Investigation of Vercital Column Discontinuity in Reinforced Concrete Buildings

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Abstract— Most reinforced concrete buildings sustain significant damage or completely collapse after an earthquake due to structural irregularities. In this study, a set of investigations were conducted on the discontinuity of the vertical elements in building structures, a topic that to date has only been minimally explored. The investigation was carried out using an SAP 2000 model of an average-story height building with reinforced concrete frame. For analysis, by removing columns selected from certain floor sand axes, a total of seven load-bearing system models were formed, along with the reference model. In cases of discontinuity of the vertical element appearing in the different models, the variation in the internal forces and decrease of rigidity were comparatively analyzed. Additionally, some of the investigations were conducted using the capacity curves obtained from the periods of models, displacement rates, and nonlinear pushover analysis. The consistency and reliability of requirements given for these kinds of irregularities in the regulations were analytically tested against the results obtained from the models created in the study. As a result of the analysis carried out, it was determined that the necessities specified in the Turkish Earthquake Code (TEC – 2007) for these kinds of constructions were safe.

Index Terms— Earthquake, reinforced concrete, vertical irregularity, regulation, damage

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1 Introduction

The large majority of Turkey's population lives in 1st and 2nd degree earthquake regions. In the moderate and strong earthquakes that have occurred around the country throughout the years, the losses experienced by the earthquakes were not isolated to the rural areas alone, but the cities, where most of the buildings are strengthened with reinforced concrete, also sustained heavy damage. The design defects, such as the soft story short column, combination of strong beam-weak column, insufficient lateral rigidity and irregularities in the vertical and horizontal directions, constitute some of the causes responsible for the damages sustained during earthquakes.

In the damages observed in the reinforced concrete buildings after earthquakes, buildings that had not received any kind of civil engineering services tended to sustain heavy damage or were completely collapsed [1], [2], [3], [4]. Particularly in the buildings that had the structural irregularities cited in the earthquake regulations, it was observed in the field studies conducted that the degree of damage increased and the total collapse of the building was more likely.

A number of studies in the literature have examined the impact earthquakes have on structural irregularities. These studies have largely focused on weak story, soft story and torsion irregularity [5], [6], [7] while others have examined floor discontinuities and cantilever projections in the plan [8], [9].

Diminishing the irregularities associated with the impact of earthquakes on the bearing system became obligatory due in large part to architectural concerns and surveying arrangements. What is important there is to conduct a thorough analysis on the effect of these irregularities on the bearing system and to eliminate the negativities the irregularities form.

In the earthquake codes [10], [11], [12], [13] the reason for the negativities in the behavior of an irregular building in response to an earthquake, and the points and precautions that require special attention in the design of these kinds of constructions are provided and grouped according to the type of irregularity. Irregularities that are basically the same differ in terms of the details and necessities regulating them. Some irregularities are absolutely not permitted according to the conditions due to incapability for requirements. For example, discontinuity of a vertical element, such as the placement of a reinforced concrete shear walls at the bottom floor is not permitted. In the studies related to the effect of vertical element discontinuity on the response of bearing systems, the primary focus is the behavior of different types of construction to seismic activity [14], [15], [16], [17], [18], [19], [20], [21]. In these studies, rather than simply investigating the requirements of regulations, the general behavioral changes were studied.

This present study conducts a set of investigations that examine the discontinuity of the vertical members using different construction models of an average-story height building with are reinforced concrete frame. To date, only a limited number of studies have been conducted on this topic. For analysis, the columns selected from some stories and axes were removed and in cases where there was a resulting discontinuity of a vertical member, the variation in the internal forces and the decrease of rigidity were comparatively analyzed. Moreover, analyses were conducted on the capacity curves, periods, and displacement rates of models. According to the results obtained from the models, the consistency and reliability of various rules given in the regulations for these kinds of irregularities were analytically tested.

2 Vertical irregularities and relevant codes

Most reinforced concrete buildings sustain significant damage or completely collapse after an earthquake due to structural irregularities. In view of this, as specified in regulations, predicting the destructive effects that structural irregularities can generate in the event of an earthquake is important in terms of the safety of construction. In order to eliminate the negative effects of irregularities, earthquake regulations impose a set of necessities. The Turkish Earthquake Code-2007 [10] presents the irregularities in two parts. As specified in TEC 2007 [10], it is necessary that irregular buildings be placed under regulatory control due to the hazards that the irregularities pose in the event of earthquakes (in plan and vertical configuration).In the regulation, each irregular case is defined along with solution suggestions, and cases of irregularity in vertical configurations are examined in the same section as the other irregularities. The regulation groups irregularities in horizontal configurations with the abbreviation A and those in the vertical configurations with the abbreviation B (Table 1). As specified in TEC 2007 [10], the other earthquake codes also classifies the irregular buildings in approximately similar way.

