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SOFT STORY LIMITS FOR SAFETY OF FRAMED BUILDINGS

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Abstract

In past earthquakes in Peru and worldwide it has been observed that soft story irregularity in building structures represents a serious hazard for its integrity and stability. To prevent collapse to preserve occupant lives inside a structure is an objective in all modern design standards. Therefore to know from which first story height this irregularity becomes critical to determine the possibility of collapse due to soft story. This is important for both design of new structures as for assessment and rehabilitation of existing structures. Several worldwide codes were reviewed to learn how this irregularity is defined and a summary is presented. Framed buildings of three, five, nine and fifteen stories, with two spans in both directions were analyzed. Openings span is five meters, typical height is three meters and the first floor height varies from three to nine meters. These frames were previously designed according to Peruvian Building Regulations. For comparison, a regular pattern structure, both in plan and elevation model was developed. Cases representing irregular structures were defined by modifying the vertical distribution of stiffness, increasing the height of the first floor model pattern to identify the weakest structural elements to fail first.

The goal was to find the limit of the irregularity to ensure the stability of the structure and prevent collapse. Thus it is ensured that the structure reaches a collapse mechanism chosen during the design stage (weak beams strong columns), evaluating interstory drift limits for various performance levels according to Vision 2000. The procedure followed was (a) define analytical models of buildings designed under Peruvian standards, (b) compute parameters of models for inelastic behavior of elements experiencing nonlinear behavior, (c) analyze nonlinear performance in these models (pushover), and finally, (d) evaluate results obtained from these nonlinear analysis methods. With this information, behavior of soft story was investigated and factors, causes and results from this irregularity are explained in detail.

In all buildings studied (three, five nine and fifteen stories) for first story height varying from three to under seven meters (6.5m) drift is between immediate occupancy (IO) and life safety (LS) performance level. For first story height varying from seven to nine meters drift lies between life safety (LS) and collapse prevention (CP) performance levels. Therefore it can be concluded that maximum first story height of a framed building, for it not to present soft story and have acceptable performance, must be under seven meters. This means a height ratio (first story height to typical) of under 42%. This limit is much lower than percentage that declares soft story in Peruvian Standards E.030-2003 (75%) and also in International Standards. In 2016 version of Peruvian Standard, soft story is declared based on drift relations (first floor to typical), height relation becomes now (60%). Compared to the maximum height of the first floor for analyzed buildings (linear analysis), it could be said seismic Peruvian standard E.030 is safe, somehow conservative as in International Standards .

Keywords: Soft story, irregular structures, irregularity limit, collapse mechanism, performance level.

1. Introduction

There are many earthquakes that have occurred in Peru and the world, leaving a large number of deaths and serious damage to infrastructure, and that in the majority of cases damage is due to vulnerability of the buildings caused by bad structural configurations, low resistance structures, poor construction techniques, low quality materials, among others. While more complex is the structure, more difficult it is to predict its seismic behavior. For this reason it is advisable that the structure be as simple as possible, so that necessary modeling for seismic analysis approaches as much as possible the actual structure. One of the most common and dangerous structural problems is called soft story. To concentrate the inelastic behavior and damage on a single floor is very dangerous; it is very likely that damage exceeds the capacity of inelastic deformation (ductility) of columns, leading to the structure to have stiffness degradation and possibly partial or total collapse.

2. Soft Story

Soft story occurs when there is a sudden change of rigidity or a significant discontinuity of stiffness between the structure of a floor and the rest of the floors above in the structure. If a structure has a much more flexible area under a rigid area, there will be a vulnerable area, most of the absorption of energy is concentrated in the flexible portion, and the upper rigid portion absorbs rather little.

Fig.1 ─ Soft story in first floor [13]

2.1. Comparison soft story stiffness irregularity after various countries standards

The UBC (Uniform Building Code) [2] and the IBC (International Building Code) [3], consider that in order to determine if a soft story exist, it must be established depending on the stiffness of its structural elements K_i; IBC classifies it in two ways , 1a and 1b, irregularities for soft story and extreme soft story respectively, being the last more critical, as shown in Table 1. If stiffness of floor meets at least one of the two criteria listed in this Table, the structure is considered having soft story.

Many codes from around the world define structures to be irregular if they do not comply with the "limits" of irregularities established by them. In this section a review of criteria used in seismic design codes to determine if a structure is regular or irregular, as well as the limits imposed to such structures. An overview of codes of some countries of major seismic activity around the world such as Peru-2003 [5], Peru-2016 [6], EEUU IBC [3], Mexico [8], Colombia [11], New Zealand [9], India [1], Turkey [7] and SEAOC [14] is made.

For the comparison of irregularity of stiffness in different standards the term K_i, which is the lateral stiffness of floor, must be taken into account, Δ_i is the interstory drift distortion and ΣA_i the sum of areas of the cross sectional areas of shear resisting vertical elements

Table 1 – Comparison of soft story stiffness irregularity after various countries standards

