

# Review of the Soft First Story Irregularity Condition of Buildings for Seismic Design

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**Abstract:** The present study evaluates how the soft first story irregularity condition should be defined: (a) as a significant reduction of the lateral shear stiffness of all resisting frames within a given story, as established in the seismic provisions of Mexican building codes or, (b) as a substantial reduction of the lateral shear stiffness of one or more resisting frames within a given story, as proposed by the author. Both definitions are evaluated through nonlinear dynamic analyses of buildings systems with a suspected soft first story condition in order to discern which option is closer to define the soft first story condition.

**Keywords:** Soft first story, Structural irregularity, Design of irregular buildings, Lateral shear stiffness.

## INTRODUCTION

Major damaging earthquakes (for example, San Fernando, 1971 and Mexico, 1985) have shown the vulnerability of buildings with soft first story, as many of them were severely damaged or collapsed during these events. Nevertheless, buildings with soft first stories are popular among architects, because this structural system allows them to use the first story for vehicle parking and/or retail stores, etc.

Structural engineers in seismic regions of Mexico and worldwide often face the pressure of architects and owners to design buildings with soft first story, even though they know these buildings are seismically vulnerable to potential failure or collapse under seismic loading. Modern seismic codes (among them, Mexico's Federal District Code, MFDC) have some provisions intended to prevent undesirable responses for buildings with soft first story. However, these provisions are based upon a few number of analytical and experimental researches.

The soft first story condition is recognized as an undesirable condition of structural irregularity for seismic design worldwide. Since 1987, MFDC has included soft story as a condition of structural irregularity to account for design [1,2] and the recent 2004 version has defined as one of the two conditions of strong irregularity [3], as discussed in the following section. In the United States, the UBC code also included the soft story condition since 1988 [1,4] as one of the recognized vertical structural irregularities to account for design, and most recent regulations such as ASCE7-05 [5] and IBC-06 [6] endorse also these recommendations. Many other building codes worldwide have followed the pioneer

ing recommendations of MFDC and UBC codes in this regard.

It is worth noting that there are some differences between Mexican and United States seismic codes in the definition of a soft story irregularity and how to account it for design purposes.

As per ASCE7-05 [5], a stiffness-related soft story irregularity is defined to exist when there is a story in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above, whereas a stiffness-extreme soft story irregularity is defined when target reference values of the conditions mentioned above are respectively 60% and 70%. For design purposes, there are some restrictions on the permitted analytical procedures to use, as well as for some seismic categories.

As it will be described more precisely in the following section, according to current seismic norms of MFDC [3], an irregularity condition defined in terms of stiffness exist where there is a story in which the lateral stiffness or the strength is less than 67% of that in the story above and a stiffness-extreme soft story irregularity when the lateral stiffness or the strength of a story is less than 50% of that in the story above. For design purposes, these structures must be designed for higher forces but required to comply with the lateral story drift criteria specified for regular buildings.

Therefore, in Mexican Codes stiffness and strength are grouped together to define a soft story irregularity, whereas in seismic codes of the United States the soft story irregularity is defined in terms of lateral stiffnesses, and a weak story irregularity is defined independently in terms of lateral strength [4-6]. The design philosophy to account for the soft story condition in US codes also differs from Mexican codes.

The present study evaluates the provisions available in Mexican codes for buildings with soft first story. In particu-

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general dimensions of the typical plan are shown in Fig. (3). The total height of the building is 39.6 m, with a typical story height of 3.3 m.

To illustrate the differences that can be obtained using a shear modeling or a flexural modeling to compute indicative values for the story lateral shear stiffnesses, the results obtained for building PSUAVE in the X direction (Fig. 3) using the structural sections and properties given in Table 1 are provided in Table 2.

For the shear modeling, as often done, it was assumed that all beams are axially rigid and beams and columns end rotations are neglected (Fig. 2b). Therefore, it can be demonstrated that indicative values for the story lateral shear stiffness of braced frames can be estimated under such modeling as:

$$K_i = \sum_{j=1}^{ncol} \frac{12E_{col_j} I_{col_j}}{L_{col_j}^3} + \sum_{m=1}^{nbr} \frac{E_{br_m} A_{br_m}}{L_{br_m}} \cos^2 \theta_m \quad \dots(1)$$

where *ncol* is the total number of continuum columns in story *i*, *nbr* is the number of braces in story *i*;  $E_{col_j}$ ,  $I_{col_j}$  and  $L_{col_j}$  are the elastic modulus, the corresponding moment of inertia and the length of column *j* of story *i* for the direction of interest, respectively; and  $E_{br_m}$ ,  $A_{br_m}$ ,  $L_{br_m}$  and  $\theta_m$  are the elastic modulus, axial area, length and angle of inclination with respect to a horizontal axis of brace *m* of story *i* for the direction of interest.

