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INELASTIC RESPONSE STUDY OF REINFORCED CONCRETE STRUCTURES UNDER DYNAMIC ACTIONS.

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ABSTRACT

Three frames were designed, two-story four-bay, according to Venezuelan Building Code 1753-87 (reference 5) and Venezuelan Code for Seismic Buildings 1756-82 (reference 6), due to level design philosophy.

This paper main purpose, is to evaluate the frames response, introducing reinforced concrete inelastic behavior considerations, focussing mainly in flexural elements. Following that idea, it was employed the Drain-2D program as a calculation tool, that fits to the intented goals .

KEYWORDS

Beam-column frames, ductility, histeresis loops, yield point, curvature, story shear, stiffness, deformation, reinforced concrete, elastic and inelastic behavior.

ANALYSIS MODEL

It was used girders and columns to array a perpendicular system, as it is shown in the figure 1, following the failure theory guidelines for the three design levels, as the procedures establish.

The difference between design levels bases basically in two aspects : force reduction sfactors based on the energy dissipation capacity, and the elements design. The first one will condition the magnitude of lateral forces to be applied for the static analysis (according to the Static Equivalent method, reference 6) therefore a greater reduction factor will cause structure elements to be more slender and thus, less rigid than those structures related to smaller factors. The second one influences the steel percentages to tension and compression (flexure elements), crucial cause in the inelastic range excursion, defining then particular behavior trends, for our case : ductility and tenacity (toughness).

Due to the nature of the model, lateral forces were amplified in order to guarantee to control over the gravity loads, maintaining the model hypothesis that they would be clearly differentiable, as it happens in common practice in tall buildings.

Over an elastic design ground, the moment-curvature diagrams were calculated, to establish the pattern behavior of bending members (figure 2), as well as interaction surfaces were calculated for bending-compressing elements, as fundamental parameters taken into account for the Drain-2D calculations, to carry out the corresponding inelastic analysis. Perfect Elastic-Plastic moment-curvature (reference 2) were employed, as well as symmetrical interaction graphics. The Damping was characterized exclusively through the structural damping factor 0.05.

The structural elements were defined as beam-columns elements, according to Drain-2D classification, introducing 4 stiffness and resistent patterns and 4 interaction surfaces.

One of Drain-2D options affords to accomplish an elastic-static analysis of the structure before applying dynamic actions, as a most realistic approach to the input that the buildings have to deal. To such matter, fixed end forces were calculated considering the dead and live loads effect as permanent forces in time.

Ground connection consisted of 3 degrees of freedom restriction (2-dimension case) of the lower nodes. The horizontal displacements were restricted in each floor, despising beam axial deformation. 14 Freedom degrees establish the model displasability.
Masses were modeled lumped on each free node, as gravity loads corrected by gravity acceleration ($g = 981\ cm/s^2$).

The dynamic excitation is specified with time-acceleration pairs, in which were managed 3 sort of increments : dynamic action step, calculation step and the corresponding analysis report, which influence is quite decisive in numeric accuracy and output stability.

Five outputs were employed according to each dynamic excitation: the first four were generated through a Q-Basic program to control the amplitude, frequency, time and generation steps, through a sine function. They were made following a logic sequence and taking into account the models main vibration periods. The fifth excitation was an earthquake.

From the program output, were taken out all free node rotations, story lateral displacements, bending moments at both nodes that define flexure elements, and shears at the lower nodes of each column, so that we could generate Moment-Curvature and Shear Floor-Lateral Displacements graphics, as basic tools for developing this paper.

DYNAMIC ACTIONS INTERPRETATIONS

Dynamic Excitation #1 : Rising Steady Acceleration.

The first output obtained was based on the application of a rising steady acceleration, as the first step forward interpretations less simplistics.

The Moment-Curvature curves showed 4 behavior aspects quite outstanding : an inelastic response range, a sharp breakpoint corresponding in some cases to a yield point, and in other cases to a stiffness loss , and finally, a plastic behavior range.

The first important observation is the stress-strain condition of the elements before the applying dynamic excitations, thus there will be an initial condition of bending that will influence the future response. The gravity loads cause moments of different direction over each element node, therefore, when a lateral force effect is consummated, this will cause same direction moments. Following this idea, moments in one node will increase faster than in the other node, because of the initial condition.

