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INFLUENCE OF GROSS vs TRANSFORMED CROSS SECTION IN COMPUTATION OF LATERAL DISPLACEMENTS

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Abstract

Lateral displacements due to earthquake loading are a limit state in design of building structures. After Loma Prieta (1989), Mexico (1985), Northridge (1994), Kobe (1995) and Nazca, Peru (1997) extended damage was attributed to excessive displacements. This meant large economic losses. Afterwards proposals were made to design based on displacement control. It became an important concern (SEAOC Vision 2000). After 1997 Peruvian Seismic Standard became very demanding lateral displacements and which effective stiffness should be considered in seismic analysis became an important issue.

World standards and researchers have proposed different criteria as to what moment of inertia, or effective stiffness, should be considered in seismic analysis. This paper summarizes a study to evaluate how computed lateral displacements in buildings change due to various stiffness reduction criteria for reinforced concrete members (ACI 318, FEMA, Paulay & Priestley, E.030 Peru).

A set of reinforced concrete buildings were design and spectral dynamic analyses performed. Variables included: a) structural configuration (regular or irregular in plan), b) earthquake resistant system (framed or dual) and c) height (4, 8, 12 and 20 stories). Amounting to a total of 16 building prototypes. Each of these was then analyzed with gross cross section (uncracked) and again for each of the three effective stiffness reduction criteria (cracked sections) given a total of 64 buildings.

Lateral displacements for each of these buildings in both directions were tabulated for each of the stiffness reduction criteria to evaluate increment in displacements as compared to buildings with elements with uncracked sections. As expected an important increment on displacements was found with significant differences depending upon the reduction criteria and structural system. Differences were also found with building height. Largest increments were due to ACI criteria, smallest with FEMA,s and Paulay and Priestley criteria produced intermediate results.

As an average, displacements using cracked sections increased around 60% as compare to those with uncracked sections. This information was taken into account in the 2016 version of Peruvian seismic standards that will now require seismic analysis be performed using uncracked sections.

Keywords: Performance based design, occasional seismic level, limit states

1. Introduction

This research was made having in mind the lack of definition in many seismic standards in relation to stiffness of reinforced concrete elements used in seismic analysis, for generally uncracked cross section are taken in structural analysis. Actually this is not the case since even at small earthquakes cracking will reduce stiffness. This may suggest that predimensioning computations could give imprecise results (mainly underestimate lateral displacements.

The problem of a cracking in reinforced concrete elements will arise the need to evaluate the influence of the criterion of effective stiffness used in seismic analysis of buildings, taking into account the type of structural system, the structural configuration and the number of floors. To achieve this it will be defined several criteria for effective stiffness to be used, as well as various structural models appropriate for analysis, taking into account the above mentioned variables. The assessments of the different models will be made considering the criteria established by the Peruvian standard of earthquake-resistant design E.030 [1].

In this investigation stiffness reduction factors will be applied for columns, beams and shear walls to get a real value of interstory distortions as compared to distortions obtained with no stiffness reductions. This reduction shall be considered in seismic analysis performed with program ETABS, applied to models of 4, 8, 12 and 20 stories for two types of structural systems and also taking into account structural configuration. The methods used to reduce stiffness were ACI 318 regulation, which proposes the reduction in the moments of inertia for items subjected to compression and bending. Another criterion used was FEMA (Federal Emergency Management Agency) standard which proposes effective stiffness and same as ACI 318 regulation contains data for stiffness in flexion, torsion and shear. Reduction factors proposed by Paulay & Priestley (1992), will also be employed which are a little more complex because previous computations are required to obtain a reduction factor.

2. Accuracy in Stiffness Estimation

In reinforced concrete structures codes specify a broader and more detailed requirement for ductility. One of this stringent requirements is to maintain stiffness of the structure as close as possible as to its design values.