Standards	Irregularity condition	
	1a.-Irregularity soft story	1b.-Irregularity soft story extreme
Peruvian E.030-2003	$\sum A_i < 0.85 \sum A_{i+1}$ $\quad \left(\frac{h_i}{h_d}\right) \sum A_i < 0.85 \sum A_{i+1}$ $\sum A_i < 0.90 \left[\frac{\sum A_{i+1} + \sum A_{i+2} + \sum A_{i+3}}{3}\right]$	
Peruvian E.030-2016	$\frac{\Delta_i}{h_i} > 1.4 \frac{\Delta_{i+1}}{h_{i+1}}$ $\frac{\Delta_i}{h_i} > 1.25 \left[\frac{\frac{\Delta_{i+1}}{h_{i+1}} + \frac{\Delta_{i+2}}{h_{i+2}} + \frac{\Delta_{i+3}}{h_{i+3}}}{3}\right]$	$\frac{\Delta_i}{h_i} > 1.6 \frac{\Delta_{i+1}}{h_{i+1}}$ $\frac{\Delta_i}{h_i} > 1.4 \left[\frac{\frac{\Delta_{i+1}}{h_{i+1}} + \frac{\Delta_{i+2}}{h_{i+2}} + \frac{\Delta_{i+3}}{h_{i+3}}}{3}\right]$
IBC-USA	$K_i < 0.70 K_{i+1}$ $K_i < 0.80 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right]$	$K_i < 0.60 K_{i+1}$ $K_i < 0.70 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right]$
Mexico	$K_{i+1} > 1.5 K_i$ $\quad K_i < 0.67 K_{i+1}$	$K_{i+1} > 2 K_i$ $\quad K_i < 0.50 K_{i+1}$
Colombia	$0.60 K_{i+1} \le K_i < 0.70 K_{i+1}$ $0.70 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right] \le K_i < 0.80 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right]$	$K_i < 0.60 K_{i+1}$ $K_i < 0.70 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right]$
India	$0.70 K_{i+1} \le K_i < 0.80 K_{i+1}$	$K_i < 0.60 K_{i+1}$ $K_i < 0.70 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right]$
SEAOC	$0.7 \frac{\Delta_i}{h_i} > \frac{\Delta_{i+1}}{h_{i+1}}$ $\quad 0.80 \frac{\Delta_i}{h_i} > \left[\frac{\Delta_{i+1}}{h_{i+1}} + \frac{\Delta_{i+2}}{h_{i+2}} + \frac{\Delta_{i+3}}{h_{i+3}}\right]$	
New Zealand	$K_i < 0.70 K_{i+1}$ $\quad K_i < 0.80 \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right]$	
Turkey	$\eta_{ki} = \frac{(\Delta_i)_{ort}}{(\Delta_{i+1})_{ort}} > 1.5$	

In Fig. 2 two cases, factors γ_{K1} and γ_{k2} are compared in different standards:

$$K_i < \gamma_{K1} K_{i+1} \tag{1}$$

$$K_i < \gamma_{k2} \left[\frac{K_{i+1} + K_{i+2} + K_{i+3}}{3}\right] \tag{2}$$

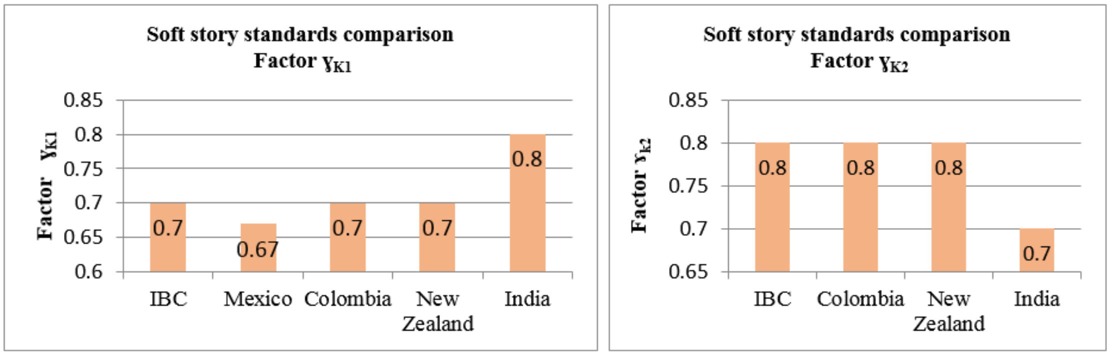


Fig. 2 – Comparison of soft story stiffness irregularity after various countries standards

3. Buildings to be analyzed and results from dynamic analysis

3.1. Notation for regular and irregular cases

To describe the irregular cases, the following parameters are defined: the modification of stiffness KN is a parameter that represents the variation in the distribution of the rigidity of the standard case.

$$\text{KN-Z} \quad (3)$$

Where:
K: Stiffness modification factor,
N: Number of stories of structure,
Z: First story height, in meters.

For example, K9-5, represents a 9 story structure and first floor height of 5 meters.

