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The Effect of Out-of-Plane Displacement of Lateral Bracings on the Dynamic Performance of Steel Structures

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Abstract: *The method of distributing lateral load-bearing elements in a structure influences the building's performance against seismic loads. In practice, the distribution style of these elements is specified by architectural, structural and economic constraints. In the current research paper, the effect of out-of-plane displacement of lateral load-bearing elements on the dynamic behavior/response of the structure, including the displacements, relative inter-storey drift, columns' axial force distribution as well as ductility and over-strength, has been investigated in threefold18- and 24-storey steel building model with 1:1 plan ratio that incorporates diverse models with various arrangements of different lateral load-bearing elements. It was found out that the out-of-plane displacement of the lateral load-bearing elements cannot be recounted as harmful to the structure and that, if it is done carefully, it would be accompanied by advantages to the structure amongst which the reduction in the relative drift of the storeys, reduction in the storeys' total displacement, reduction in the columns' force and balanced distribution of the axial forces on the columns, reduction and, in some of the cases, perfect elimination of the upward thrust in the columns can be pointed out. In the meanwhile, this method of arranging the lateral load-bearing elements can provide better responses if implemented in nearly square buildings with 1:1 plan ratio and heights below 50 meters. Of course, some other effects have to also be taken into account in performing such a displacement including the rigidity status of the diaphragms and concentration locus of the stresses. Moreover, the way the lateral load-bearing elements are displaced is also of a great importance.*

Keywords: *Seismic Loads, Storeys' Displacement, Lateral Load-Bearing Elements*

INTRODUCTION

Earthquake is one of the most substantial natural disasters causing the incurrence of large financial and life losses every year. In between, Iran that is situated on Alps-Himalaya belt has always been at the risk of earthquake. The properties of the lateral load-bearing system are amongst the important structural parameters influencing the structures' behaviors subject to seismic loads. In the past devastative earthquakes, it was frequently seen that factors related to lateral load-bearing systems have been the causes of failures and this is reflective of the necessity of doing research in this regard.

Procedures of the irregular structures consider the implementation of more exact dynamic analysis and some increases in design forces. But, it seems that the dynamic analyses are not indicative of the real performance of the structures for some irregularities. Therefore, the present study offers suggestions for optimal way of arranging the lateral load-bearing elements.
A substantial part of architectural decisions, like aesthetics, value, recreation, spatial relations and consideration of the other factors such as dimension, form and position of the structural and nonstructural components, proper placing of walls and cores influence the general form of the structure.
The most essential parameters determining the various specifications of a plan's shape are:

1) Symmetry;
2) Proportion; and,
3) The extent to which the corners are indented or protruded.

On the other hand, the vulnerability of a structure in regard of its plan shape subject to seismic loads depends on the following factors:

1) Proportion in the rectangular segments constituting the general shape of the plan
2) Position of indentions
3) Number of symmetrical axes
4) Distance between gravity center and hardness

Based on the abovementioned materials, not all the structures belonging to a family in terms of shape have similar seismic responses and they differ in their extents of damage subject to earthquake.
Many of the procedures treat the plan shape and amount of indention leading to the formation of an irregular system are in a general manner and disregard the details. An even larger number of the procedures fall short of making thorough references to the various shapes of plan irregularities as mentioned in the previous pages. They usually adopt a constrained approach to indention extent in terms of plan dimension-indention proportion that would otherwise cause irregularity in the structure (Procedures of Standard 2800 for Designing Buildings Resistant to earthquake, 1988; Procedures of Standard 2800, version 2, for Designing Buildings Resistant to earthquake, 2000; FEMA 273, 1997; FEMA 302, 1994; Regulations for seismic design a wordlist 1996, 1996; Regulations for seismic design a wordlist – supplement 2000, 2000).