Lack of precision in the estimation of stiffness (effective stiffness) in reinforced concrete elements during seismic analysis, does not allow to obtain true results due to considering uncracked section of these elements in design, this being strictly incorrect according with specifications of various standards and current studies (ACI 318, FEMA and Paulay & Priestley). Since small fissures, sometimes imperceptible to the human, due to gravitational loads or seismic events are expected to occur, that means early cracking in reinforced concrete elements and producing thus a reduction of stiffness. It is therefore necessary to consider its effect during the seismic analysis.

If a building is designed on the basis of the stiffness of uncracked sections, the building will have shorter periods with an apparently high basal shear, the consequence is not a conservative design, but a building that actually will have large mostly unacceptable distortions due to larger forces. Because of that, some codes take into account the influence of cracking and considere effective stiffness as a proportion of that of the uncracked section (EIg), specifying reduction factors to be applied to this of uncracked section during stiffness computation.

3. Variables selection for this study

During the process of this research, in order to verify different criteria for evaluation of influence of stiffness of cracked section, a series of buildings were designed, which were subjected to seismic analysis with of cracked sections elements. To carry out an adequate seismic analysis it is necessary that structures meet certain requirements that allow a desired behavior within the established seismic parameters, and at the same time these produce reliable results.

To carry out this it was decided to perform modal-spectral dynamic analyses, however in order to response reflects adequate design and pre-dimensioning of the building, structures were grouped based on three variables, which are important in seismic response. These were:

- *Structural configuration*
- *Structural system*

- *Building height (number of stories)*

The structures had to be classified according to their structural configuration as **regular or irregular**. Regular structures are those that do not have significant discontinuities horizontal or vertical in their lateral load-resistant configuration, while the irregular structures have one or more irregularities that affect their response during a seismic event, even more so if this is severe. For this research will be used only structural irregularities in plan, that is irregularities are called re entrant corners.

Structural systems are classified according to the material used, being in this case the reinforced concrete and the prevailing earthquake resistant structural systems in every direction were **framed and dual systems** (a combination of shear walls and frames).

For the third variable structures of four, eight, twelve and twenty floors were design, making the **height** of the building variable.

4. Criteria for Effective Stiffness

There are different standards, codes and studies of reinforced concrete around the world, that there are differences among them or how it would affect the performance of a structure. This is related to uncertainty on which reduction factor should affect gross moment of inertia, or stiffness, closer to actual cracking of reinforced concrete elements. Criteria used in this research were taken from three different sources, ACI 318, FEMA and Paulay & Priestley (1992).

4.1 Effective Stiffness after ACI 318 [5]

ACI Code requirements establishes: The following properties are allowed to be used in the elements of the structure:

- *Modulus of elasticity .... Ec*
- *Moments of inertia .... I*

  Elements in compression:
- *Columns 0.70Ig*
- *Uncracked walls 0.70Ig*
- *Cracked walls 0.35Ig*

  Elements in bending:
- *Beams 0.35Ig*
- *Flat walls and plates 0.25Ig*
- *Area 1.0Ag*

4.2 Effective Stiffness after FEMA

FEMA criteria for "*Values for effective stiffness*" are established in *Table 6-5 of FEMA 356 Chap.6; Concrete*. [4]. Table 1 contains data for stiffness in bending, torsion and shear

Table 1. Values of effective stiffness FEMA 356 [4]

Components	Bending Stiffness	Shear Stiffness	Axial Stiffness
Non prestressed beams	*0.5EcIg*	*0.4EcAw*	-
Prestressed beams	*EcIg*	*0.4EcAw*	-
Columns with compression due to gravity loads ≥ 0.5Agfc	*0.7EcIg*	*0.4EcAw*	*EcAg*
Columns with compression due to gravity loads ≥ 0.3Agfc or with tension	*0.5EcIg*	*0.4EcAw*	*EcAg*
Uncracked shear walls	*0.8EcIg*	*0.4EcAw*	*EcAg*
Cracked shear walls	*0.5EcIg*	*0.4EcAw*	*EcAg*
Flat slabs nonprestressed	-	*0.4EcAg*	-
Prestressed flat slabs		*0.4EcAg*	-

