The Quadrants Method: A procedure to evaluate the seismic performance of existing buildings

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SUMMARY:
In this work a new simple procedure for the evaluation of the seismic performance is formulated. It combines the results of non-linear static analysis with a specific Limit State defined by inter-storey drift-based damage threshold and the seismic demand obtained from the inelastic design spectrum. With both values it is possible to define four zones in the capacity curve which characterizes four different seismic performances.
The procedure is used to evaluate two reinforced concrete framed buildings, the first one consist in a typical low-rise building designed according to current Venezuelan codes; the second one is a four-storey building designed according to older code, whose had been damaged by fire. Results shown both cases do not meet the Quadrants Method criterion then they need to be redesigned. Redesigned buildings were submitted to a non-linear dynamic analysis, representative of three hazard levels associated with three Limit States. These redesigned buildings met all the objectives associated with the hazard levels, showing the efficiency of the method for the rapid evaluation of the seismic performance of existing buildings.

Keywords: Quadrants Method, Seismic evaluation, non linear analysis, damage thresholds, limit states.

1. INTRODUCTION

Lessons learned from the destructive earthquakes in past two decades, shown that the seismic performance of the reinforced concrete framed buildings strongly depends on the sizing and detailing of the structural members. Recent observations have been demonstrated that RC framed buildings that collapse during a strong motions, did not have adequate levels of confinement or efficient detailing in order to dissipate the energy in a stable way. Some of those damaged buildings were designed according to old seismic codes or without seismic provisions.

In countries with a large number of buildings with inadequate seismic design, it is very important to have a method which let to evaluate quickly and accurately the seismic performance of these buildings. The method should allow to decide if the buildings need to be reinforced in order to meet the current code's provisions, in a work-frame that do not need of a set of sophisticated and time-consumer analysis. In this article, a new method to the rapid seismic performance evaluation is formulated. It is based on non linear static analysis (pushover analysis). The formulated method has been tested in two existing buildings designed and built according two different issues of the seismic Venezuelan code. The first case correspond to a three Storey building with a lot of sizing and detailing deficiencies. This building need an urgent intervention of its structure because has suffered damage for fire in the first Storey. The second one consist in a typical low rise structure used in Venezuela for residential purposes, designed according the current issue of the seismic code. In both cases the Quadrants Method has allowed to evaluate the seismic performance quickly and then it has been validated by means of a set of non linear analyses using spectrum-compatible synthetic accelerograms. Results shown that the seismic performance of both buildings does not meet the current objectives of the seismic design for a rare strong motion.

2. FORMULATION OF THE METHOD

The Quadrants Method is based on the results of the non-linear static analysis (Pushover analysis). This analysis results are plotted in a displacement vs. base shear format, this generate the capacity curve which represents the overall capacity of the whole structure against lateral forces. In order to evaluate the capacity curve two of the main structural parameters are take into consideration. The first one is the design elastic shear, obtained from the elastic analysis of the structure using the elastic design spectrum. The second parameter is the threshold that defines the Repairable Limit State, obtained from Vielma *et al.* (2011) for RC framed buildings with similar characteristics to the studied ones. The thresholds have been computed from characteristic values of three levels of damage proposed by Di Sarno and Elnashai (2008) and are showed in Table 1. Both values are used to define two axes over the capacity curve, the elastic base shear defines an horizontal axis and the damage threshold defines a vertical axis, then Capacity curve is divided in four spaces or quadrants, see Figure 1.