Out-of-Plane Displacement of Lateral Load-Bearing Elements:

The need for creating irregular buildings has been pointed out in (Guevara et al., 1992) meanwhile referring to the vulnerability of the majority of the irregular buildings during the past earthquake. Architectural decisions are in proportion and related to such functions as aesthetics, value, recreation, spatial relations as well as consideration of the effects of other factors like dimension, shape and position of structural and nonstructural components and/or proper placement of the walls and/or cores resisting earthquake. States of plan shape, such as square, L and H shapes, are investigated the current study and ten vibration periods and shear force rates are taken into consideration in regard of the floors. It will be subsequently suggested that L and H shapes should be separated using seismic joints and turned into rectangular segments.
In (Alami and Haji Kazemi, 2000), the behaviors of various bracings are explored and their advantages and disadvantages are explicated and compared based on such scales as displacement and force dissipation. Efforts have been made in a part of this article under the title of "the effect of placement method of bracings on structure's behavior" to examine the effect of placing concentric bracing elements in within the format of a 3-storey three-span building in five various models.

Study Method

In the present study, buildings with 1:1 plan ratio have been analyzed based on dynamic method (linear time history) using Tabas Earthquake Data. The ratio of plan's length to width in these buildings is 1:1 and the buildings have been classified in two height types, namely 83.90m (24-storey) and 55.30m (18-meter). The method of distributing the lateral load-bearing elements along y-axis in these models has been illustrated in figures (1) and (2). The models lack the torsional irregularity. The 24-storey and 18-storey buildings have been per se categorized into two groups of A and B. The common specifications of the aforementioned buildings' plans have been demonstrated in figure (3).

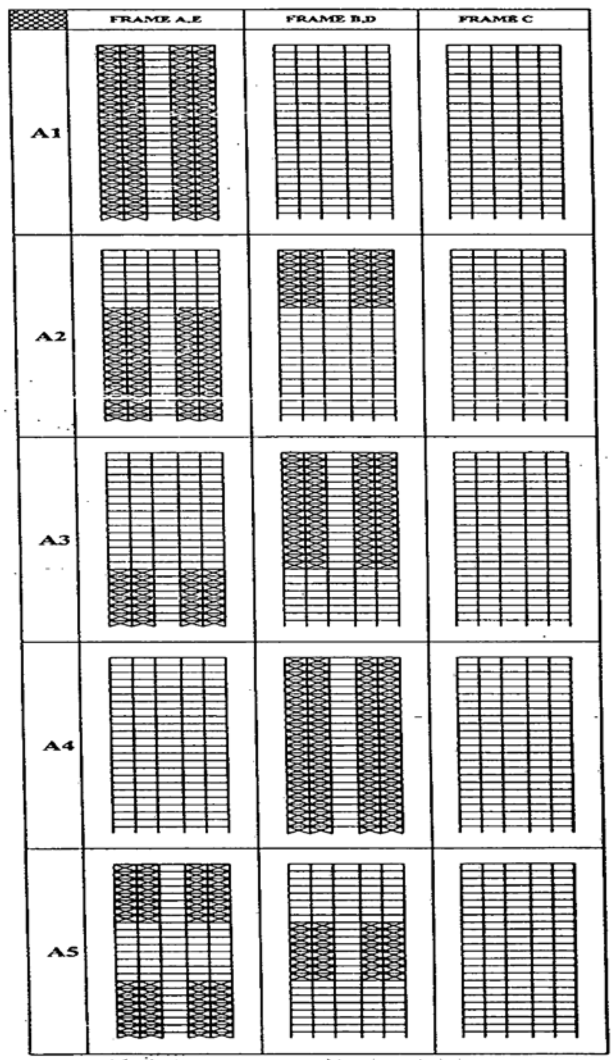

Figure 1: distribution of resistant lateral load-bearing elements in 24-storey buildings with 1:1 plan ratio (Group A)