4.3 Effective Stiffness after Paulay & Priestley (1992) [3]

Reduction factors proposed by Paulay & Priestley are a little more complex, since in all of them there is no a unique reduction factor, instead they propose limits that can be vary according to different criteria of the elements. For beams, they set limits of reduction of the gross moment of inertia, without any prior computation, based on geometry, either for "T", "L" or rectangular beams, which makes it more accurate, since in ACI nor FEMA there is no reference to shape of the cross section. Column stiffness is based on axial load, this includes permanent gravity load, which is taken by the authors as 1.1 times dead load plus column axial load resulting from seismic action. The resulting axial forces in columns due to seismic effects are not known prior to structural analysis, as a result Paulay & Priestley propose an alternative for an approximation of the axial seismic forces.

$$P_i = \frac{V_{bf}\ l_c}{jl} \sum_{i}^{n} \left[1 - \left(\frac{i}{n}\right)^2\right]$$

Dónde:

- *"V_{bf}" is frame based shear*
- *"Pi" is axial load due to seismic effects in floor i.*
- *"j" is an aproxímate value of similar opennings in the structures.*
- *"l" is the of average size value of each openning.*
- *"lc" is average interstory height.*
- *"n" is the number of floors of the structure es el número de pisos de la estructura.*

In case of shear walls the authors mention that to obtain reasonable values of fundamental periods, movements and distribution of lateral forces appropriate between walls, the properties of the stiffness in walls of reinforced concrete, the effects of cracking must be taken into account. Paulay & Priestley proposed that the stiffness of the walls that are usually subjected to bending can be based on an equivalent moment of inertia of the cross section and this can relate to the moment of inertia of the uncracked section through the following expression:

$$I_e = \left(\frac{100}{f_y} + \frac{P_u}{f'c\ A_g}\right) I_g$$

Where:

- *"Pu" is the axial force in the wall during the earthquake.*
- *"fy" is the steel yield stress in MPa.*

The formula suggests, since there are no values of reduction for walls, that the inertia reduction factors on the walls be calculated manually, which means there will be values for each floor of the structure as well as columns, making it more complex and at the same time more precise.

5. Models description

Different prototypes were design with the purpose of comparing results among themselves and get reliable results, its dimensions and structural properties were standardized. The total number of structures designed and studied was sixteen, the three reduction criteria were applied making a total of forty eight analysis to evaluate the research variables.

To obtain the total weight of the buildings, the values from the Peruvian loads standard E.020 were considered. According to their height models were typical at all levels and therefore had the same area and amount of structural elements in each floor, in order not to introduce discontinuity of vertical or horizontal elements, this ruled out irregularities in height, mass, vertical geometry and discontinuity in structural systems. Also discontinuities in diaphragm and unparallel systems were discarded. Stiffness and torsional irregularities were checked for the uncracked section.

Standards from the Peruvian National Building Regulation were used in the whole research process, including Reinforced Concrete Design E.060. [11]

Element dimensions used are as follows:

- Column = 60 x 60 cm.
- Beam = 40 x 50 cm.
- Wall 1 = 15 x 350 cm.
- Wall 2 = 15 x 750 cm.
- Slab = 20 cm. de espesor.
- Interstory height = 2.6 m.