For the flexural modeling,  $K_i$  was directly computed from story drifts obtained using inverted triangular lateral force distribution (first mode) in the direction of interest from a 3D ETABS analysis. The building was assumed to be fixed at its base.

From the results presented in Table 2 it is shown that for the same building, one can obtain very different results to assess the soft story conditions based on the method used to

estimate  $K_i$ . This fact is relevant, as some engineers like to use simple calculations (for example, shear modeling) whereas other engineers rely heavily on results of detailed 3D models. Therefore, it would be convenient that building codes would specify in their commentaries which method of analysis should be used in order to define the story lateral stiffness of buildings when assessing the likeliness of a soft story irregularity condition.

Different ETABS models of building PSUAVE were designed for the lakebed zone of Mexico City (zone III) according to MFDC code [1] and its technical norms for reinforced concrete, steel members (bracing) and seismic design criteria [2]. Details on the seismic design according to the key specifications of NTCS-95 are provided in Tena-Colunga [8]. The models were designed using response spectrum analyses according to NTCS-95 and considering bidirectional effects for the ground motion, with the procedure outlined elsewhere [1].

Reductive seismic force factors  $Q'_{regular}=Q=4$  (regular) or  $Q'_{irregular}=0.8Q'_{regular}=3.2$  (irregular) were used to evaluate the factor of safety involved in designing a building with a deliberate soft first story, as discussed in more detail elsewhere [8]. It is worth noting that  $Q'$  factors of Mexican seismic codes are conceptually equivalent to the R factors of the US seismic codes [1]. Then, four different models of building PSUAVE were designed to assess the validity of the definition of the soft story condition (in terms of regularity condition # 10), computing the lateral shear stiffness as reported in Tables 3 and 4 depending if a shear or a flexural modeling was used:

a) Using  $Q'_{irregular}=0.8Q'_{regular}=3.2$ , considering that, in a given direction, when the lateral shear stiffness of one frame in the second story ( $K_{2m}$ ) is at least 100% greater than the one of the first story ( $K_{1m}$ ), that is, when  $K_{2m}/K_{1m} \geq 2.0$  is obtained with an indicative shear modeling (Table 3), a soft first story irregularity condition is introduced. This model was named M100Q32.

Table 1. Design Sections for PSUAVE Building to Illustrate Computation of Story Lateral Shear Stiffness,  $K_i$

Stories	Columns (Concrete)				Bracing (Steel)				
	Section (cm)	<i>ncol</i>	$E_c$ (kN/mm)	<i>L</i> (cm)	Section (cm)	<i>nbr</i>	$E_s$ (kN/mm)	<i>L</i> (cm)	$\theta$
9-12	60x60	20	217.2	330	35x35x1.91	8	2000.3	865.4	22.42
5-8	70x70	20	217.2	330	35x35x2.22	8	2000.3	865.4	22.42
2-4	80x80	20	217.2	330	35x35x2.54	8	2000.3	865.4	22.42
1	80x80	20	217.2	330	-	-	-	-	-

Table 2. Evaluation of the Soft-Story Condition for PSUAVE Building, Depending if a Flexural or Shear Modeling is Used to Assess  $K_i$

Shear Modeling (Eqn. 1)			3D ETABS Modeling		
$K_2$ (kN/mm)	$K_1$ (kN/mm)	$K_2/K_1$	$K_2$ (kN/mm)	$K_1$ (kN/mm)	$K_2/K_1$
10,163	4,950	2.05	3,674	2,877	1.28

b) Using  $Q'_{\text{regular}}=Q=4$ , considering that, in a given direction, when the lateral shear stiffness of one frame in the second story ( $K_{2m}$ ) is at least 100% greater than the one of the first story ( $K_{1m}$ ), that is, when  $K_{2m}/K_{1m} \geq 2.0$ , the structure should be considered regular according to NTCS-95 because  $K_2/K_1 \leq 2.0$  is computed using an indicative shear modeling (Table 3). This model was named M100Q4.