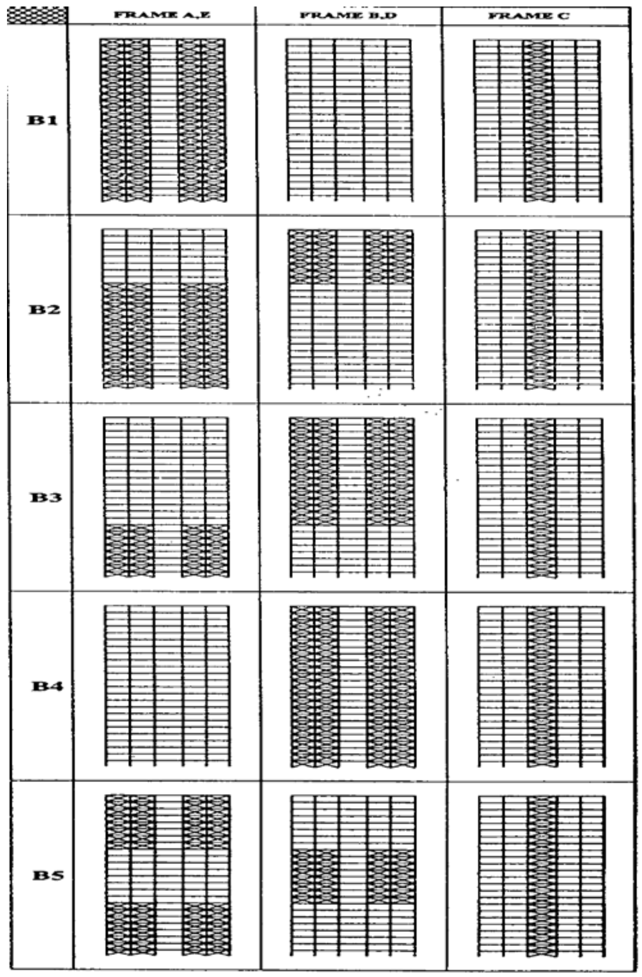

Figure 2: distribution of resistant lateral load-bearing elements in 24-storey buildings with 1:1 plan ratio (Group B)