Table 1. Inter-storey drifts adopted for the damage thresholds determination

Limit State	Damage type	Seismic hazard	Probability event	Inter-storey drift in (%)
Service	Non-structural	Frequent	50% in 50 years	0,2<δ<0,5
Damage control	Moderate structural	Occasional	10% in 50 years	0,5<δ<1,5
Collapse prevention	Severe structural	Rare	2% in 50 years	1,5<δ<3,0

The performance point is a common procedure accepted among the scientific community to evaluate the seismic performance of a structure under a specific demand. It is usually obtained from the idealized shape of the capacity curve as is shown in the Figure 1, Park (1988). The Quadrants Method also uses this parameter in order to define the roof displacement of the case studied, defined according to the N2 method, Fajfar (2000). If the performance point is under the axis defined by the elastic base shear (quadrants III or IV), the design does not meet the basic objective of the seismic design because the building does not have enough lateral strength. If the performance point is on the right side of the vertical axis (quadrant I) means that the building has adequate stiffness, otherwise (quadrant II) it means that the stiffness is very low and the displacements can be longer than the displacements that can produce advanced damages, technically or economically irreparable. These lateral displacements are usually computed from the dynamic response of the structure submitted to a strong motion with a return period of 475 years, or an occurrence probability of 10% in 50 years, Vielma *et al.* (2011).

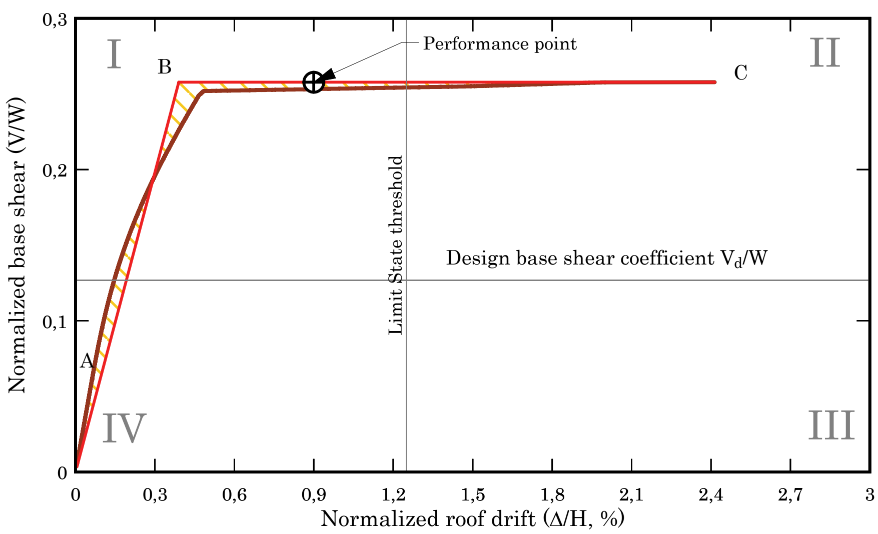

Figure 1. Capacity curve and the axis that define the Quadrants Method

The Quadrants Method can provide an objective criterion in order to upgrade the seismic capacity of a structure. If the performance point is on the Quadrant I, the structure has enough lateral strength and stiffness, so does not need to be reinforced. If the structure is on the Quadrant II, it is necessary to provide additional stiffness by using conventional procedures like RC or steel jacketing. If the performance point is on Quadrant III, the structure requires a more radical intervention, adding stiffness and lateral strength. In this case it is possible to combine some traditional reinforcement techniques with new ones like FRP jacketing. In this case the columns are the subject of the main intervention. Finally, if the performance point is on the Quadrant IV, the structure does not has enough lateral strength and then the reinforcement technique must be FRP jacketing.

2. DESCRIPTION OF CASES STUDIED

The Quadrants Method has been used in order to evaluate the seismic performance of two typical existing low rise RC framed buildings. They were built according to two different issues of the Venezuelan seismic code (COVENIN, 2001).