Due to the large number of observations directed towards soft story and weak story mechanisms, the irregularities B_1 and B_2 have been studied far more extensively in the literature. Similarly, as the damage caused by torsion forming in buildings, whose gravity center and rigidity center do not meet with each other, is commonly seen, the literature features many studies addressing A_1 type irregularities. The literature, however, has an inadequate number of studies that examine the discontinuity of vertical elements, specified as B_1.

Other regulations, such as TEC-2007 [10] Eurocode 8[22] and UBC [12], use different approaches in relation to the irregularities under consideration. For example, Eurocode8 [22], emphasizes the vertical irregularity of the masonry wall in buildings irregularly configured when the masonry walls are diminished on any floor. In these incidences, this regulation requires that the lateral force coming to that floor be distributed to the floor members, multiplying it with a coefficient larger than 1.0. In UBC[12],the discontinuity in the vertical direction is referred to as the discontinuity in the plane of the vertical members showing resistance against seismic movement, and in the event of such an irregularity, it is required that minimum earthquake load reduction factor (R) be taken into account.

The TEC-2007 [10] regulation defines the discontinuity of vertical elements and details the removal of the vertical elements (columns and partitions) on some floors, explaining that they should be placed on or to the beams or thickened edge columns, or laying out the placement of the partitions in the upper floor onto the columns in the lower floor (Figure 1). In the figures below, cases a, c, and d are abso lutely prohibited by TEC-2007 [10], while case b is not prohibited but heavily regulated, i.e. it is only permitted if all values of internal forces consisting of the common influence of the vertical loads and seismic movement (G+Q +E) in all sections of beam are increased by 50%, as well as in all sections of the other beams and columns combining with all connection points to which the beam is attached, taking seismic movement into consideration. Here, the presence of the increase,

TABLE 1

THE CASES OF IRREGULARITIES IN PLAN AND IN VERTICAL CONFIGURATION ACCORDING TO TEC-2007

Names of Irregularities	Cases of Irregularities
Twisting (Torsional) irregularity(A1)	**Cases of Irregularities in plan - A**
Flooring discontinuity(A2)	
Projections in plan(A3)	
Beam axes not in parallel with each other (A4)	
Strength irregularities between the neighboring floors(Interstory Strength Irregularity (Weak Story)) (B1)	**Cases of irregularities in vertical configuration-B**
Rigidity irregularities between the neighboring floors (Interstory Stiffness Irregularity (Soft Story) (B2)	
Discontinuity of vertical members of bearing system (Discontinuity of Vertical Structural Elements) (B3)	

resulting from the other elements sharing of the force of the seismic movement, that the column removed will bear, is also considered. In TEC-1998, the previous version of TEC-2007 [10], the case was permitted on the condition that they be increased by 50%.

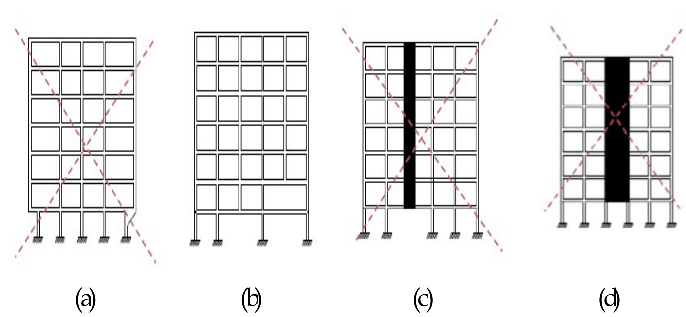

Fig. 1. Irregularity B_3, specified in TEC -2007

In Turkey as well as many other countries, reinforced concrete structures that have vertical discontinuity, despite the prohibition or heavy regulations against this irregularity in the codes, were built and continue to be built for architectural-related reasons and surveying purposes, such as to obtain large openings, especially on ground floor levels. In Figure 2, some examples of reinforced concrete buildings are shown.

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Fig. 2. Some reinforced concrete buildings having the vertical discontinuity

3 ANALYTIC STUDY

In this study, to investigate B_3 irregularities, are in reinforced concrete model, featuring a relatively simple bearing system and not containing any other irregularities, was formed. In the model, 5 m was selected as the height of the ground floor and 3 m on the other floors. In the plan, the axial internals of the building, whose total length is 25 m in both directions, were selected as 5 m. The five-floor reinforced concrete building designed was modeled in SAP2000 [25].