c) Using  $Q'_{\text{irregular}}=0.8Q'_{\text{regular}}=3.2$ , considering that, in a given direction, when the lateral shear stiffness of all frames in the second story ( $K_2$ ) is at least 100% greater than the one of the first story ( $K_1$ ), that is, when  $K_2/K_1 \geq 2.0$  is obtained with an indicative shear modeling (Table 3), a soft first story irregularity condition is introduced, as specified by NTCS-95. This model was named ED100Q32.

d) Using  $Q'_{\text{regular}}=Q=4$ , considering that, in a given direction, although the lateral shear stiffness of all frames in the second story ( $K_2$ ) is at least 100% greater than the one of the first story ( $K_1$ ) using an indicative shear modeling (Table 3), a smaller ratio ( $K_2/K_1 < 2.0$ ) is obtained with a 3D flexural modeling (Table 4) and, taking the flexural modeling as the most representative, then the structure should be considered regular according to NTCS-95. This model was named ED100Q4.

As it can be observed with the additional information provided in Tables 3 and 4, models M100Q4 and ED100Q32 were designed according to the definition of the soft story irregularity established by NTCS-95 when indicative stiffness values are obtained with the simplest shear modeling. Model M100Q32 was designed according to what the author believes it should be the definition of the soft story condition in Mexican codes, as discussed earlier. Model ED100Q4 represents a design where the structure was classified as regular as a consequence that the designer selected a 3D

flexural modeling to compute the lateral shear stiffnesses, so the designer in fact computed that  $K_2/K_1 < 2.0$  (Table 4).

The final relations obtained for the different models of PSUAVE building are reported in Table 3 when using the simpler shear modeling criteria given in Eqn. 1 and in Table 4 when using a 3D ETABS modeling. It can be observed from the results reported in Table 4 that all buildings should be designed as regular if the results of 3D flexural models are used, despite the fact that the building geometry suggests otherwise.

The details of the design (structural sections, reinforcement ratios, etc) are presented in Tena-Colunga [8]. Braces are of square box sections made with A-36 steel. The section of the braces from the second to fourth stories are 25x25x1.27cm for models M100Q32 and M100Q4, and 35x35x2.54 cm for models ED100Q32 and ED100Q4. The typification of square cross sections for the columns of the first and second stories of all models are reported in Table 5 and the provided flexural and shear reinforcement are reported in Table 6.

The assessment of the design shear capacity for each story according to NTCS-95 is presented and discussed in detail elsewhere [7]. It was checked that the estimated shear capacity of the columns associated to a flexural failure according to a SMRF design would be smaller than the estimated shear capacity calculated from the provided transverse shear reinforcement and the own shear strength of the concrete section. Design buckling loads were used to estimate the contribution of the braces in the story shear.

Normalized design story shears obtained assuming a ductile flexural failure for the columns and the buckling loads for the braces are reported in Table 7 for the building

**Table 3. Stiffness Ratios Obtained for the Building Models Under Study Using a Shear Modeling (Eq. 1)**

Model	X Direction		Y Direction		Soft First Story Irregularity According to		Designed as
	$K_2/K_1$	$K_{2m}/K_{1m}$	$K_2/K_1$	$K_{2m}/K_{1m}$	NTCS-95	NTCS-2004	
M100Q32	1.66	2.31	1.70	2.41	No	Yes	Irregular
M100Q4	1.66	2.31	1.70	2.41	No	Yes	Regular
ED100Q32	2.36	3.72	2.46	3.92	Yes	Yes	Irregular
ED100Q4	2.36	3.72	2.46	3.92	Yes	Yes	Regular

**Table 4. Stiffness Ratios Obtained for the Building Models Under Study Using a 3D ETABS Modeling**

Model	X Direction	Y Direction	Soft First Story Irregularity According to		Designed as
	$K_2/K_1$	$K_2/K_1$	NTCS-95	NTCS-2004	
M100Q32	1.13	1.14	No	No	Irregular
M100Q4	1.13	1.14	No	No	Regular
ED100Q32	1.28	1.30	No	No	Irregular
ED100Q4	1.28	1.30	No	No	Regular