As was mentioned before, the method requires the results of the static non linear analysis. It was performed using PLCd (PLCd, 2012) finite element code. PLCd works with two and three-dimensional solid geometries as well as with prismatic, one-dimensional, members. It provides a solution combining both numerical precision and reasonable computational costs. It deals with kinematics and material nonlinearities and uses various 3-D constitutive laws to predict the material behaviour (elastic, visco-elastic, damage, damage-plasticity, etc.) with different yield surfaces to control their evolution (Von-Mises, Mohr–Coulomb, improved Mohr–Coulomb, Drucker–Prager, etc.). Newmark's method is used to perform the dynamic analysis. A more detailed description of the used procedure can be found in Barbat *et al.* (2008) and Mata *et al.* (2008). The contribution of the transverse reinforcement was take into consideration applying the procedure formulated by Mander (1988).

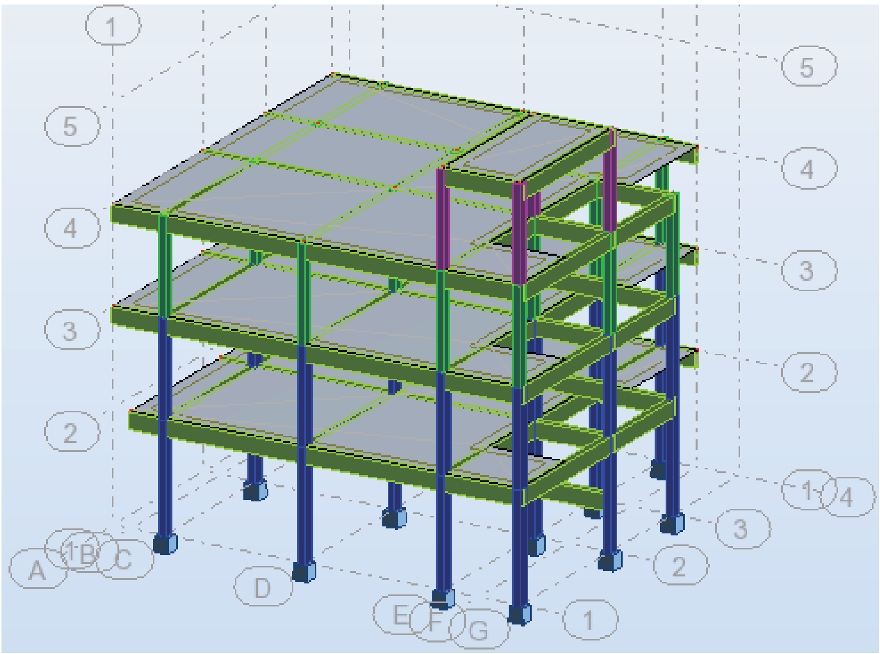

Figure 2. 3D view of the three levels building

2.1. Three levels residential building

The first case studied consist in a three levels residential building. This building was built at the middle of the 1980 decade, so it was designed according to the old issue of the Venezuelan seismic code, that was less exigent than the current issue in the detailing procedures. It is important to mention that the building was damaged by fire two years ago. Forensic inspections of the structural members revealed that the reinforcement of the columns and beams does not meet the main regulations of the code, mainly in the transverse reinforcement. The building was modelled following the geometric and strength data obtained of the direct survey applied on the whole structure.

Table 2 contain the sizes of the structural members of the building as it was built, note the low sizes of the rectangular-shaped columns. These sizes do not meet the minimum dimensions prescribed by the old issue of the seismic code, and have been partially disaggregate by a recent fire which reduced the cross sections of the first storey structural members, also originating the reinforcement yielding. However, the whole building was modelled using the original cross sections in order to obtain the design capacity and then proceed to choose the reparation/reinforcement technique.

Table 2. Original sizes of the cross sections of the three storey building

	Main beams (cm)	Secondary beams (cm)	Columns (cm)
Original sizes	20x50	20x40	20x35
Upgraded sizes	35x65	35x60	55x55

In Figure 3 it is possible to observe the capacity curve with the axes which define the quadrants in order to apply the method in combination with the results of the N2 method, that let to determine the performance point of the building. The resulting position of the performance point indicates that the seismic capacity of this building is adequate according to the global strength, but the structure does not has enough stiffness in order to reduce the displacement seismic demand, then it could reach displacements which can cause irreparable damage to the primary components during an occasional earthquake defined in Table 1.