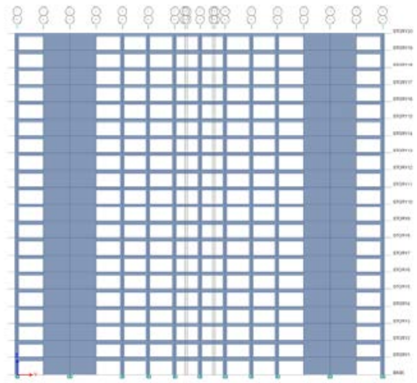

Fig. 1. Typical dual (frame with shear walls) 20 story structure

5.1 Classification of prototypes

For easier following of results each prototype is named in the following way: for structural configuration if it is regular (R) and irregular (I), for the structural system is framed (A) and dual (D) and the variation in height according to the number of levels is 4, 8, 12 and 20. From this it follows:

<u>For 4 stories:</u>

- *Framed Regular* = *RA4*
- *Dual Regular* = *RD4*
- *Framed Irregular* = *IA4*
- *Dual Irregular* = *ID4*

<u>For 8 stories:</u>

- *Regular Framed* = *RA8*
- *Regular Dual* = *RD8*
- *Irregular Framed* = *IA8*
- *Irregular Dual* = *ID8*

<u>For 12 stories:</u>

- *Regular Framed* = *RA12*
- *Dual Regular* = *RD12*
- *Irregular Framed* = *IA12*
- *Dual Irregular* = *ID12*

<u>For 20 stories:</u>

- *Framed Regular* = *RA20*
- *Dual Regular* = *RD20*
- *Framed Irregular* = *IA20*
- *Dual Irregular* = *ID20*

5.2 Parameters Definition for seismic analysis

The sixteen buildings were located on the coast of the Peru or zone 3. The use or importance factor (U) to was assigned the category C, common buildings. Soil profile was considered for a rigid stratum (S1), a soil factor S and period that defines the flat zone of the spectrum (T_P). According to the Peruvian standard E.030 [1], Spectral acceleration is computed as follows: $Sa = \frac{ZUCS}{R} g$. The following factors were used:

- Z = 0.4
- U = 1.0
- S = 1.0
- T_p = 0.4
- $C = 2,5 \frac{T_P}{T}$

The seismic force reduction coefficient (R) was established according to the classification of the prototypes presented in section 5.1. Irregularities in plant were considered in both axes, therefore seismic reduction coefficient is equal in both directions (X-X, Y-Y).

5.3 Computed Distortions with uncracked cross sections

Distortions of all structures with uncracked sections were computed using dynamic response spectrum analysis with Peruvian Seismic Standards. In all cases computed values were lower than limit established in the Standards, that is 0,007. Complete tables containing all values are presented in Ref (11)

6. Influence of configuration and structural system in distortion increment with height

In what follows plots are presented, that combined the influence of structural configuration and structural system to observe how distortions vary according to the three proposed criteria to reduce stiffness throughout all levels in height and the proposed structures.

6.1 Configuration and structural system with height. ACI-318 stiffness reduction criteria

It is observed that prototypes of 4 levels can reach maximum distortion increments at its ultimate level, with values even greater than a prototype of 20 stories. In the four graphs (Fig. 2,3,4,5) it can be seen distortion growth as height increases, with very similar values, especially among the prototypes of 8 and 12 stories in height, which have smaller distortions than the prototypes of 4 and 20 levels, this is more noticeable in framed prototypes.