models under study. If the shear strength ratios  $V_{2m}/V_{1m}$  for the frames with the discontinuity of resisting elements could be considered to evaluate the soft-story condition due to strength (weak story), all models should be designed as irregular buildings as  $V_{2m}/V_{1m} > 2.0$  (Table 7). From the shear strength ratios  $V_2/V_1$  reported in Table 7 it can be deduced that according to NTCS-95, models M100Q4 and M100Q32 do not have a soft-story irregularity due to strength ( $V_2/V_1 < 2.0$ ). It can also be deduced from the shear strength ratio  $V_2/V_1 = 2.81 > 2.0$  reported in Table 7 that model ED100Q4 should be designed again to account for soft-story irregularity due to strength according to NTCS-95, despite the fact that the initial decision based upon a flexural stiff-

ness modeling suggested otherwise (Table 4). However, it is also worth noting that if a practicing engineer estimated the design shear capacity of the columns from the provided transverse shear reinforcement and the own shear strength of the concrete section, then for ED100Q4 model the following values are obtained:  $V_2/W = 0.619$ ,  $V_1/W = 0.314$  and  $V_2/V_1 = 1.97 < 2.0$ . Therefore, according to such assessment [7], ED100Q4 model can be designed as a regular structure according to NTCS-95, as it was finally done.

Peak story drift angles associated with the designs, all of them found in the first story as expected, are reported in Table 8. In most models, peak story drift angles were below

**Table 5. Typification of the Columns for the First and Second Stories of the Models Under Study**

Model	Sections for Columns Intersecting Axes									
	A1,D1	A2,D2	A3,D3	A4,D4	A5,D5	B1,C1	B2,C2	B3,C3	B4,C4	B5,C5
M100Q32	M-R3	M-R3	M-R4	M-R4	M-R3	M-R2	M-R4	M-R4	M-R4	M-R2
M100Q4	M-R1	M-R1	M-R1	M-R1	M-R1	M-R1	M-R4	M-R4	M-R4	M-R1
ED100Q32	E-R4	E-R4	E-R2	E-R4	E-R4	E-R4	E-R4	E-R4	E-R4	E-R4
ED100Q4	E-R1	E-R3	E-R1	E-R3	E-R1	E-R3	E-R3	E-R3	E-R3	E-R3

**Table 6. Section and Reinforcement for the Columns of the First and Second Stories of the Models Under Study**

Type	Section	Flexural Reinforcement		Transverse Reinforcement	
	Dimensions (cm)	Bars	$\rho$	Ends	Center
M-R1	70x70	24#8	0.0248	6 S#3 @ 9 cm	6 S#3 @ 35 cm
M-R2	70x70	20#8+4#10	0.0272	6 S#3 @ 9 cm	6 S#3 @ 30 cm
M-R3	70x70	20#10	0.0323	6 S#3 @ 9 cm	6 S#3 @ 35 cm
M-R4	70x70	24#10	0.0388	6 S#3 @ 9 cm	6 S#3 @ 25 cm
E-R1	75x75	16#8	0.0144	6 S#3 @ 8 cm	6 S#3 @ 35 cm
E-R2	75x75	20#8	0.0180	6 S#3 @ 8 cm	6 S#3 @ 35 cm
E-R3	75x75	24#8	0.0216	6 S#3 @ 8 cm	6 S#3 @ 35 cm
E-R4	75x75	20#8+4#10	0.0237	6 S#3 @ 8 cm	6 S#3 @ 30 cm

Note: #8 bars = bars one inch in diameter, #3 bars = bars 3/8 inch in diameter.

**Table 7. Normalized Design Story Shear Forces Obtained for the Building Models Under Study**

Model	Soft-Story Frame Concept (Frame A or Frame D)			All Frames Concept (Frames A, B, C and D)		
	$V_{2m}/W$	$V_{1m}/W$	$V_{2m}/V_{1m}$	$V_2/W$	$V_1/W$	$V_2/V_1$
M100Q32	0.114	0.053	2.16	0.333	0.210	1.58
M100Q4	0.104	0.042	2.45	0.308	0.185	1.66
ED100Q32	0.212	0.049	4.29	0.526	0.201	2.62
ED100Q4	0.205	0.042	4.85	0.504	0.179	2.81













