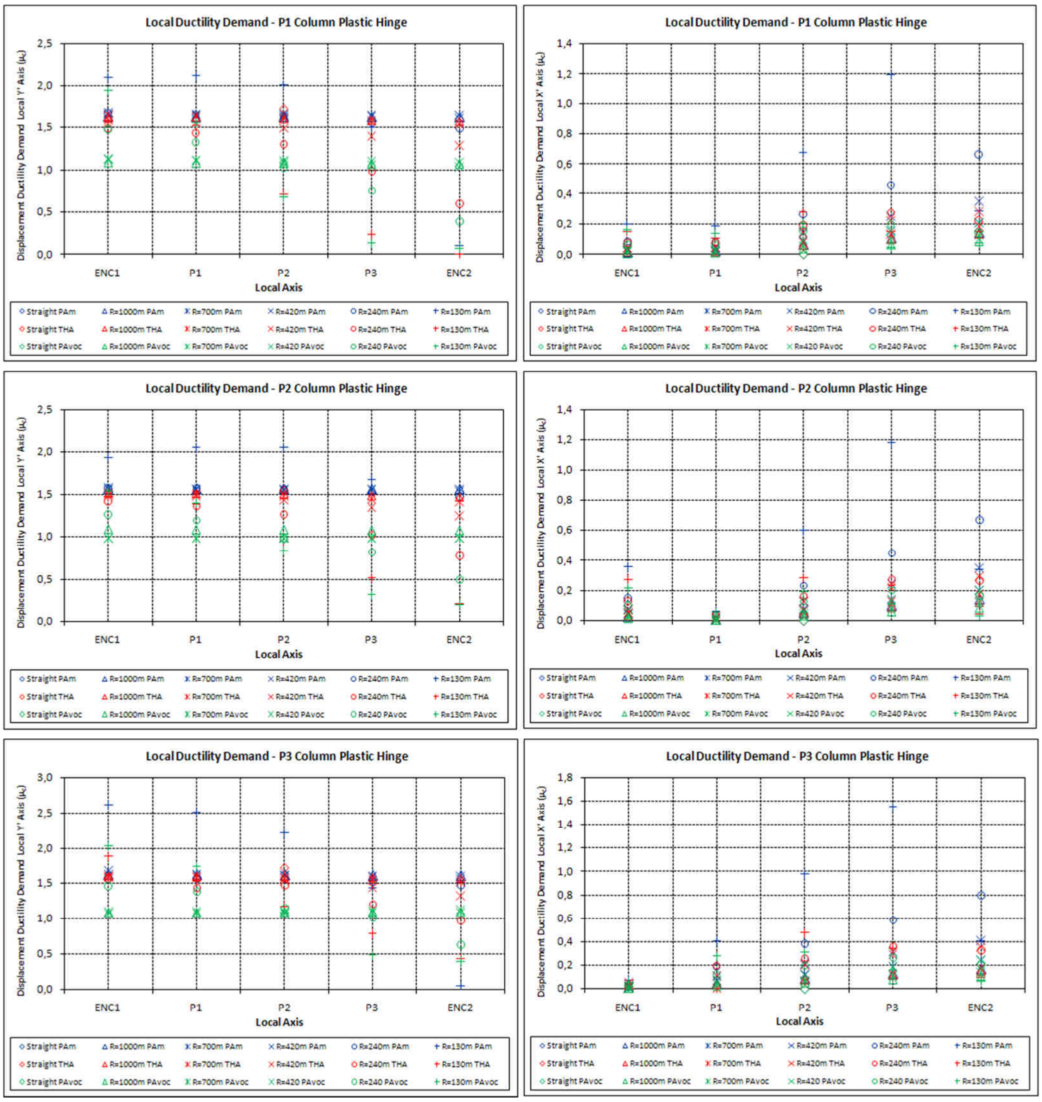


Figure 24: Local ductility demands at the columns of the various analysed bridges in both transverse and longitudinal directions.