It was considered that the building was in a 1st degree earthquake region, the effective spectrum acceleration was included in the calculation as 0.4 g, as specified in TEC-2007 [10].The ground on which the building lies was set as Z3 type soil type, which represents the middle class ground in TEC-2007 [10].On these kinds of grounds, corner periods are taken in to account as 0.15 sec. and 0.60 sec.

The sections in the bearing system were set at 40/40 cm for columns and as 25/60 cm for beams. Every floor had these same measurements. The floor was designed as beam system and its thickness was set at 12 cm. After configuring the structural geometry of the system, type C25 concrete mix and type S420 reinforcement elements were used. According to TS-500-2000 [23], the distributed load coming from the flooring to the beams was uniformly accepted as g=0.625 t/m and q= 0.25 t/m. On the beams, the wall load of 20cm was defined in such away that q_d=0.75 t/m. In Figure 3, the plan geometry of the relevant construction is presented. The examination of the beams and columns were carried out according to TS-500-2000 [26] and TEC-2007 [10], which are in parallel with ACI 318 [24]. In the earthquake calculation of the building, the value R, which is valid for constructions with this kind of frame, was set as 8. According to TEC-2007, [10], for buildings whose heights do not exceed 25m, and which do not contain torsion irregularity, the system of equivalent earthquake load can be used. Therefore, the earthquake load was implemented to the building as triangular and distributed according to the equivalent earthquake force. In modeling, the columns were assigned to the ground as fixed from the lower part. The regions of column-beam points were modeled as rigid. In TEC-2007 [10], vertical loads and the value of all internal forces ((G+Q+E)) consisting of common effect of earthquake are required to be increased by 50%, but since in this study, only the relevant load was being investigated , the loading of (G + Q+ E) is taken as a base.

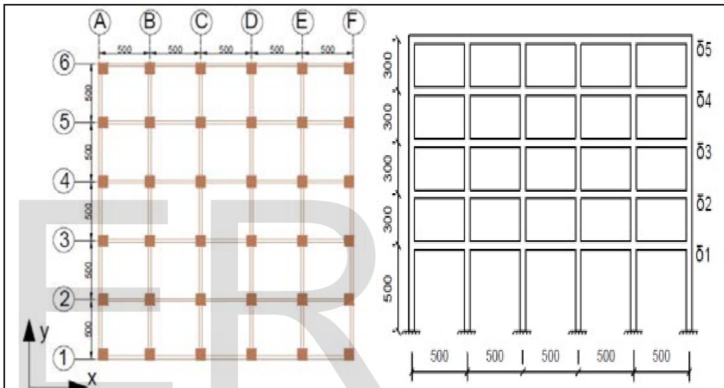

Fig. 3. The floor plan of the building modeled and vertical section

From the base model that was formed, 6 different irregular models were created according to the vertical irregularities of columns. Therefore, a total of 7 different models were used for analyses. The over views of the models and floor plans are shown in Table 2.

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In addition to the linear analysis of models used to evaluate the capacity and mechanism bearing the horizontal load of each frame, nonlinear static pushover analyses were conducted. Using pushover analysis on the potential plastic joint regions of frame elements, the hinges were assigned to their section properties and calculations were made accordingly, given that the other parts of the element were linear. The longitudinal and tie bars necessary for pushover analysis were calculated according to the norms of TS-500 [23] and TEC-2007 [10]. Based on the principles of TEC-2007 [10], FEMA 440 [26] and ATC-40 [27], in the pushover analysis carried out, triangular distribution was accepted as horizontal loading. The frames were pushed to the point of collapsing mode and for each model, the percentage of columns hearing strength, plastic class formation data, and the cases of its order and mechanism were examined.

Four different performance stages, as established by those used in the performance assessment of the elements of bearing system in TEC-2007 [10],were used in this study. These were specified in the code as Slight Damage (SD), Moderate Damage (MD), Heavy Damage (HD), and Failure (F); and the global performance levels of buildings are identified according to the levels of section damage.