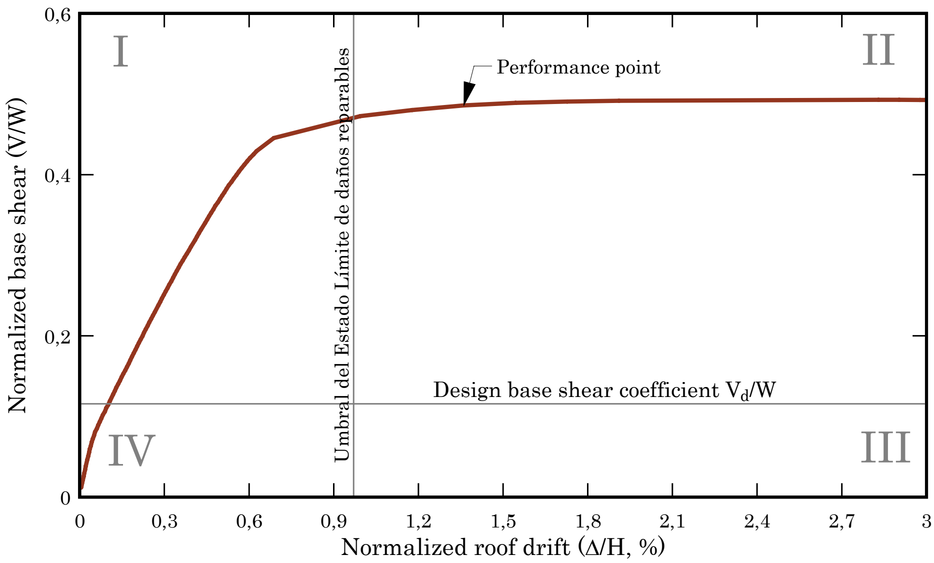

Figure 3. The Quadrants Method applied to the three levels building

Non linear dynamic analysis was applied to both buildings in order to verify if the performance evaluated by the Quadrants Method is reliable in order to evaluate the fulfilment of the thresholds defined in the precedent section. For this purpose they has been computed three synthetic elastic design spectrum-compatible accelerograms by means of the PACED program (PACED, 2009). In Figure 4 are showed the Venezuelan rigid-soil elastic design spectrum with the response spectrum obtained from the synthetic accelerograms.

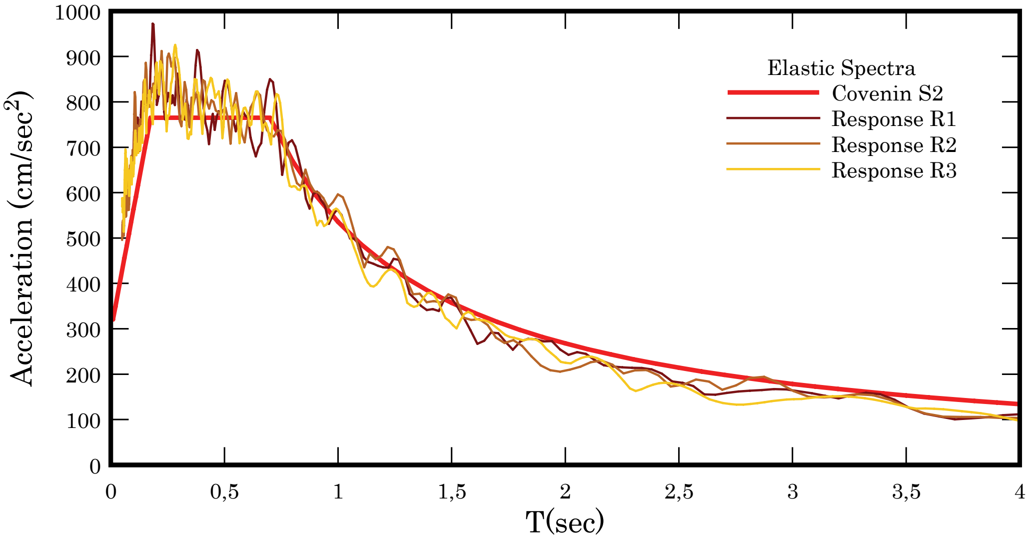

Figure 4. Elastic response spectra from elastic design spectrum-compatible accelerograms