Comparing the plastification ranges that were reached out for the 3 design levels employed, we found a level 3 large excursion (due to an early plastification, in relative terms), an expected characteristic for this case, about to the curvature ductilities that were calculated. However, the level 1 response was predominantly elastic, linked to higher moments, minor curvatures and a poor plastic range excursion.This particular case permitted to verify the obvious connection between both extreme sections of a flexure element, that represent different nodes. It was observed the exclusive plastification of the right node and at the same time its influence in a slope decrease at the left one, that is interpreted as a stiffness loss.

The design level 2, showed a moderate excursion, placing itself in the middle of the cases already mentioned.

Comparing the beams response that belongs to the same floor, it was observed a basically identical behavior, at strain and moment levels. Referring to beams (comparing between both floors) we got basically the same behavior , except for yielding which occurred in different times according to model's own properties.

The Shear-Displacements curves evidenced the known fact that the first floor is under greater forces than the second floor, and at the same time the first floor reached out lower displacements, this is related to sections diminishing with height. The beam plastification importance over the system response was observed through obvious stiffness reductions.

Dynamic Excitation #2 : 1 Acceleration Cycle.

The second excitation applied was a sine function which first phase was fitted to the previous action, conceived in order to reproduce a complete load cycle, so that to study the models' response facing a reversible action, verifying the histeretic loops appearance (see figure 3).

As the same as for the first action, the moment-curvature curves observed at the first load stage, an elastic range until yielding ocurred, as well as inelastic excursions, that were extended differently relying on the design level. The contribution in this case begins at the first unloading stage (the phase when the acceleration reaches out its peak and starts to go down), where the moment as well as the curvature suffered a proportionally decrement with the same slope of the initial elastic zone, begining from the last developed strain. When this stage is over, at the time instant related with zero acceleration, it could be observed a strain and force's state notably altered if we compare it to the initial gravity state (this concerning the design level 3, as the most illustrative). Then, under different conditions the process continued to the reversion stage, maintaining the slope developed before. The inelastic excursion took place, and assuming the same slope the second unloading stage begins , to reach out finally, a state linked to zero acceleration, again definitely different. The extreme wideness of histeresis loop observed on the design level 3 is interpreted as a measure of a great energy dissipation capacity at a local level, as a straight consequence of the surface enclosed by itself (see figures 4 and 5).

This behavior pattern it is evidenced repeatedly in each bending element, with his respective variations for each design level. The design level 2 developed discreet histeretic loops, comparing it to design level 3, linked, as it was expected, to a moderate local energy dissipation. At the design level 1, loops were almost noticeable, showing again a very remarkable elastic behavior (see figure 6 and 7).
The fact of the slope inexorable steady condition in the moment-curvature graphic under the excitation effects, is reasonable because it hasn't been developed routines to introduce the material's stiffness degrading effect, common feature in laboratory test under cyclic loads, on reinforced concrete elements (reference 4).

Regarding the shear-displacements graphics, it was evidenced the histeretic loops make up, which response it's directly linked with beams behavior. In this case, the enclosed area over the histeretic loops it is interpreted as a dissipation energy capacity direct measure, this time at a system level.
It was observed a behavior according to the typical patterns that it has been interpreting for each design level (see figure 8).

Dynamic Excitation #3 : 3 Acceleration Cycles.

This excitation was selected with the purpose of imposing the several histeretic loops make up over the models, as an attempt to the seismic effect (see figure 9).

Any possible interpretation of the curves corresponding to this case, fits to the characteristics that have been mentioned before. It's worth to outline the steady behavior observed, the moment-curvature as well as the shear-displacement graphics, when a superposition tendency took over clearly. This can be interpreted in order to the model's idealization, to set up the need to introduce more model considerations towards a more realistic approach to the problem (see figure 10).

Present results will be more useful in the interpretations that will take place in the next output.

Dynamic Excitation # 4 : 3 Acceleration Cycles, with an Specific Period.

It was employed a 3-cycle periodical function, developed according to an average period of the structures' first vibration modes , in order to verify resonance effects in model's response (see figure 11).

Structural periods calculations determined : 0.395 s, 0.290 s and 0.193 s for the design levels 3, 2 and 1, respectively.