3.2. Characteristics of structure models

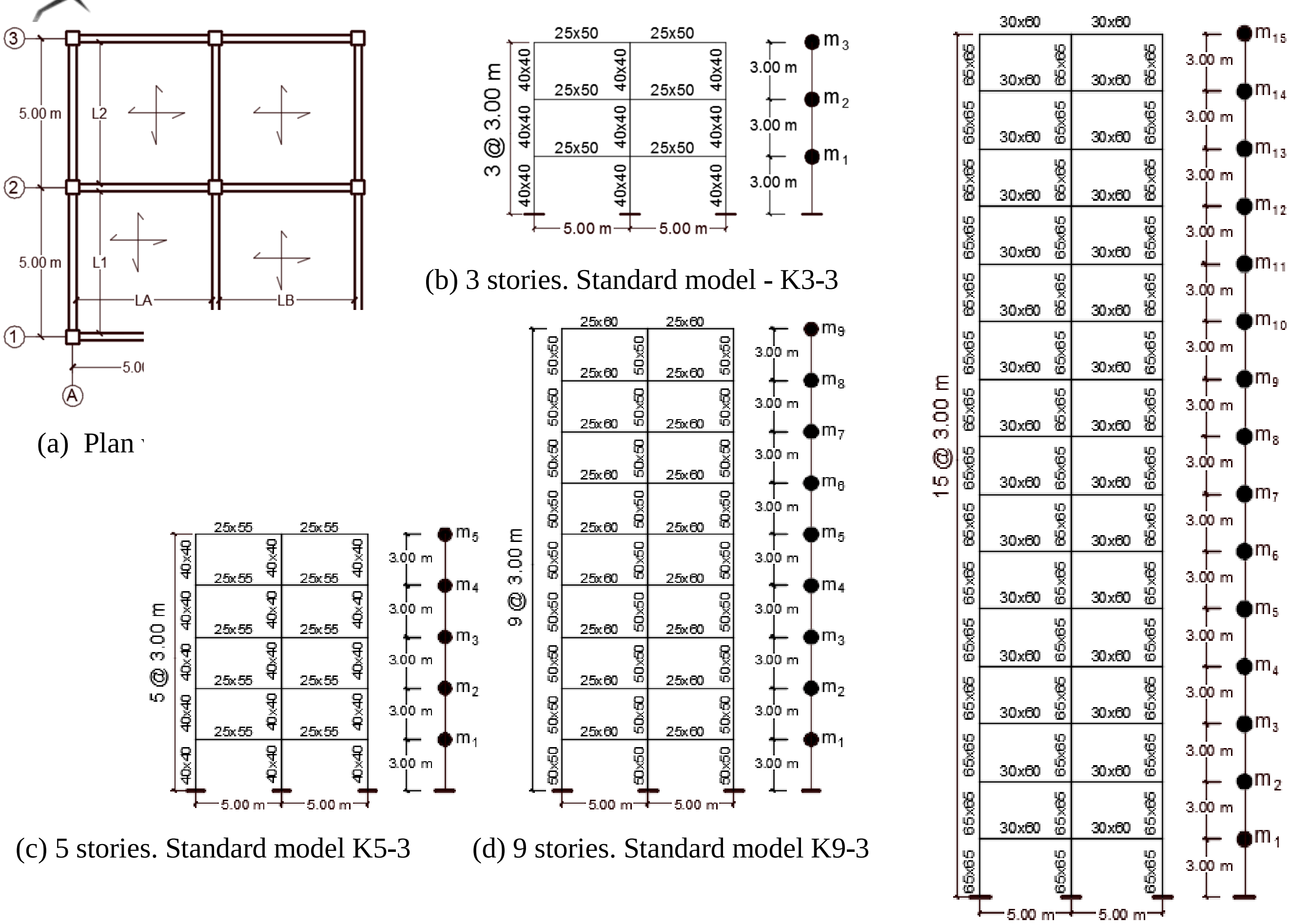
For purposes of comparison a standard model or pattern of regular typology was developed: K3-3, K5-3, K9-3 and K15-3, with the same typical height and a constant mass at every level.

Table 2 – Model identification for linear and nonlinerar dynamic analysis

Building	**Linear analysis models**							**Nonlinear analysis models**			
3 stories	K3-3	K3-3.5	K3-4	K3-4.5	K3-5	K3-7	K3-9	K3-3	K3-5	K3-7	K3-9
5 stories	K5-3	K5-3.5	K5-4	K5-4.5	K5-5	K5-7	K5-9	K5-3	K5-5	K5-7	K5-9
9 stories	K9-3	K9-3.5	K9-4	K9-4.5	K9-5	K9-7	K9-9	K9-3	K9-5	K9-7	K9-9
15 stories	K15-3	K15-3.5	K15-4	K15-4.5	K15-5	K15-7	K15-9	K15-3	K15-5	K15-7	K15-9

Table 3 – Stiffness ratio compared to basic structure, in first floor

3 stories				**5 stories**				**9 stories**				**15 stories**			
K3-3	K3-5	K3-7	K3-9	K5-3	K5-5	K5-7	K5-9	K9-3	K9-5	K9-7	K9-9	K15-3	K15-5	K15-7	K15-9
1.0	0.27	0.11	0.05	1.0	0.26	0.1	0.05	1.0	0.29	0.12	0.06	1.0	0.33	0.15	0.08

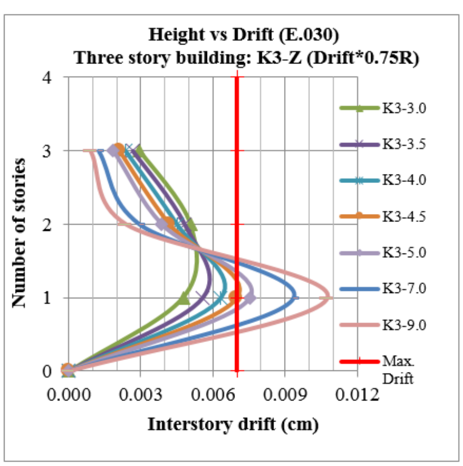


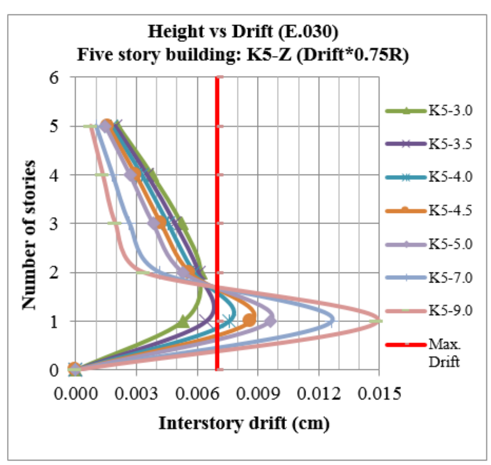
(a) Plan
(b) 3 stories. Standard model - K3-3
(c) 5 stories. Standard model K5-3
(d) 9 stories. Standard model K9-3
(e) Fifteen stories. Standard model K15-3