In Figure 5 the dynamics results are showed, note that all the inter-storey drifts of the building have been plotted in the same Figure with the positive and negative values of the threshold defined by an inter-storey drift of 1,5 %. It is important to observe that the inter-storey drift values are very large, especially in the first level of the structure. These values exceed so far the threshold established to define the Limit State of repairable damage. This threshold was also exceeded by the second level's inter-storey drifts, demonstrating the inadequate overall performance of the structure, as predicted by the Quadrants Method. Results obtained from the other two accelerograms are very similar to the showed in Figure 5.

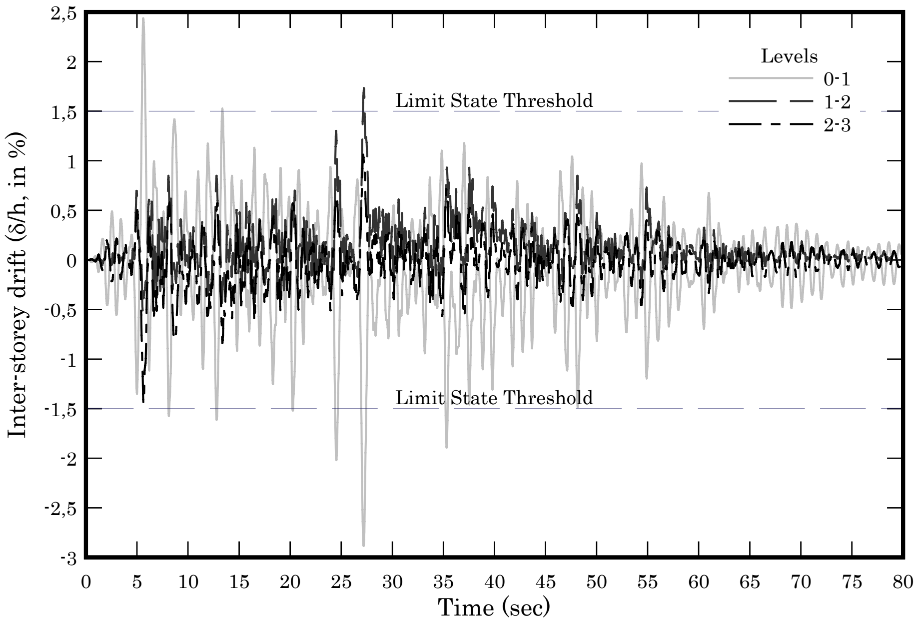

Figure 5. Inter-storey drift of the three storey building

According to those results it was necessary to restore the capacity of the building to resist service gravity and seismic loads and to restore the cross sections destroyed by fire. The technique chosen for the rehabilitation and upgrade of the structure was the RC jacketing. The calculation procedure of the additional sections was based on a new Performance-based method formulated by Vielma *et al.*

(2011). The chosen dimensions of the cross sections of the structure can be observed in Table 2. It is important to mention that the upgraded structure was modelled and analyzed in order to apply the Quadrants Method again, in this case the performance point was on the quadrant I, indicating that the new structure has adequate stiffness and strength. In sake of brevity, the results of the upgraded structure are not showed in this paper, but they met all the Limit States of Table 1 for all the applied dynamic analyses.

2.2. Two levels building

The second analyzed building is a two levels RC framed structure. It was designed and built according to the current issue of the Venezuelan seismic code. Among this main characteristics it is possible to mention that the building is not regular in plan because it has openings in the first's level slab. Other important characteristic is that the secondary beams are flat beams, not explicitly prohibited by the Venezuelan seismic code.