4 RESULTS OF ANALYTIC STUDY

Analyses were carried out on a total of 7 different models, one of which was the reference model, where there was discontinuity of vertical elements. Columns selected from the same stories and axes were removed and in cases of the resulting discontinuity of vertical element, the variation in the internal forces was analyzed. In the models, the variation in the internal forces was grouped for the columns and beams according to the data obtained from SAP2000 [25]. In Table 3, the increase of the values of normal force (N) in the column sections, shearing force (V), and moment (M) according to the baseline are presented as a percent. Results of the analysis showed that the discontinuity that will occur in the columns led to increases of between 23.38% - 52.93% in the value N, 28.32%-50.81% in the value V and 27.05%-56.68 % in the value M.

TABLE 3

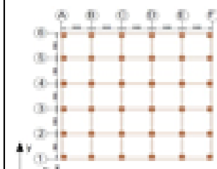
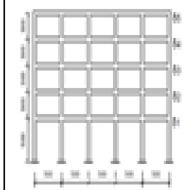
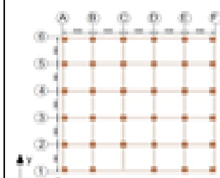
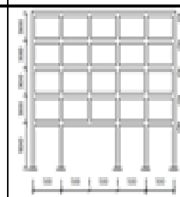
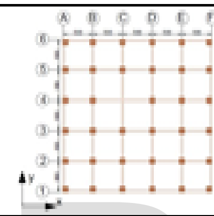
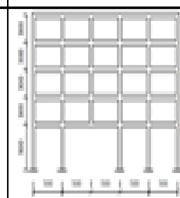
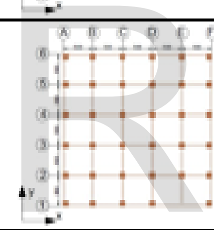
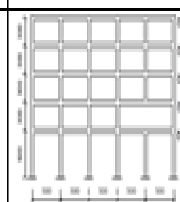
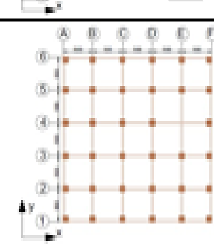
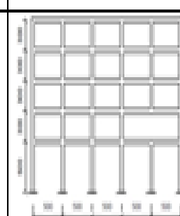
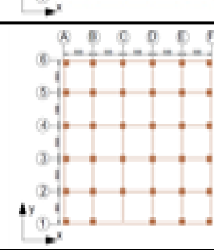
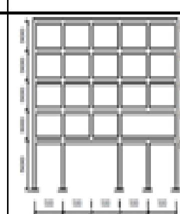
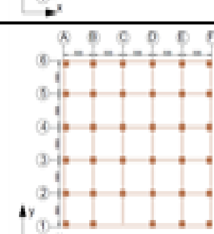
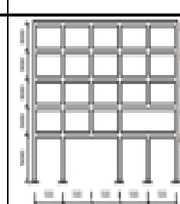
THE PERCENTAGE VALUE OF INCREASE IN THE EFFECTS OF COLUMN SECTİON

Force	T_1/T_0 (%)	T_2/T_0	T_3/T_0	T_4/T_0	T_5/T_0	T_6/T_0	$T_{average}/T_0$
N	37.87	23.41	39.43	23.38	52.93	36.88	**35.65**
V	35.1	28.32	50.81	42.07	37.90	29.16	**37.22**
M	33.43	27.05	56.68	46.96	40.55	30.83	**39.25**

In Table 4, the increases in the values of the shearing force in beam section (V) and moment (M) in relation to the reference model are shown. The analysis revealed that this was caused due to the increases of between 26.45% - 37.98% in the values

TABLE 2

NAMES OF MODEL AND EXPLANATION

Model (Type) Name	Plan of ground floor	Vertical Section
T_0 (Reference model, assuming all columns are existing)		
T_1 (Assuming Column C1 is absent in the relevant floor)		
T_2 (Assuming Column C4 is absent in the relevant floor)		
T_3 (Assuming Column E1 is absent in the relevant floor)		
T_4 (Assuming Column E4 is absent in the relevant floor)		
T_5 (Assuming Columns C1 and E1 are absent in the relevant floors)		
T_6 (Assuming Columns C4 and E4 are absent in the relevant floors)		

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V while in the values M between 35.73%-59.95% in the M values.