Fig. 3 – Standard models for 3, 5, 9 and 15 story buildings (Regular structure). Dimensions shown

3.3. Drift with linear modal spectral analysis

From linear analysis of buildings drift of the first story (height varying from three to nine meters) was cheked in order to satisfy allowable drift limit of 0.007, for reinforced concrete structures (according to Peruvian seismic standard E.030. It was found that maximum height to comply with design drift limits for the three-, five-, nine-, and fifteen-storey buildings, was 4.5, 3.5, 4.5 and 5.0 meters respectively.





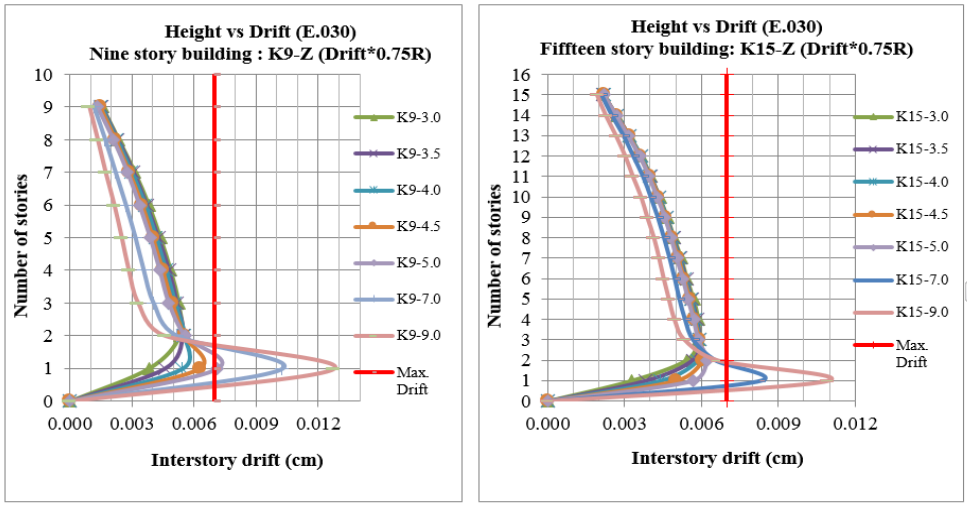


Fig. 4 – Interstory drift verification, after linear analysis, three, five, nine and fifteen story buildings

Table 4 – Comparison of irregularity conditions for soft story. First floor height

Standard	**Irregularity condition**	**Irregular beyond this first story height (m)**			
		3 Stories	**5 Stories**	**9 Stories**	**15 Stories**
Peruvian E.030-2003	$\left(\frac{h_i}{h_d}\right)\sum A_i < 0.85\sum A_{i+1}$	4.0	4.0	4.0	4.0
Peruvian E.030-2016	$\frac{\Delta_i}{h_i} > 1.4\frac{\Delta_{i+1}}{h_{i+1}}$	5.0	5.0	7.0	9.0
	$\frac{\Delta_i}{h_i} > 1.25\left[\frac{\frac{\Delta_{i+1}}{h_{i+1}} + \frac{\Delta_{i+2}}{h_{i+2}} + \frac{\Delta_{i+3}}{h_{i+3}}}{3}\right]$	-.-	5.0	5.0	7.0

It can be said that Peruvian Standard E.030-2016 issued January 2016) is less stringent than the same of 2003 (E.030-2003) and other standards from different countries.

Analyzing the two conditions of irregularity of the Peruvian standard E.030-2016, and if at least one of them applies the structure is declared irregular; then for structures of three, five, nine and fifteen stories are irregular starting at first story heights of 5.0, 5.0, 5.0 and 7.0 meters respectively.

Table 5 shows a comparison of the condition of first floor soft story stiffness irregularity K_i/K_{i+1}. In this case for the first two floors K_1/K_2, according to codes in different countries (IBC, Mexico, Colombia, New Zealand, and India). For three, five, nine and fifteen floors buildings are irregular from first floor heights of 4.0, 4.0, 4.5, and 5.0 meters respectively.

Table 5 – Verification of soft story irregularity (K_i/K_{i+1}) after various countries standards