According to these numbers, and having calculated the average period, 0.293 s, it's noticeable its closeness to design level 2. According to this, important amplificaction were expected for such case, as it was observed in the graphics. Futhermore, differents amplification levels were observed also in design levels 1 and 3, due to the relative closeness between the structure/action frequency.

The graphics obtained matched to the expectations mentioned before, outlining that great deformations performed by the design level 2 were even greater than the design level 3 at resonance (see figure12).

The general pattern of the graphics, obey to a loop histeretic systematic out-of-phasing due to the load cycles application of the excitation, taken into place a widening loop effect plus a plastic zone greater extension. This is the clear and several times demonstrated cause of why structures collapse under important and not so important earthquakes (see figure 13).

Dynamic Excitation #5 : Earthquake.

This record was employed with the purpose of having the elements and structure response under a real dynamic effect, such an earthquake (see figure 14).
It was observed a random, not-predictable response, and a hard to understand behavior. It seems to be a difficult way to learn something about inelastic response (see figure 15 and 16).

CONCLUSIONS

1. The moment-curvature graphics and the shear floor-displacement for each design level, confirmed the expected behavior according to the differents design levels philosophy.
2. The design level 3 model showed relevant excursions into the inelastic range, related to great strains not only for curvature but also for displacement. Histeretic loops were developed, widened and opened, as direct measure of a great energy dissipation capability, at local and system levels.
3. The model for design level 2, presented moderate inelastic excursions and moderate strains.
4. The model for design level 1, observed low excursions into the plastic range linked to low strains too, verifying this way, a clear elastic trend.
5. The presence of the gravity loads proved to be an influential factor to the structure stress-strain state under dynamic loads.
6. It was evidenced the moment distribution effect through the different time lapses needed for the plastic hinges make up at the ends of the bending elements.
7. The beams plastification as well as the stiffness losses, play an important role in the structure straining, even though it can be guaranteed the columns elasticity, avoiding any inelastic possibilities, thus the initial strain state will be modified notably in ductile system cases under important dynamic excitations. This can lead to think that geometry changes surely will set the structure at a highly susceptible condition to earthquakes.
8. Concerning the beams that belong to a same floor, they showed almost an identical behavior, revealing uniformity and independence. At the same time, comparing bending elements in both floors, it was observed an equal demand level (stress-strain) and similar behavior patterns.
9. The dynamic action effect over a ductile structure, sets up strain states quite different from the gravity loads initial states.
10. The common engineering practice, making element section reductions as the structure height increases causes a major deformability trend, increasing the displacement levels, even though the demand in strength is lower compared to near base floors.
11. Amplification effects were evidenced related to frequencies′ synchronization.

RECOMMENDATIONS

This present study represents a modest contribution towards the inelastic response understanding in reinforced concrete framed structures. More investigation in this field will set a solid ground to discuss with firm criteria the design proposals that will be used in our codes.