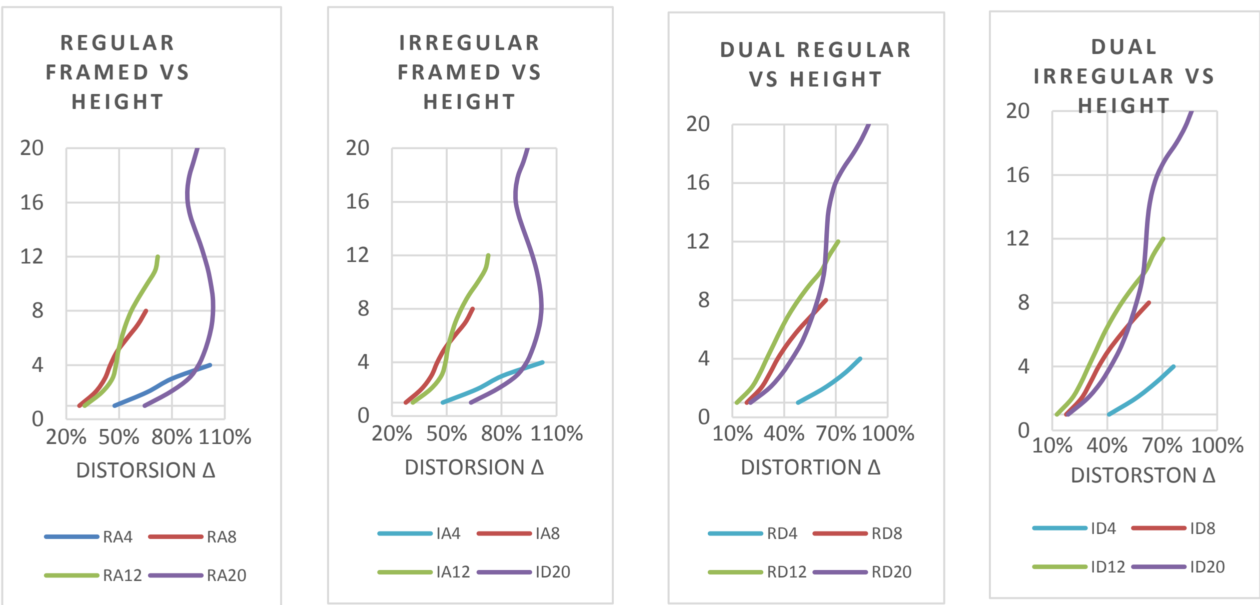

Fig. 2.-. ACI: RA vs height; IA vs height ; RD vs height ID vs height

6.2 Configuration and structural system with height. FEMA stiffness reduction criteria

It can be seen that the maximum distortion increments were reached in all of 4 level prototypes, becoming more noticeable in the dual prototypes, which increase up to almost in 30% more than the other three in the base, which will be increasing with its height until reaching values near 60% in the last level. While for framed prototypes distortions increments in the 4 levels remained constant, varying less than 1% among all levels. (Fig. 6,7,8,9)