Building	Model	First story stiffness (t/cm)	Second story stiffness (t/cm)	Stiffness ratio (K_1/K_2)	Country Standard				
					IBC	Mexico	Colombia	New Zealand	India
3 Stories	K3-3.0	122.93	92.82	1.32	Regular	Regular	Regular	Regular	Regular
	K3-3.5	84.33	88.13	0.96	Regular	Regular	Regular	Regular	Regular
	K3-4.0	59.91	83.55	0.72	Regular	Regular	Regular	Regular	Irregular
	K3-4.5	43.82	79.87	0.55	Irregular	Regular	Irregular	Irregular	Irregular
	K3-5.0	33.02	75.94	0.43	Irregular	Irregular	Irregular	Irregular	Irregular
	K3-7.0	12.92	64.32	0.20	Irregular	Irregular	Irregular	Irregular	Irregular
5 Stories	K5-3.0	129.46	101.63	1.27	Regular	Regular	Regular	Regular	Regular
	K5-3.5	88.02	97.80	0.90	Regular	Regular	Regular	Regular	Regular
	K5-4.0	62.07	94.65	0.66	Irregular	Regular	Irregular	Irregular	Irregular
	K5-4.5	45.40	91.01	0.50	Irregular	Irregular	Irregular	Irregular	Irregular
	K5-5.0	34.06	87.89	0.39	Irregular	Irregular	Irregular	Irregular	Irregular
	K5-7.0	13.26	76.55	0.17	Irregular	Irregular	Irregular	Irregular	Irregular
9 Stories	K9-3.0	238.03	164.22	1.45	Regular	Regular	Regular	Regular	Regular
	K9-3.5	167.91	156.96	1.07	Regular	Regular	Regular	Regular	Regular
	K9-4.0	121.95	151.04	0.81	Regular	Regular	Regular	Regular	Regular
	K9-4.5	91.28	145.49	0.63	Irregular	Regular	Irregular	Irregular	Irregular
	K9-5.0	70.02	139.37	0.50	Irregular	Regular	Irregular	Irregular	Irregular
	K9-7.0	28.72	121.43	0.24	Irregular	Irregular	Irregular	Irregular	Irregular
15 Stories	K15-3.0	437.22	258.87	1.69	Regular	Regular	Regular	Regular	Regular
	K15-3.5	319.75	245.23	1.30	Regular	Regular	Regular	Regular	Regular
	K15-4.0	240.25	233.49	1.03	Regular	Regular	Regular	Regular	Regular
	K15-4.5	185.52	222.73	1.03	Regular	Regular	Regular	Regular	Regular
	K15-5.0	145.74	213.14	0.68	Irregular	Regular	Irregular	Irregular	Irregular
	K15-7.0	64.80	181.52	0.36	Irregular	Irregular	Irregular	Irregular	Irregular

4. Nonlinear analysis and limits for soft story irregularity

For analysis and evaluation of reinforced concrete structures simplified or idealized stress-strain relationship are used. For reinforcing steel it was decided to use the model proposed by Park and Paulay (1975) [10], this divides the stress strain curve in three zones: linear elastic, yield and strain hardening and for concrete a model proposed by Mander et al. [4].

Idealization of moment - curvature diagram was made following Restrepo criteria [12] where performance limits are first computed and located for concrete and longitudinal reinforcement. Fig. 5.

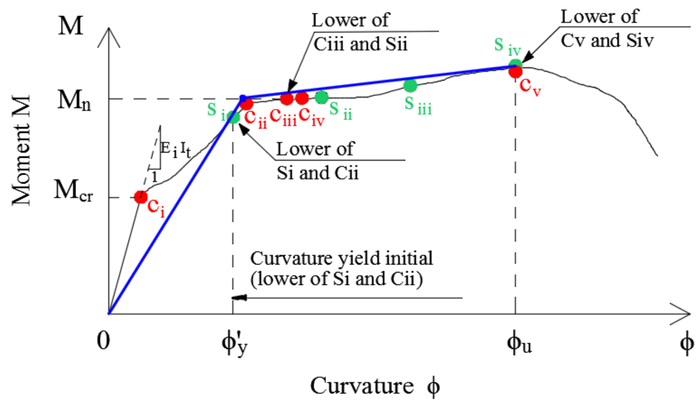


Fig. 5 – Performance limits of concrete and steel and bilinear approximation by Restrepo [12]

After computed and located performance limits of concrete and steel in moment-curvature diagram an idealization is made determining: “first yield”, “nominal bending strength”, “yield curvature”, and “ultímate strength”.

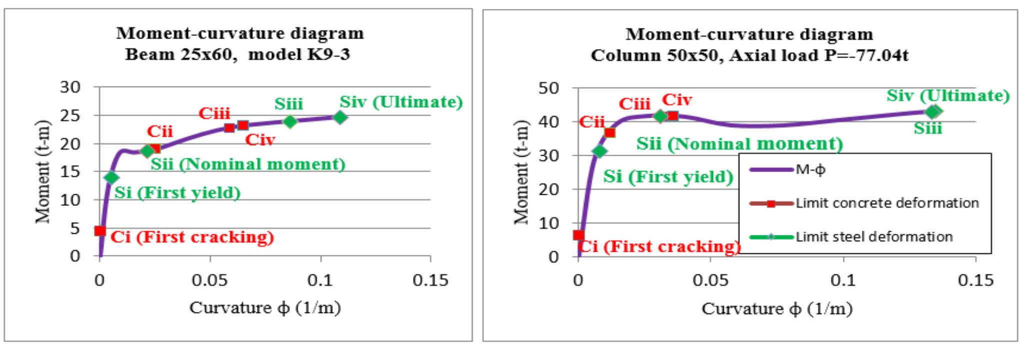


Fig. 6 – Moment-curvature diagram and limit deformation states. Model K9-3 (beam 25x60 y column 50x50)

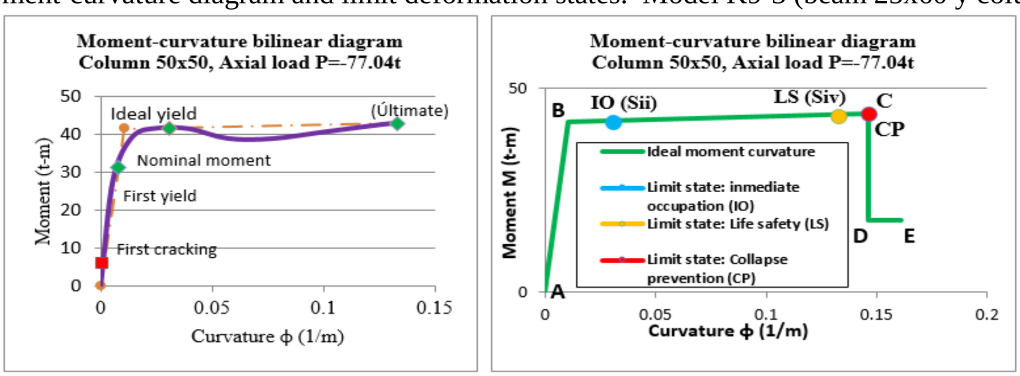


Fig. 7 – Bilineal idealization of moment M –curvature ϕ and location of performance points. Column 50 x 50. 9 story building: model K9-3