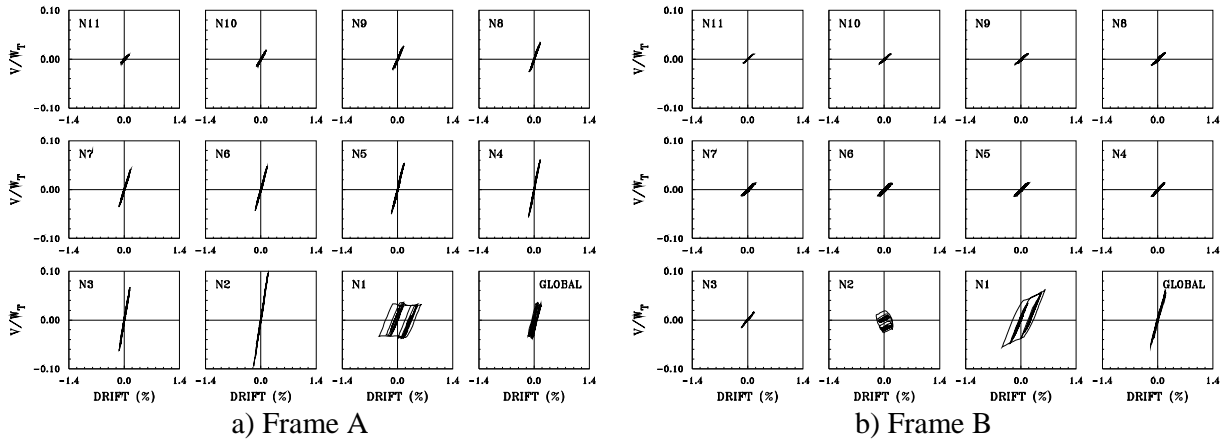


Fig. (12). Hysteresis curves for model ED100Q32 under SCT-EW acceleration record.

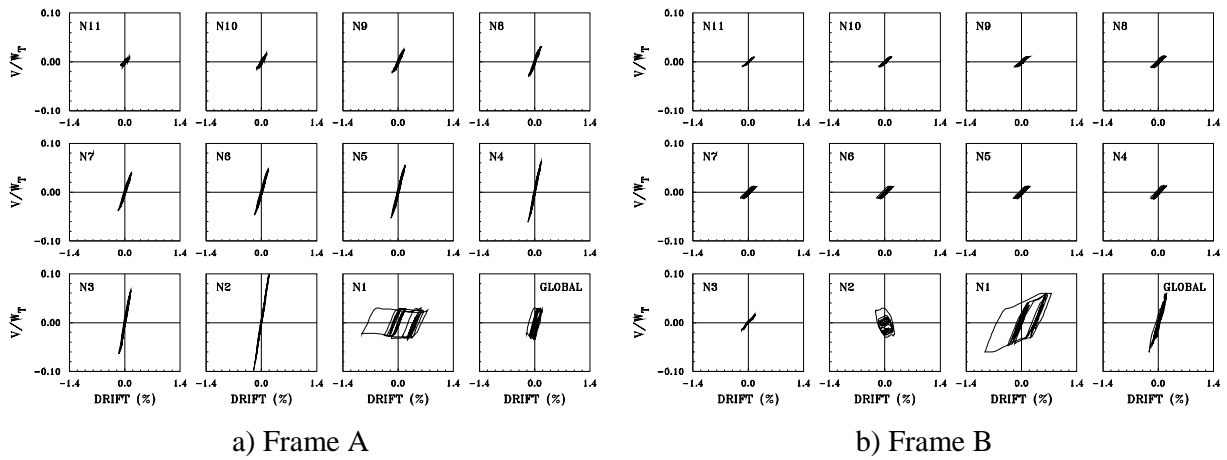


Fig. (13). Hysteresis curves for model ED100Q4 under SCT-EW acceleration record.