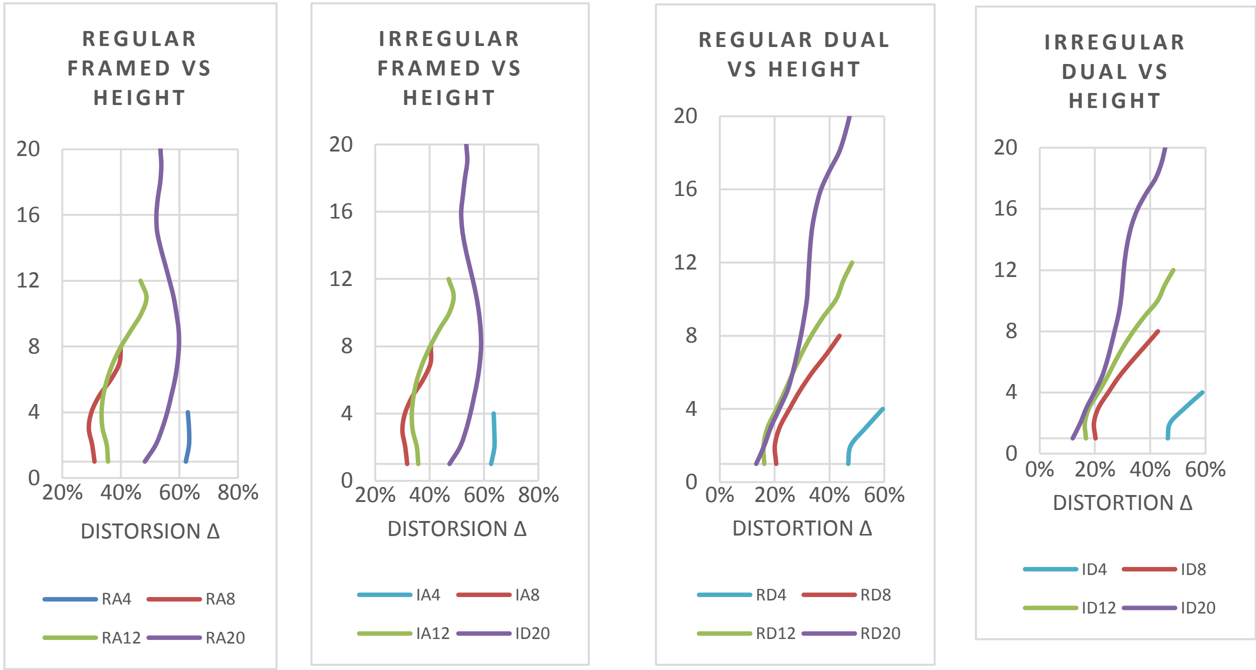

Fig. 3.-. ACI: RA vs height; IA vs height ; RD vs height ID vs height

6.3 Configuration and structural system with height. Paulay & Priestley stiffness reduction criteria

Again a noticeable increment is observed on the graph of the prototypes of 4 levels, this because their distortions increase significantly with respect to the other three prototypes. Along the 4 Figures (10,11,12,13) sudden changes are noticed either in an increase or decrease of the distortion, which makes trends in the graph are not maintained.

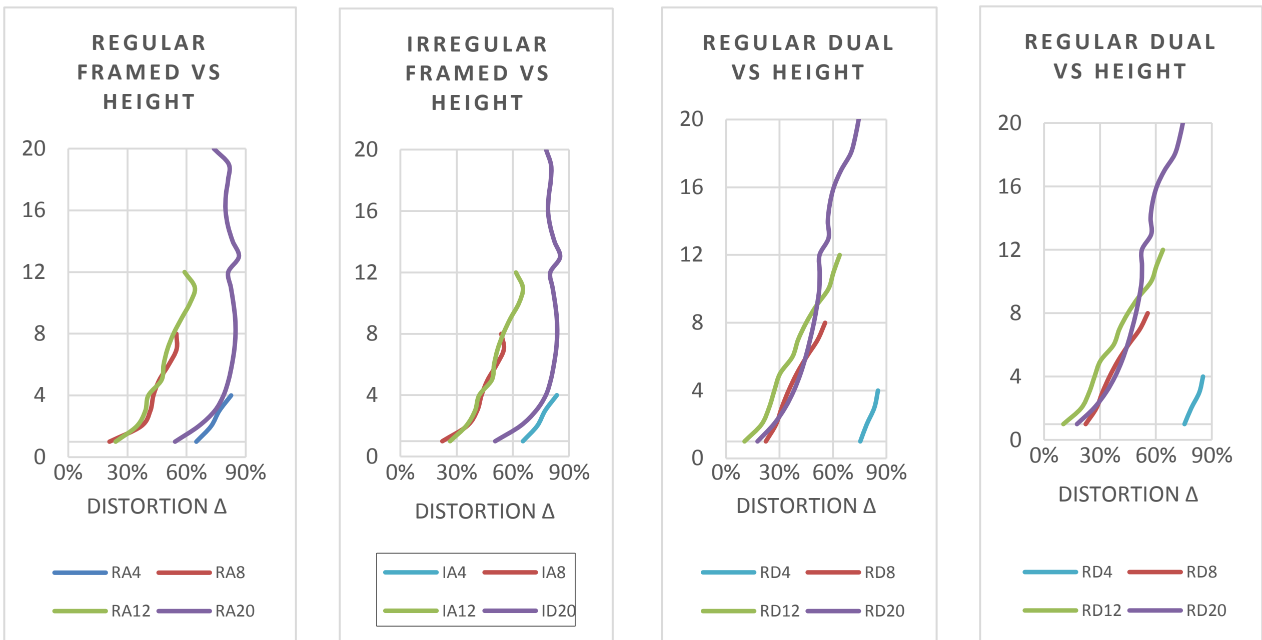

Fig. 4.-. P & P: RA vs height; IA vs height ; RD vs height ID vs height

7. Influence of Configuration and Structural system in height

Plots (not presented) [11] of influence of structural configuration in distortion increment is almost unnoticeable. Regular or irregular structures show the same increment.