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FIGURE SHEET 1

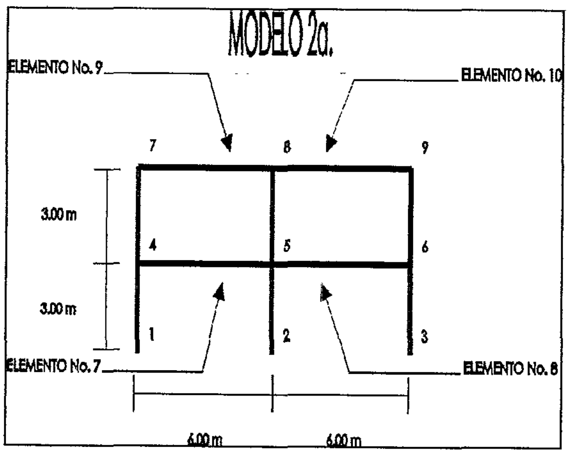

Fig.1
Model Analysis

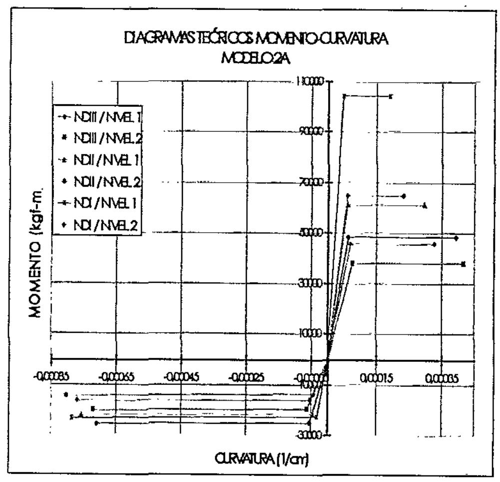

Fig. 2
Moment-Curvature Theoric Relationship

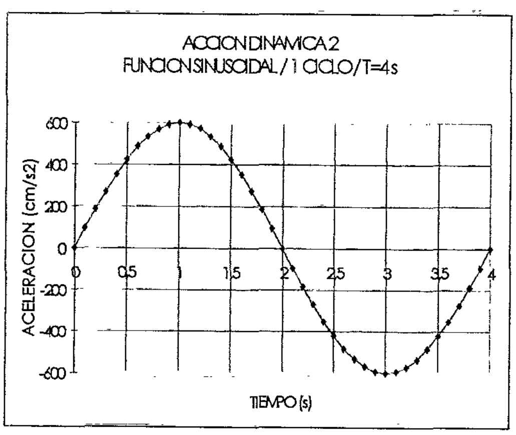

Fig.3
Dynamic Action 2
Sine Function - 1-Cycle - T= 4 sec.