4.1. Hinge sequence and collapse mechanism

Sequence of hinge formation allows to identify points of the capacity curve:

- First yield point
- Performance point of the structure "Immediate occupancy" (IO).
- Performance point of the structure "Life Safety" (LS).
- Performance point of the structure "collapse prevention" (CP).

Points A, B, C, D, and E are identify to define behavior of elements besides to points IO, LS and CP that are used to define the acceptance criteria for the hinge. Values that belong to each of these points vary depending upon the type of structural element as well as other parameters defined by Restrepo criteria. Color in joints indicates their location along the force-displacement curve. Meaning for each color is explained at the side of each picture. Acceptance criteria B, IO, LS, CP, points C, D and E are shown as levels, according to status of the hinge in accordance with performance level. When first hinges appear, it means that first yield occurs in one structural element, when moment in the element reaches nominal yield moment, they are at the point B of the force displacement curve. But when a joint reaches point C in the force displacement curve, it ceases to resist loads, moment in the hinge reaches the ultimate capacity (yellow hinge), which reached its rotation limit at the level of collapse prevention (CP). Then force applied in the pushover (base shear) is reduced until the joint force is consistent with the force at point D. As this force decreases, all elements stop loading and displacement is reduced. Once the hinge has yielded and reaches force level point D, force in pushover analysis (base shear) increases again and displacement starts to grow again.

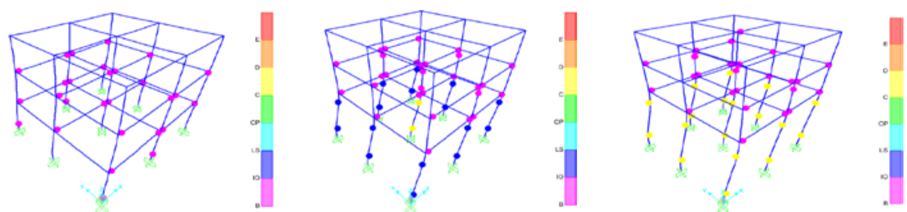


Fig. 8 – Sequence of plastic hinge formation. Three story building: Models: K3-3, K3-5 y K3-7

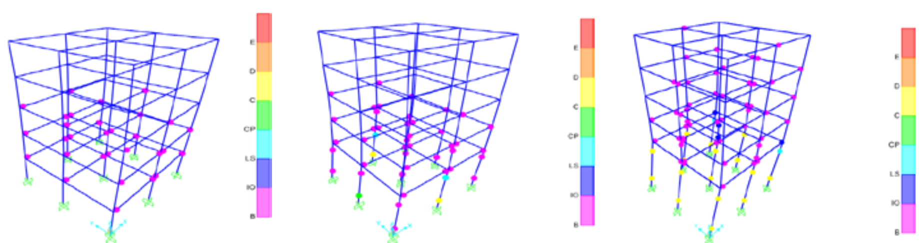


Fig. 9 – Sequence of plastic hinge formation. Five story building: Models: K5-3, K5-5 y K5-7

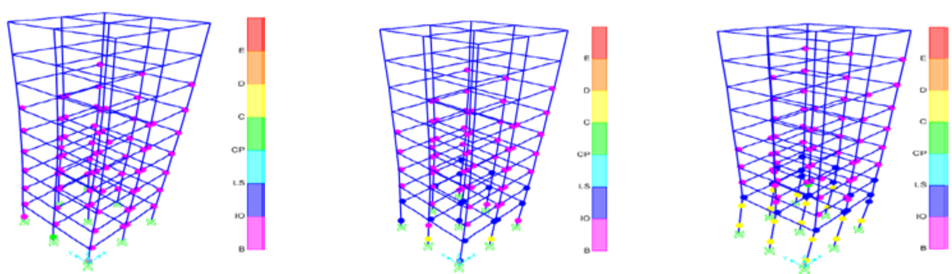


Fig. 10 – Sequence of plastic hinge formation. Five story building: Models: K9-3, K9-5 y K9-7