TABLE 4

THE PERCENTAGE VALUE OF INCREASE IN THE EFFECTS OF BEAM SECTİON

Force	T_1/T_0 (%)	T_2/T_0	T_3/T_0	T_4/T_0	T_5/T_0	T_6/T_0	$T_{average}/T_0$
N	37.87	23.41	39.43	23.38	52.93	36.88	**35.65**
V	35.1	28.32	50.81	42.07	37.90	29.16	**37.22**
M	33.43	27.05	56.68	46.96	40.55	30.83	**39.25**

Since the discontinuity of columns will reduce the lateral rigidity when there is a soft story (referred to as B_2 in TEC-2007) and considering that this issue is addressed in the earthquake codes, it is important that this matter be investigated. As shown in the equation in Table 5, in TEC-2007 [10], for the formation of a soft story, the rigidity discontinuity coefficients expressed as (η_{ki}), reduced relative floor displacement in i^{th} floor of building as Δ, and the height of i^{th} floor of building as h. For the irregularity of soft story, the coefficient of rigidity irregularity (η_{ki}) should result in a number larger than 2.0. Given that all the models remained below this critical (threshold) value, there was no incidence of a soft story.

By removing the columns, since the rigidity of system will decrease, the period of first mode should be expected to increase. In analyses, the periods of the other models were found to be more comparable to the period of reference frame.

TABLE 5

CONTROL OF SOFT FLOOR

The stiffness irregularity factor between the neighboring floors	Name of Model (Type)						
	T_0	T_1	T_2	T_3	T_4	T_5	T_6
$\eta_{ki} = \frac{\left(\frac{\Delta_i}{h_i}\right)_{ort}}{\left(\frac{\Delta_{i+1}}{h_{i+1}}\right)_{ort}} > 2$	0.60	0.56	0.56	0.63	0.61	0.59	0.59

In table 6, the first mode period of each frame is given.

Depending on the periods, the values of displacement also vary. The floor displacement values corresponding to each floor are shown in Figure 4. As clearly seen in Figure 4, in terms of the displacement values according to the reference structure (T_0), Model T_6 makes the maximum displacement, while Model T3 makes minimum displacement. This situation can also be recognized from the values of mode period given in Table 6, where it shows that a structure whose period is low makes less displacement.

TABLE 6

THE VALUES OF MODE PERIOD

Name of Model (Type)	T_0	T_1	T_2	T_3	T_4	T_5	T_6
Period (second)	0.98	0.99	0.98	0.98	0.98	0.99	0.99

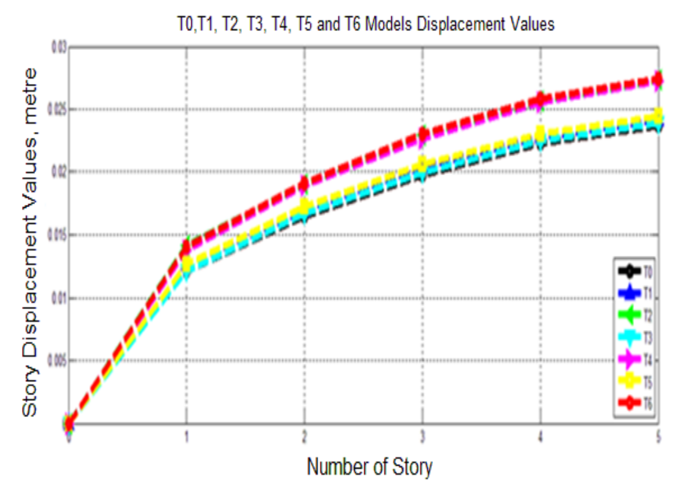

Fig. 4. Displacement values for each model

To see the change that occurs in the capacity to bear lateral load according to the pushover analysis carried out, the top displacement of each frame – the graph of base shearing force – is shown in Figure 5. In this graph, the value of base shearing force for T_0 is 308.50 ton, while for T6, it is 290.09; thus, in the base shearing force, there is a decrease of 5.96%.

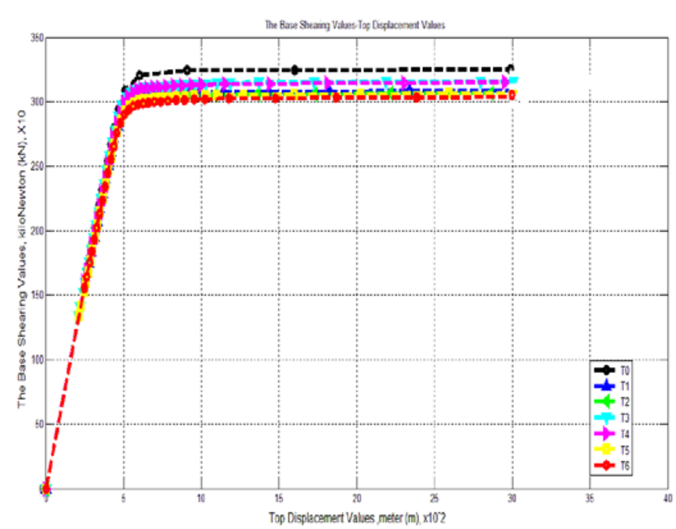

Fig. 5. Top displacement values corresponding to the base shearing values of frames.