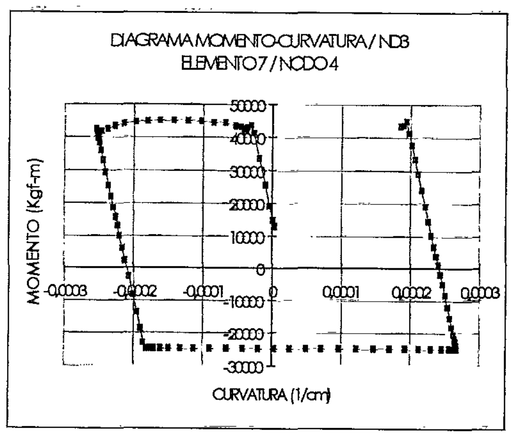

Fig.4
Moment Curvature Diagram
Design Level 3 - Element 7 - Node 4

FIGURE SHEET 2

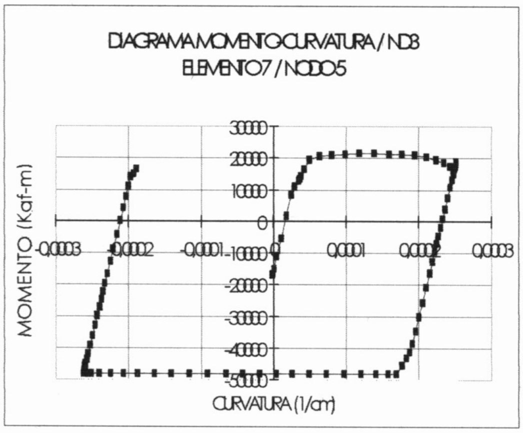

Fig.5 Moment-Curvature
Element 7-Node 5-Design Level 3
Dynamic Action 2

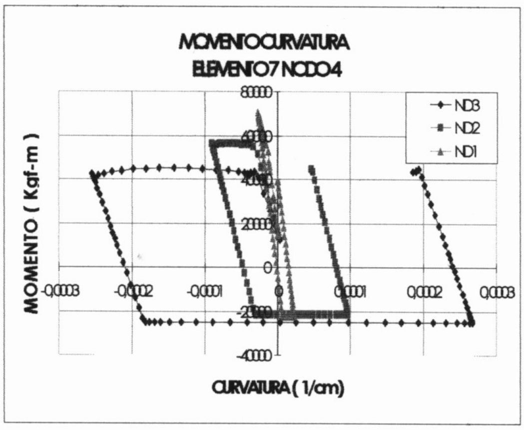

Fig.6 Moment-Curvature
Element 7-Node 5-Design Level 3,2,1
Dynamic Action 2

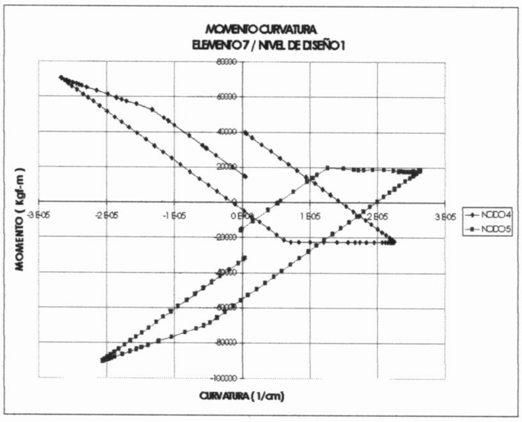

Fig.7 Moment-Curvature
Element 7-Node 4,5-Design Level 1
Dynamic Action 2

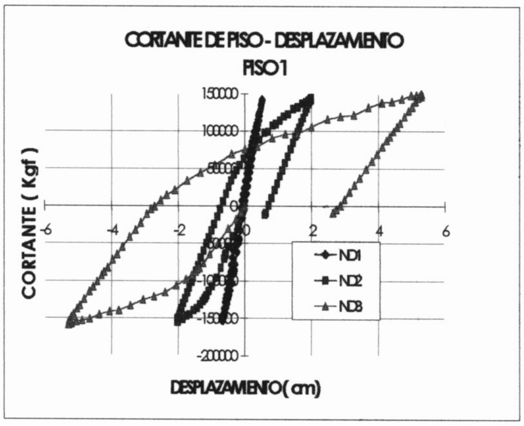

Fig.8 Story Shear-Displacement
Design Level 3,2,1-Story 1
Dynamic Action 2

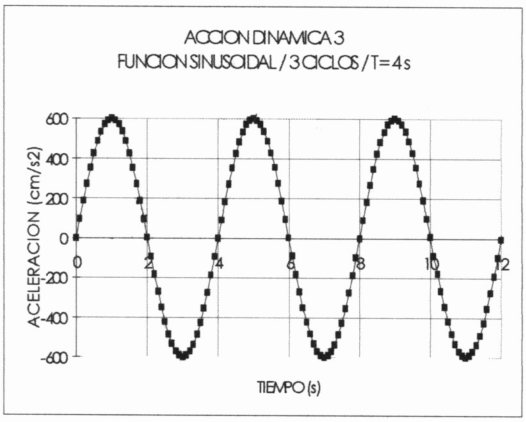

Fig.9 Dynamic Action 3
Sine Function - 3-cycle - T= 4 secs

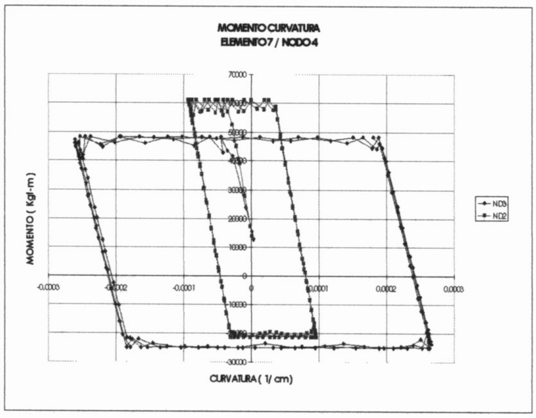