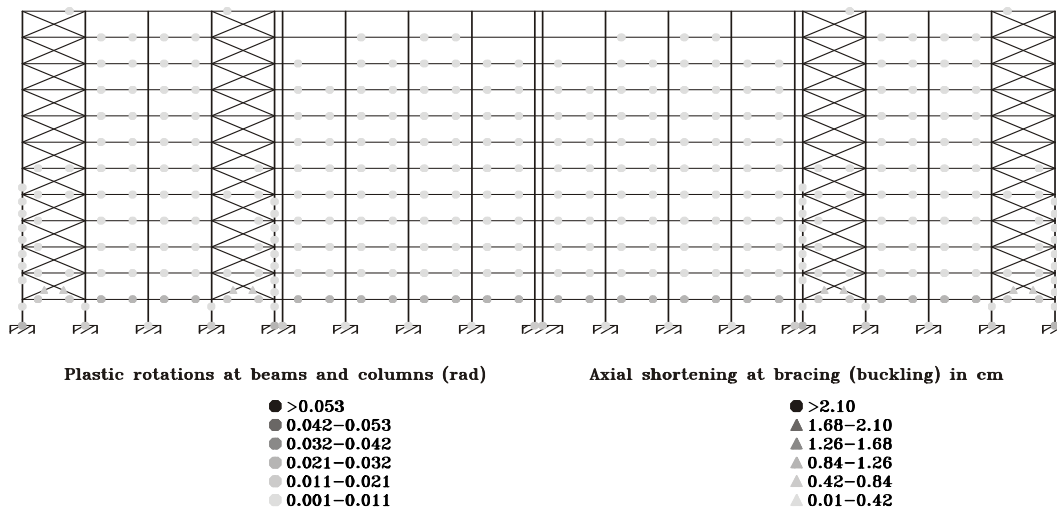


Fig. (14). Yielding mapping envelope, M100Q32 model.

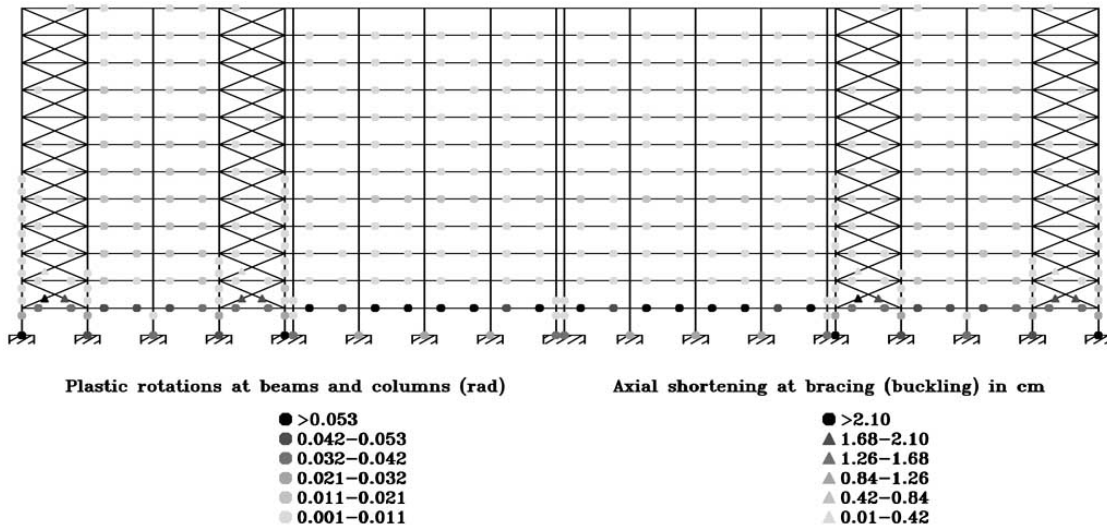


Fig. (15). Yielding mapping envelope, M100Q4 model.

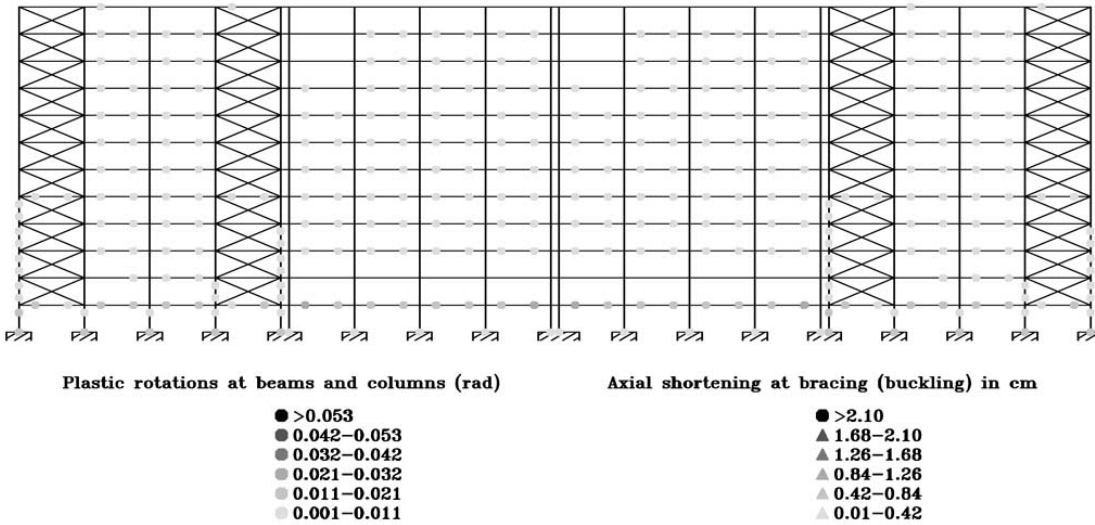


Fig. (16). Yielding mapping envelope, ED100Q32 model.