In Fig 14, 15 and 16 distortion increment due to structural system< framed versus dual, are shown. As can be observed there is constant increment of distortions due to structural system regardless of cracking criteria. In al cases framed structures present larger increments than dual systems. This is due to the difference on effective stiffness: framed or dual.

In Fig. 17 a summary of distortion increments due to all three criteria considered and all variavles, structural system, structural configuration and number of stories, is presented.

As can be seen the lowest increments are obtained using FEMA criteria. The largest increments are obtained using ACI criteria and Paulay & Priestley criteria give intermediate results. If a rough general average is to be given this would be around 60%.

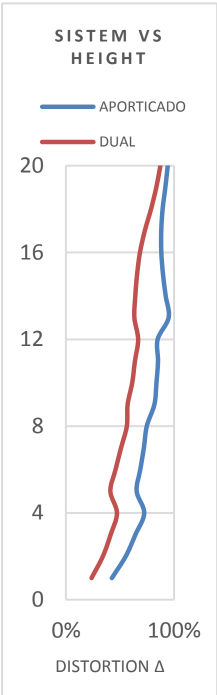

Fig. - 5 After ACI

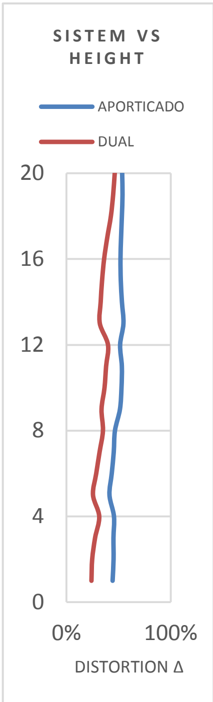

Fig. - 6 After FEMA

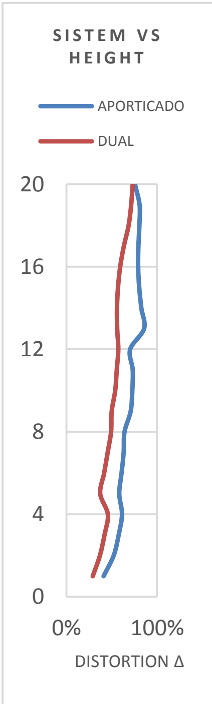

Fig. - 7 After P&P

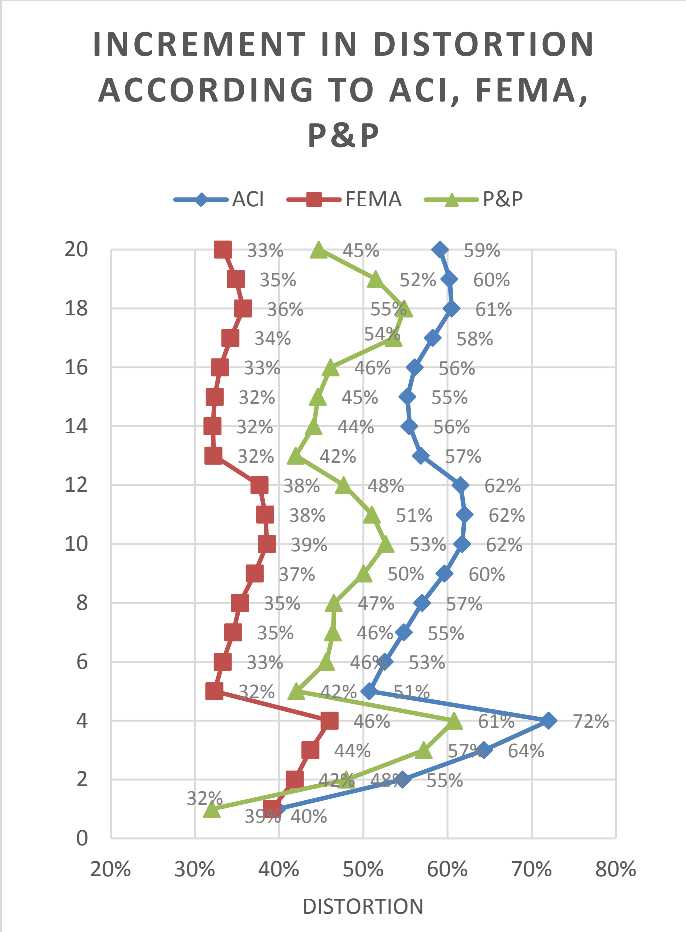

Fig. - 8 Summary of distortions increments of with each criteria including all variables

8. Conclusions

1. When ACI criteria for effective stiffness (cracked sections) is used, drift increases between 33% and 92% as compared to using uncracked section.
2. When FEMA standard was used, these increments of drift were between 34% and 50%.
3. When by Paulay & Priestley criteria was used drift increases between 35% and 74%.
4. Comparing only structural configuration between regular and irregular prototypes no noticeable difference in drift increment could be observed. Plant irregularity (cut off corners) did not increasing distortions significantly. Drift increments according to different criteria are as follows:
   - Drift increments using ACI in regular prototypes were between 33%-90% and in irregular ones 34%-92%,.
   - Using FEMA increments in regular prototypes were between 34%-49% and in irregular ones between 34%-50%.
   - Using Paulay & Priestley criteria increments for regular prototypes were between 34%-75% and for irregular ones between el 36%-74%.