Fig.10 Moment-Curvature
Element 7-Node 4-Design Level 3,2
Dynamic Action 3

FIGURE SHEET 3

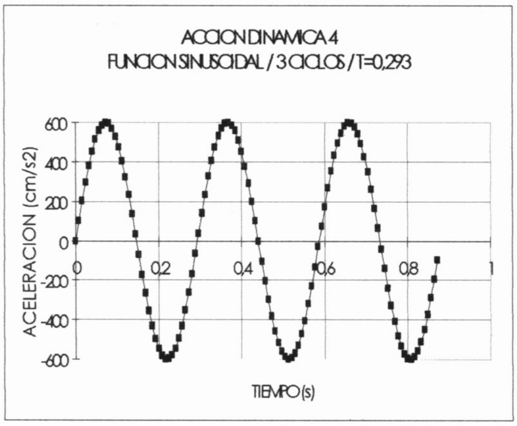

Fig. 11 Dynamic Action 4
Sine Function - 3-cycle - T= 0,293 sec

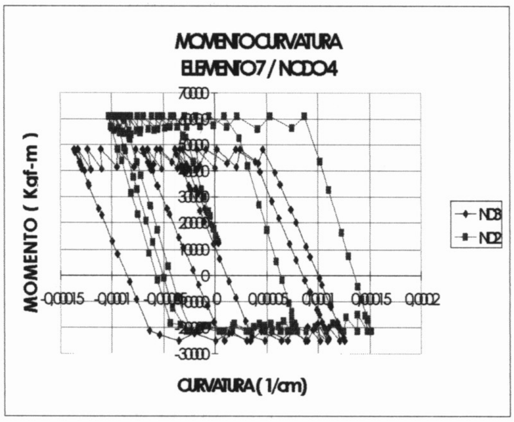

Fig. 12 Moment-Curvature
Element 7-Node 4-Design Level 3,2
Dynamic Action 4

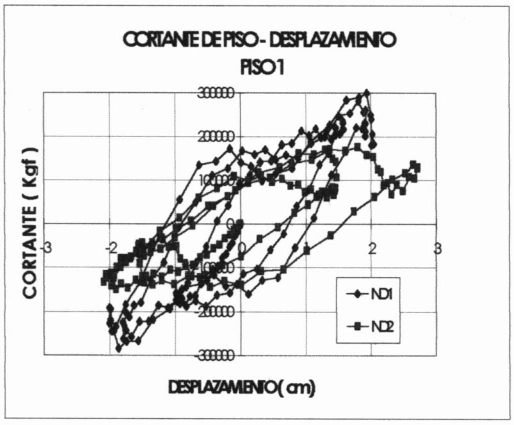

Fig. 13 Story Shear-Displacement
Design Level 1,2-Story 1
Dynamic Action 2

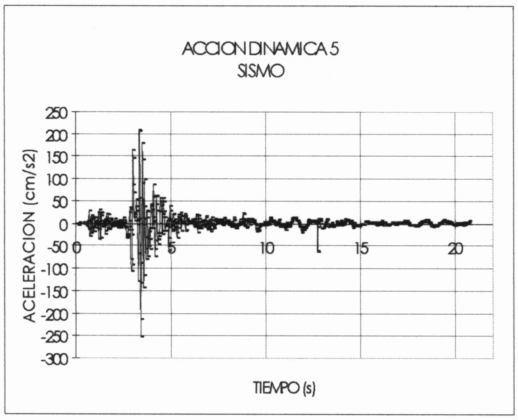

Fig. 14 Dynamic Action 5
Earthquake

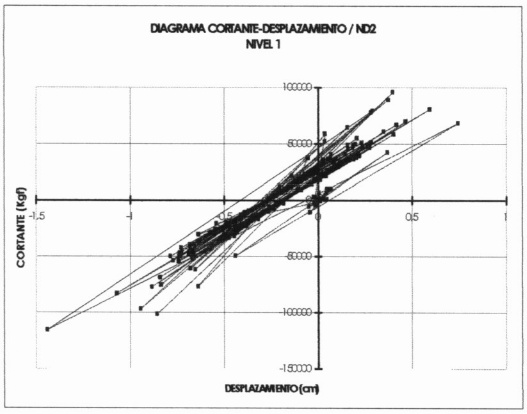

Fig. 15 Story Shear-Displacement
Design Level 2
Dynamic Action 5

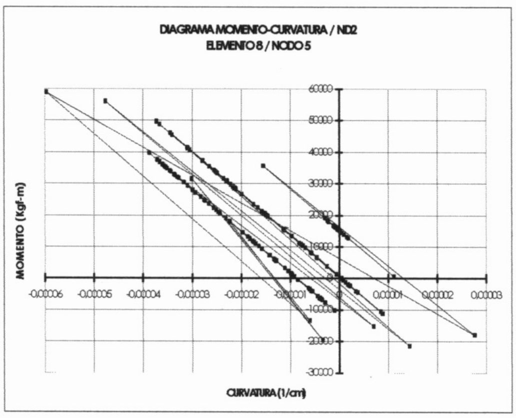

Fig. 16 Moment-Curvature
Element 8-Node 5-Design Level 2
Dynamic Action 5