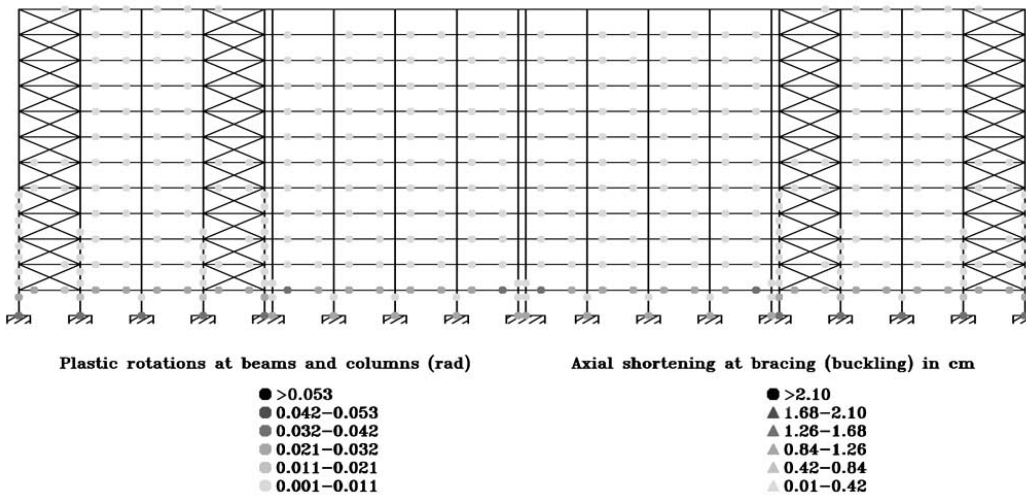


Fig. (17). Yielding mapping envelope, ED100Q4 model.

(4) A new finding of this study, perhaps the first one to model the interaction among frames of buildings with a

suspected soft first story in a given direction, is to visualize how the deficit in the shear capacity of the first story

of the perimeter frames has to be taken by the interior (regular) frames (represented by frame B). The interior frames (frame B) experience higher shear forces, ductility demands and develop smaller peak-to-peak lateral shear stiffnesses not only in the first story, but also in the second story (Table 6, Figs. 6 to 9).

- (5) Perhaps the most important finding about the interaction among frames in the longitudinal direction of interest can be addressed from the observation of the hysteresis curves of Figs. (10) to (13), which depict the details of how the buildings try to compensate the discontinuity of the perimeter frames in the first story. It can be observed for example, for model M100Q32 (Fig. 10) that, in the nonlinear range of response, the discontinuity of perimeter frames (A) forces interior frames (B) to work in the opposite direction in the second story (level N2), in order to compensate for the deficit of shear strength of the building in the first story. Not only the interior frames are subjected to this inversion of forces in the second story, but their story shear and inelastic deformation are increased in this story. When these incremented shear forces and lateral deformations in the second story are relatively large in the interior frames (model M100Q4, Fig. 11), they can trigger the yielding of columns in the interior frames at that story (Fig. 15). In addition, the story shear and inelastic deformation of interior frames are also substantially increased in the first story. This behavior was observed for all models (Figs 10 to 17). It is worth noting that the described behavior cannot be detected using elastic analyses, as: (a) it was not anticipated in the design process using ETABS software and, (b) it was not observed in the DRAIN-2DX analyses for the models depicted in Fig. (5) when other considered acceleration records drove the models to an elastic response.
- (6) As it was expected, yielding mappings (Figs. 14 to 17) depict an important number of column yielding in the soft first story for perimeter frames and, in some cases, one can observe the buckling of the braces of the second story, particularly for models M100Q32 and M100Q4 (Figs. 14 and 15) that have slender braces in the second story ( $kL/r= 89.2$ ). For models ED100Q32 and ED100Q4, where the braces in the second story have a slenderness ratio  $kL/r= 64.0$ , all braces remain elastic (Figs. 16 and 17). For the models that were not affected by the 0.8 reduction factor in  $Q'$  (M100Q4 and ED100Q4, Figs. 15 and 17), the yielding of the first story columns and some columns from stories 2 to 6 of the perimeter frames was more important than for those models designed with the 0.8 reduction factor in  $Q'$  (M100Q32 and ED100Q32, Figs. 14 and 16). In general, the column yielding of interior frames is reduced to the first two stories for all models (Figs. 14 and 17). It can also be observed from Figs. 14 to 17 that the amount of beam yielding is consistent with the weak-beam, strong-column design philosophy implicit in the seismic design of SMRFs according to the guidelines of NTCS-95. However, this condition is severely affected by the discontinuity of the braces of the perimeter frames at the first story, leading to a soft-story yielding mechanism of the perimeter frames in all models. In fact, it can also be observed from