5. It could be observed that using dual prototypes improves drift control mainly in the lower stories. It could also be observed that when height is increased drift in dual structures also increases up to similar values than for framed prototypes. There is a difference in drift due to structural system between framed and dual systems. Increments vary as follows:
   - Using ACI criteria 24% - 87% for dual systems and 43% - 94% for framed systems,

- For dual prototypes using FEMA criteria increment was between 24% - 46% and for framed systems between 44% - 54%.
- Using Paulay & Priestley criteria drift increased between 29% - 73% for dual prototypes and 41% - 76% for framed structures.

6. Increments in drift for different building heights were found. Four story buildings showed the largest drift increment as compared to 8, 12 and 20 story buildings.
    - Using ACI criteria increment was between 46% - 91%.
    - Using FEMA criteria increment was between 54% - 61%.
    - Using Paulay & Priestley criteria increment was between 68% - 84%.
7. Results obtained for all prototypes, using the three criteria of cracking, show the reduction of inertia in structural elements for seismic analysis should be considered. This will allow to get drifts values closer to reality, since this increment of distortion with cracked sections are significant.
8. Comparing three cracking criteria it could be noticed that drifts after cracking using the criteria of FEMA, produced, in all cases, the minimum increments of all criteria; therefore its use may not be recommended, since it may underestimate actual increments.
9. When using Paulay & Priestley criteria for the most cases, as a function of height, configuration and structural system, it is recommended to group cracking factors in a table. Calculations were made using this criteria for each level and in each prototype, reaching a total of 176 reduction factors only for columns, although this could ensure better accuracy, it becomes very cumbersome when compared with ACI or FEMA.
10. To use the factors of cracking in low-rise buildings could result in excessive drift increment. It was observed that using any cracking criteria in buildings of less than eight stories, drift exceeding the limits of the standard E.030 were obtained, at almost all levels

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