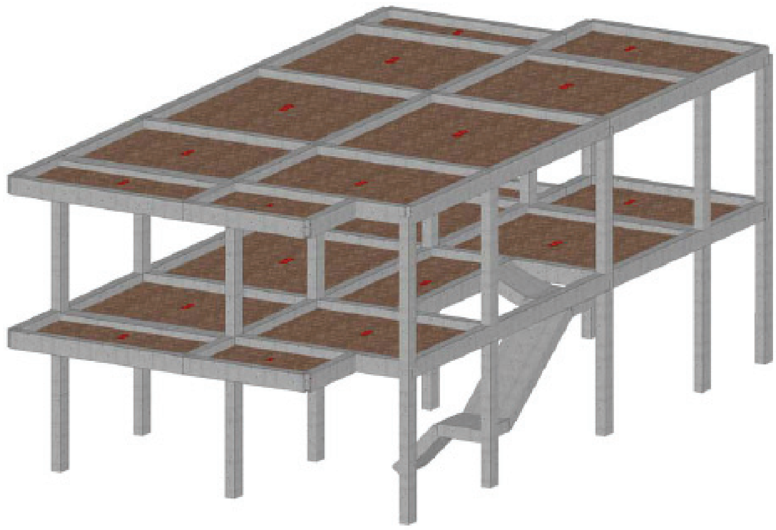

Figure 6. 3D view of the two storey building

The sizes of the original cross sections of this building are shown in Table 3.

Table 3. Original sizes of the cross sections of the three storey building

	Main beams (cm)	Secondary beams (cm)	Columns (cm)
Original sizes	20x40	20x35	20x30
Improved sizes	30x40	30x40	30x30

The model of the building was performed splitting their structural members into four finite elements, allow to analyze the structure with special attention on the zones with stresses concentration during the application of the seismic actions (zones near columns-beams joints). The static non-linear analysis was performed with a triangular pattern of lateral loads which correspond to the first vibration mode, obtaining the capacity curve for two main directions of the building and then plotting on that curve the computed performance point. Results of this case are shown in Figure, see that the performance point is on the Quadrant II as in the case of the three levels building. This means that the building as designed does not have enough stiffness despite the lateral strength is satisfactory.