In TEC-2007 [10], in the performance assessment of the elements of the bearing system, four performance situations were specified. In Table 7, the percentage distribution of damages forming in the columns was shown. In all models, the mecha-

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nism of ground floor became fact and in the columns of upper floors, no occurring of hinge was observed. In addition, hinge did not occur in beams.

5 CONCLUSION AND DISCUSSION

The aim of this study was to look at some of the differences between UBC-1997 [12] and Eurocode 8 [22], to analyze the B3

TABLE 7
THE PERCENTAGE DİSTRIBUTION OF DAMAGE FORMING IN THE COLUMNS OF GROUND FLOOR

	SD	MD	HD	F
T_0	-	29.4	10.9	59.8
T_1	-	22.2	10.9	67.0
T_2	-	22.6	10.8	66.6
T_3	-	35.0	16.0	49.0
T_4	-	18.4	10.6	71.0
T_5	-	24.4	13.7	61.8
T_6	2.8	22.1	10.9	64.2

type irregularities that negatively affect the performances of constructions in the event of an earthquake, particularly those causing the irregularity of construction in the vertical direction, and lastly to study the accuracy of the TEC-2007 [10] sensitivity values. To accomplish these aims, a 5 floor simple reinforced concrete building was taken as a model. To better understand the reason for observing their regularities forming in the vertical direction and the differences of internal forces these create, discontinuity models of different types (T1, T2, T3, T4, T5, T6) were formed. In the analytic studies, the columns and beams, specified in Table3 and Table4, were examined, and the variation in internal forces resulting from removing the columns selected from the floors and axes was calculated. In addition, a detailed study of the relevant literature was conducted. The combination of the analytical studies and the literature review yielded the following conclusions;

1. When evaluating the values of N, V, and M according to the reference model in terms of average value, Tort/T0 were found to be 35.65%, and 37.22%, respectively, for the beams, and the values of V and M were calculated as 33.88% and 50.86%. When the values are examined for the loading of G+Q+EX the increase of 50%, stipulated in the regulation for B3 irregularities, except for the moments formed in the beams, remains greatly below these values. Since the study was conducted on buildings in the 1st degree earthquake region, the rate of E in the loading of G+Q+EX will vary. The percentage variation found in cases where the analysis is conducted on other regions should be evaluated. It would be particularly useful for the TEC-2007 [10] to show the different rates for the different earthquake regions.

2. Regarding the columns on the ground floor, it was seen that some degree of increase occurred according to the displacement values shown to cause the soft story. However, the coefficient obtained was far below the critical c coefficient (η >2.0) recorded in TEC-2007 [10]. Furthermore, by ignoring the presence of the elements that are not load-bearing caused the largest rise in the coefficient due to the presence of the soft story.

3. In analyzing the capacity curves and period values of the models, the values associated with the number of decreasing columns were obtained. However, as a result of the performance analysis of the bearing system conducted on all models selected, it was seen that the case of ground floor mechanism was reached and that no hinge existed in the columns of the other stories, including the beams of the first floor, as well as all other beams. This situation is not related to the selection of bearing system. For example, when the height of the ground floor is lowered, it would be expected that the floor mechanism changes, or by slightly increasing the column sections would again impede the mechanism forming at the ground floor.

4. In B_3 types of irregularities, the actions that TEC-2007 [10] requires and, for example, the actions required by the Eurocode 8 [22] and UBC [12] are different from one other. Given that there is no distinct difference between yielding displacement, which can be defined as the first displacement of becoming hinge on the capacity curves of model, and the collapsing displacement of frame system, indicates that the R coefficient of these models may not undergo considerable change. In these regulations, however, their regularities of walls that are not load bearing, among the other irregularities in the vertical direction, the weight of floors could vary significantly.

5. This study has clearly demonstrated that other factors, such as the earthquake region, ground properties, variable floor heights, and various other properties of the system that serve as parameters in this study, will cause the results obtained to change.

6. Beside the method of equivalent earthquake load that was used as a base line in the study, other methods, such as response spectrum analysis, time history analysis and modal analysis, used to analyze the bearing system may yield considerable changes in the results obtained.

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