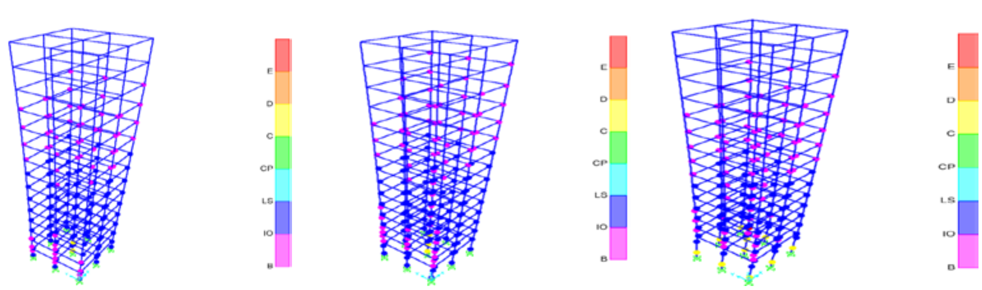
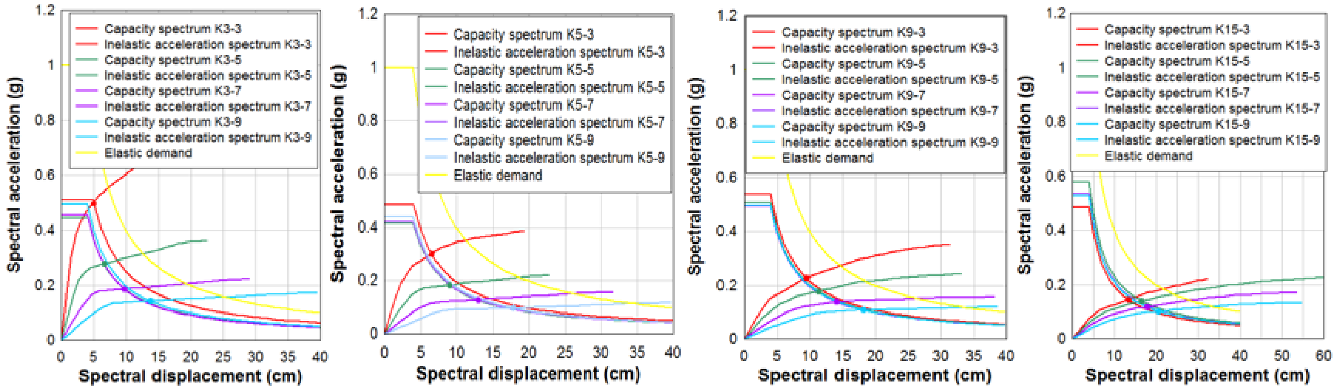


Fig. 11 – Sequence of plastic hinge formation. Five story building: Models: K15-3, K15-5 y K15-7

4.2. Capacity spectrum and performance point

As first story height increases, the structure becomes more flexible and the capacity spectrum and performance point decreases.



(a) Model K3-Z (b) Model K5-Z (c) Model K9-Z (d) Model K15-Z

Fig. 12 – Comparison of capacity curve and performance point (structure máximum response). Three, five, nine and fifteen story buildings for different heights of first floor

4.3. Evaluation of global demand of performance point

Today there is no consensus that allows establishing a unique parameter that represents the structural response, as for example the interstory drift. Below some limits of drift or relative displacement proposed in some investigations are shown:

Table 6 – Interstory drift limits for different performance levels

Perfomance level	**ATC-40**	**FEMA 273**	**Visión 2000**	**Bertero**
Inmediate occupation (IO)	0.01	0.01	0.002-0.005	0.002-0.005
Life safety (LS)	0.01-0.02	0.01-0.02	0.015	0.01-0.02
Collapse prevention (CP)	0.33Vi/Pi	0.04	0.025	0.02-0.04

To evaluate performance of the structural elements of the building, acceptance criteria proposed by Restrepo has been taken [12]. Global assessment takes into account the building distortion and interstory drift for design level earthquake. In this work the limit of interstory drift according to Vision 2000 for different levels of performance has been considered.

Table 7 – Numerical values for determination of performance point and comparison of maximum interstory drift with performance limit after Vision 2000. Three, five, nine and fifteen story buildings

Building	Models	Spectral displac. Sd (cm)	Spectral Acceleration Sa (g)	Dmax. roof (cm)	Base Shear V (t)	Global drift (%)	Máx. Interstory drift	Perfomance level (Visión 2000)
3 Stories	K3-1-3	4.995	0.498	6.33	119.70	0.703	0.012	Life safety (LS)
	K3-1-5	6.593	0.278	7.57	76.28	0.689	0.013	Life safety (LS)
	K3-1-7	9.692	0.187	10.43	53.55	0.803	0.016	Collapse prevention (CP)
	K3-1-9	13.732	0.144	14.34	42.17	0.956	0.020	Collapse prevention (CP)
5 Stories	K5-1-3	6.501	0.227	8.33	122.24	0.555	0.0097	Life safety (LS)
	K5-1-5	8.955	0.185	10.65	85.35	0.626	0.0137	Life safety (LS)
	K5-1-7	12.898	0.130	14.23	62.73	0.749	0.0202	Collapse prevention (CP)
	K5-1-7	17.807	0.098	18.86	48.45	0.898	0.0220	Collapse prevention (CP)
9 Stories	K9-1-3	9.450	0.227	12.38	171.53	0.458	0.0094	Life safety (LS)
	K9-1-5	11.290	0.178	14.43	151.14	0.497	0.0104	Life safety (LS)
	K9-1-7	14.049	0.139	16.94	127.08	0.546	0.0151	Collapse prevention (CP)
	K9-1-7	18.210	0.108	20.75	102.81	0.629	0.0195	Collapse prevention (CP)
15 Stories	K15-1-3	13.324	0.145	17.98	202.54	0.400	0.0086	Life safety (LS)
	K15-1-5	16.465	0.140	22.16	200.12	0.472	0.0098	Life safety (LS)
	K15-1-7	17.822	0.119	23.58	192.70	0.481	0.0158	Collapse prevention (CP)
	K15-1-7	20.596	0.102	26.35	174.84	0.517	0.0174	Collapse prevention (CP)