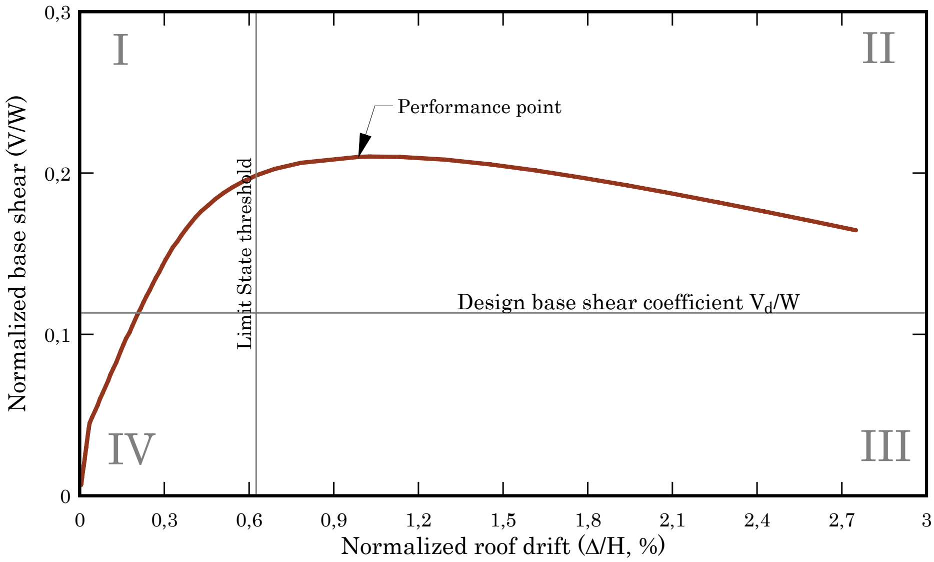

Figure 7. The Quadrants Method applied to the three levels building

Results of the dynamic analysis are shown in Figure 8. Note that for the original characteristics of the building, the inter-storey drifts of the structure are longer than the thresholds of Table 1, as the Quadrants Method predict. It confirm that the original structure does not have enough lateral stiffness to avoid excessive damage during an occasional earthquake. According to those results it was necessary to resize the whole structure, improving some of the reinforcement details of the beams and columns to achieve adequate confinement. The improved design sizes are shown in Table 3. Resized building was analyzed, applying static non-linear analysis in order to obtain the Capacity curve. In this case the performance point was on the quadrant I, verifying that the seismic performance was improved to met the performance-based criteria. Results of the method were verified using the same synthetic accelerograms, then the inter-storey drifts met all the Limit States used in this study for all the thresholds of Table 1.

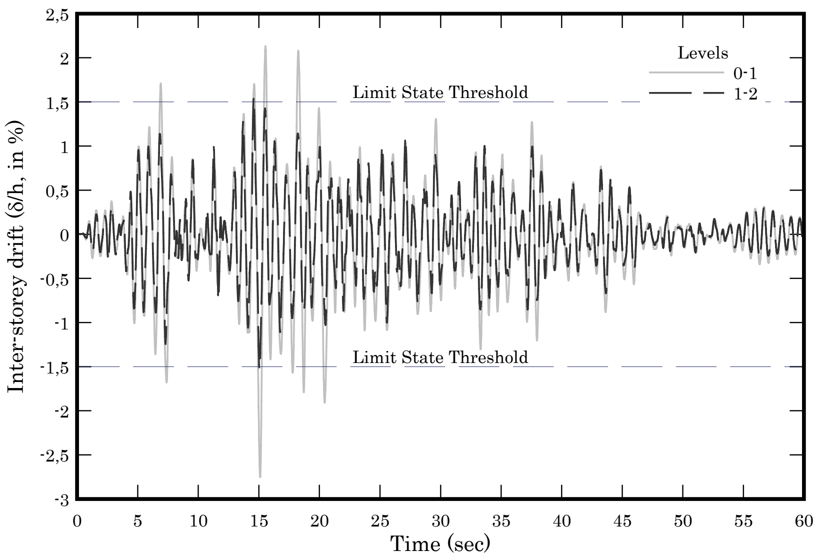

Figure 8. Evaluation of the inter-storey drifts from the dynamic response

3. CONCLUSIONS

The Quadrants Method presented in this paper is suitable for rapid and reliable evaluation of structures, with a low calculation effort. The cases studied demonstrated that the method can provide a reliable criterion to predict if any structure would have an inadequate seismic performance based on the results of static non linear analysis. Results obtained from dynamic non linear analysis confirmed the results obtained from the application of the Quadrants Method.

The case studied of two typical low rise RC residential buildings demonstrated how efficient the Quadrants Method is. Te first case was resizing take into consideration the damage caused by fire, and the deficiencies of the original design. The method could predict that the original building does not have enough lateral stiffness in order to resist the seismic demands. Dynamic analyses confirm this feature. Then this building was retrofitted and upgraded using the RC jacketing technique, obtaining a satisfactory seismic performance.

The second case studied was a two stories RC residential building. Despite the plan irregularity of this building, the Quadrants Method was suitably in order to predict that its lateral stiffness was not enough. Dynamics analysis confirmed this feature, then the cross sections of this building was resizing and details of the confinement were improved in order to met the regulations of the current version of the Venezuelan seismic code. The seismic performance of the new design was tested with the Quadrants Method and dynamic analysis, showing that the resizing structure met all the Limit States used in this research.

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