the yielding mappings that, in general, the models designed as irregular buildings (M100Q32 and ED100Q32, Figs. 14 and 16) have an improved mapping with respect to their counterpart buildings designed as regular buildings (M100Q4 and ED100Q4, Figs. 15 and 17). This is important, as it seems that the simple recommendation of Mexican codes of increasing the design strength to improve the seismic behavior of buildings with soft story irregularity is somewhat effective. Some engineers would consider that the relevant question is not whether buildings designed as irregular according to Mexican codes perform better than those designed as regular ones, but if the response of buildings designed as regular is acceptable or not. On this regard, it is worth noting that an acceptable seismic responses have been obtained and reported for regular RC-SMRFs buildings with similar configuration and that were designed according to the same code [12]. The referred buildings were designed as regular structures and the amount of beam yielding obtained is consistent with the weak beam – strong column design philosophy assumed in the code [12]. Therefore, as the global design strategy for regular SMRFs building is effective, it is also relevant to highlight that the simple design strategy specified in Mexican codes for soft/weak story irregularity seems to be practical and effective.

- (7) It can be observed from the peak dynamic normalized story shear forces obtained for the building models under study (Table 12) that the first soft-story irregularity condition due to strength (weak story) is better defined by the soft-story frame concept proposed by the author (in terms of the shear strength ratio  $V_{2m}/V_{1m}$ ) rather than the all-frames definition of NTCS-95 (in terms of the shear strength ratio  $V_2/V_1$ ), if the proposed limiting values of 2.0 (NTCS-95) or 1.5 (NTCS-2004) are considered. The results presented in peak response envelopes, hysteresis curves and yielding mappings show that a first soft-story condition is developed in all models. However, according to the results reported in Table 12, a soft-story condition due to strength “is not likely” according to NTCS-95, as  $V_2/V_1 < 2.0$ .

## CONCLUDING REMARKS

Taking into account the nonlinear dynamic analyses of the reference models, one can arrive to the following observations regarding the first soft story condition, granted the limitation of this research that only few (but detailed) models designed to fulfill all the requirements of MFDC were studied.

It would be convenient that building codes would specify in their commentaries which method of analysis (shear modeling or flexural modeling) should be used in order to compute the lateral story stiffness of buildings when assessing the likeliness of a soft story irregularity condition. In this paper it has been shown that, for a specific building, one can arrive to different answers depending on the method of analysis that was used. Also, this observation can be extended to the assessment of the shear strength capacity to decide on the likeliness of a weak story irregularity condition.

All studied building models develop a first soft story response when subjected to acceleration records associated to the design spectrum of NTCS-95. In addition, the models that were not designed as irregular buildings (M100Q4 and ED100Q4) experienced a more severe nonlinear, soft first story response than those models designed as irregular buildings (M100Q32 and ED100Q32). Therefore, it seems that the simple recommendation of Mexican codes to improve the seismic behavior of buildings with soft story irregularity is somewhat effective. In contrast, according to NTCS-95, M100Q4 model should not be designed as an irregular building; nevertheless, the building developed a strong soft story response. However, with the current definition of NTCS-2004, this model should now be designed as an irregular building (Table 3), as the new limit proposed in NTCS-2004 takes into account, among other studies, the ones that are reported in this paper.

The results of this study lead to support the proposal of the author that perhaps the definition of the soft first story irregularity condition in Mexican codes, and other seismic codes worldwide, should be reviewed. The proposal of the author is that the soft first story irregularity condition should be defined as a substantial reduction of the lateral shear stiffness of one or more resisting frames within a given story, instead of as a significant reduction of the lateral shear stiffness of all resisting frames within a given story, as established in Mexican codes. Finally, future works must also be directed to assess if the additional modifications included in NTCS-2004 allow the designer to arrive to safer designs for buildings with a soft first story condition.

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