Giving greater relevance to the THA local displacement demands, once they represent more realistically the actual seismic response of the bridges, it can be observed that, on the one hand, the transverse local ductility demands of bridges with smaller curvature in plan is similar along the various direction of analysis for each column, with a ductility factor of about 1,7. In the case of bridges with higher curvature in plan, like the bridge with a radius of curvature of 130m, the ENC1 direction of analysis is the critical one, increasing to approximately 1,9 the ductility factor of the P3 column. It should be noted that the P3 and the ENC2 directions of analysis leaded to markedly lower values of ductility demands in this type of bridges. On the other hand, the longitudinal local ductility factors are higher in bridges with stronger curvature in plan and for the P2, P3 and ENC2 directions of analysis. However, for the considered intensity level of the seismic action, the columns never experienced plastic incursions in the longitudinal direction, remaining with linear-elastic behaviour.

Finally, a global ductility demand analysis was also conducted and the results presented in Figure 25. The global ductility factors were obtained from the PAm and PAc equivalent SDOF system force-displacement relationships, as recommended in [16].

Identical conclusions may be taken regarding the local ductility demand analysis in terms of the influence of the directions of analysis and the curvature of the bridges. As mentioned above, the PAm procedure leaded to higher structural responses and to an average global ductility factor of 2,5, while the PAc procedure leaded to a lower average global ductility factor of 2, which decreased to approximately 0,5 in the bridge with a radius of curvature of 130m and for the ENC2 direction of analysis.

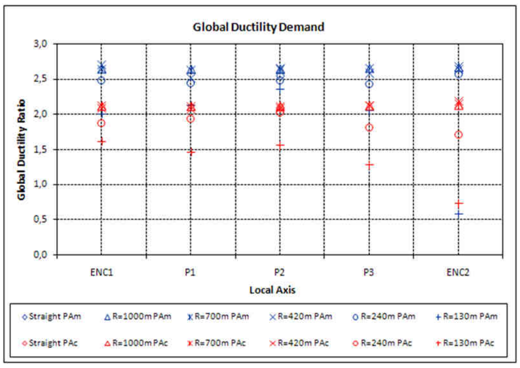


Figure 25: Global ductility demands at the various analysed bridges obtained from an equivalent SDOF system with the Eurocode's idealised elastic-perfectly plastic force-displacement relationship.

6 CONCLUSIONS

A set of short regular bridges with a radius of curvature in plan ranging between straight and 130m was selected to investigate the feasibility of the application of the N2 pushover method to curved bridges. A key issue in this work was the attempt to include the influence of different directions of analysis and seismic action input angles in the simplified PA procedures, so as to make them a reasonable alternative to the more complex and demanding, but yet reliable, THA method. The seismic response of the bridges was also evaluated in terms of its local and global capacity demands.

By applying the presented PAm, PAc and PAvoc procedures, as well as the THA, to the set of straight and curved bridges, the following conclusions were drawn:

- Complex three-dimensional structures, such as curved bridges, exhibit a multidirectional dynamic response that is more and more sensitive to earthquake directions as the level of curvature in plan increases. In the case of the bridge with the higher curvature in plan a 80% response variation between two different seismic action input directions has been observed. Therefore, a careful seismic safety assessment analysis must be conducted in these cases, otherwise the seismic response demands could be significantly underestimated.

- The Eurocode's PAm procedure proved to be quite accurate when applied to bridges with a regular curvature in plan and with a fundamental mode mass participation ratio equal or greater than 80%. On the other hand, for the same geometric type of bridges, the PAc procedure considerably underestimated its structural response, and so have no practical value. Equally, the PAxm procedure conducted to significantly low values of the response and, therefore, its use is not representative.

- With regard to bridges with a stronger curvature in plan, characterized by a decreasing importance of the fundamental mode in the dynamic response and a counterbalanced increase of the higher modes importance, the PAm provided an inaccurate estimate of the seismic response, generally overestimating it. On the contrary, as the irregularity of the curved bridges grows the PAvoc procedure is the one that best fits the more reliable THA results.

- The proposed deck displacements and shear forces conversion method, which seeks the inclusion of the various directions of analysis in the simplified pushover procedures, leaded to quite good results in bridges with regular curvature in plan and which response is governed by its fundamental mode. However, it accuracy decreased when applied to bridges with stronger curvature in plan. Thus, its application is not recommended in the latter case.
- More work is clearly required, not only to continue the investigation of the effectiveness of the Eurocode's pushover analysis method, but also the feasibility of the "conversion technique" by applying them to curved bridges with a higher degree of irregularity and different dynamic characteristics

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