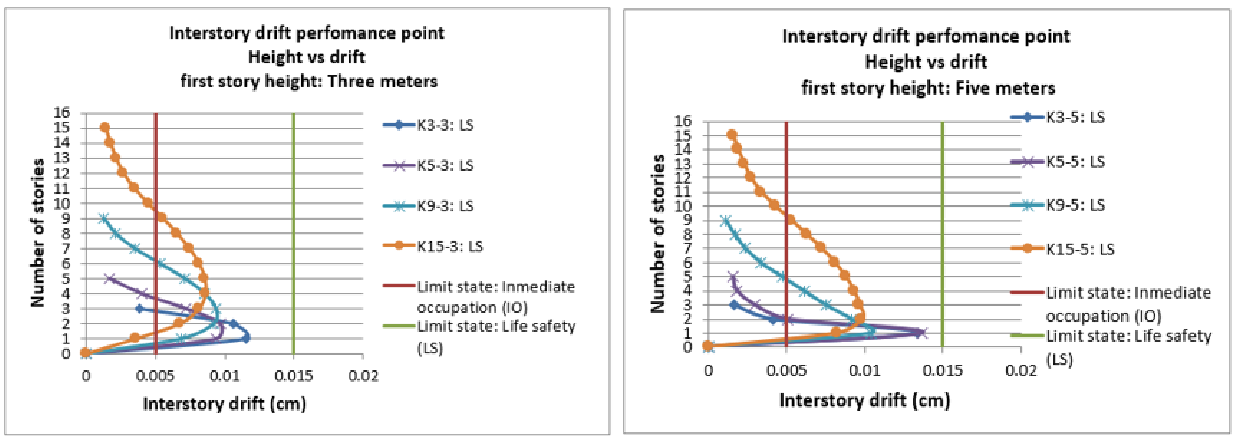


Fig. 13 – Comparison of drift of performance point of three, five, nine, and fifteen story buildings for first story heights of three and five meters. Performance level: Life Safety (LS)

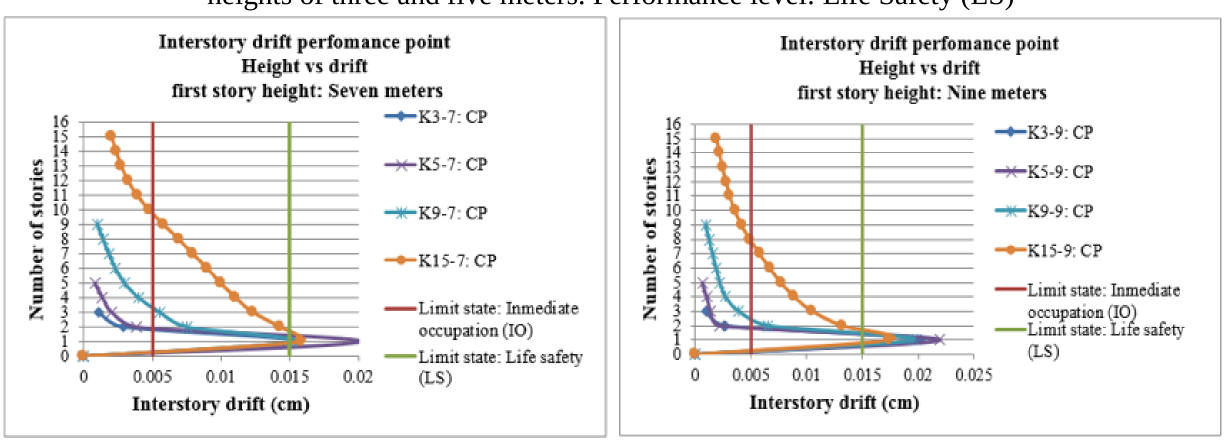


Fig.15 – Comparison of performance point of three, five, nine and fifteen story buildings for seven and nine meters first story height. Performance level: Collapse prevention (CP)

5. Conclusions

In all buildings studied (three, five nine and fifteen stories) varying first story height from three to under seven meters, drift is between immediate occupancy (IO) and life safety (LS) performance level. When first story height varies from seven to nine meters drift lies between life safety (LS) and collapse prevention (CP) performance levels which is unacceptable. Therefore it can be concluded that maximum first story height of a framed building, for it not to present soft story (and have acceptable performance), must be under seven meters (6.5m). This means a height ratio (first story height to typical height) of under 42%. This limit is much lower than percentage that declares soft story in Peruvian Standards E.030-2003 (75%). In 2016 version of Peruvian Standard, soft story is declared based on drift relations (first floor to typical) height relation becomes now (60%). Compared to the maximum height of the first floor for buildings analyzed with linear analysis in this regard, it could be said seismic Peruvian standard E.030 is safe (conservative).

A comparison was made using different definitions for soft story from country standards. For the first condition $K_i < \gamma_{k1} K_{i+1}$, value of γ_{k1} is 0.7, 0.5, 0.7, 0.7 y 0.8 for codes IBC, Mexico, Colombia, Nueva Zealand and India respectively; being the Mexican the least restrictive and Indian the most stringent. For the second condition $K_i < \gamma_{k2}\left[\frac{K_{i+1}+K_{i+2}+K_{i+3}}{3}\right]$, value of γ_{k2} is 0.8, 0.8, 0.8, 0.7 for codes IBC, Colombia, Nueva Zealand and India respectively; being Indian standard the least stringent. Since soft story is declared from heights of 4,0; 4,5 and 5,0 m international standards can be considered safe and even conservative

In the structures analyzed due to the increment in first floor height it was noted that the first floor is the one that fails due to soft story and the other levels are almost in the elastic range. This study has allowed to estimate quantitatively when soft story condition arises and its effects in the performance of building so they can be mitigated in the initial design phase.

6. References

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