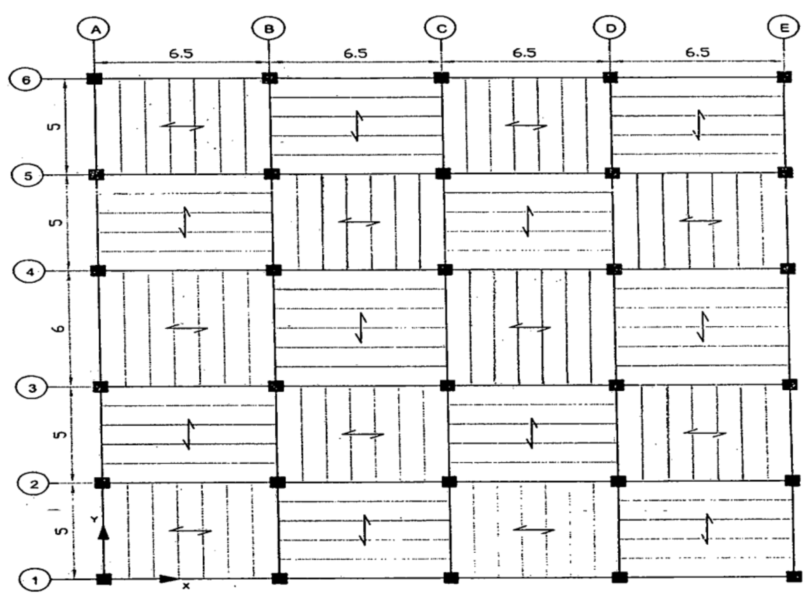

Figure 3: general specifications of the buildings with 1:1 plan ratio

- Skeleton System: simple frame with X concentric bracing along transversal direction (y-axis) and ordinary moment frame along the longitudinal direction (x-axis)
- Roof System: composite roof with 10-centimeter-thick diaphragm comprised of a concrete slap and steel joists of IPE profile types for the transmission of the gravitational loads
- Building's dimensions in plan
- Loads imposed on the building
  A) Dead load+ live load
  B) Seismic load (acceleration-time spectrum of Tabas earthquake with 1250 data entries and time spans of t=0.02s)
  F_x: seismic load along x-axis; F_y: seismic load along y-axis
- The buildings are assumed to serve administrative purposes.
- Specifications of the constructional materials used in the modeling are as follow:
  1) Concrete masonry:
- Elasticity module: $E_c = 2.5 \times 10^5\ ^{Kg}/_{cm^2}$
- Unit volume weight: $W = 2400\ ^{Kgf}/_{m^3}$
- Unit volume mass: $M = 240\ ^{Kg}/_{m^3}$
- Poisson coefficient: $\upsilon = 0.2$
- Compressive strength of the concrete: $f'_c = 280\ ^{Kg}/_{cm^2}$
- Yield stress of the longitudinal rebars: $f_y = 4000\ ^{Kg}/_{cm^2}$
- Yield stress of the shear stirrups: $f_{ys} = 3000\ ^{Kg}/_{cm^2}$
  2) Steel Masonry:
- Elasticity Module: $E_s = 2.5 \times 10^6\ ^{Kg}/_{cm^2}$
- Unit volume weight: $W = 7850\ ^{Kgf}/_{m^3}$
- Unit mass weight: $M = 785\ ^{Kg}/_{m^3}$
- Poisson coefficient: $\upsilon = 0.3$
- Yield stress of the steel: $F_y = 2400\ ^{Kg}/_{cm^2}$
- Final stress of the steel: $F_U = 4000\ ^{Kg}/_{cm^2}$
  Loading Details:
- Partitions' equivalent overburden: $100\ ^{Kg}/_{m^2}$
- Dead load of the storeys' floors: $490\ ^{Kg}/_{m^2}$
- Dead load of the roof's floor: $440\ ^{Kg}/_{m^2}$
- The load of the peripheral and lateral walls of the structure: $260\ ^{Kg}/_{m^2}$
- The unit load of the length of the structure's lateral beams in storey level: $728\ ^{Kg}/_{m^2}$
- The unit load of the length of the structure's lateral beams in roof level: $208\ ^{Kg}/_{m^2}$
- The live load of the storeys' floors: $200(70\%\ office\ room) + 500\ (30\%\ corridor) = 290 kg/m^2$

In estimating the live load of the storeys, it has been assumed that 70% of the building is used for office work and the remaining 30% is served as corridor.

- Live load of the roofs: 150 $^{Kg}/_{m^2}$
- Dead load of the storeys minus the weight of the roof and members' concrete slab: 250 $^{Kg}/_{m^2}$
- Dead load of the roof except the weight of the roof and members: 200 $^{Kg}/_{m^2}$

The members of 24-storey and 18-storey frames with 1:1 plan ratio, including beams, columns and bracings, were designed according to the amounts of load imposed on them as specified in earthquake standard 2800, version 2, loading Standard 519 and chapter ten of the national building regulations. To do the present research, the models were concomitantly analyzed using two methods of linear dynamic analysis (time history) and P-Δ analysis. All of the analyses were carried out in ETABS2000, version 7.21.
The properties of the 24-storey building, with a height of 73.90m (over 50m), and 18-storey building, with a height of 55.30m (up to 50m), have been listed below:

A) Group A: the set of models for investigating the effect of out-of-plane displacement of lateral load-bearing elements without fixed braced frame:

Model A1: in this model, Frame A and its counterpart Frame E have been braced in all 24 storeys. The resistant lateral load-bearing members have been placed in spans adjacent to one another and there is no out-of-plane and in-plane displacement of the load-bearing elements seen in this model.
Model A2: in this model, the resistant lateral load-bearing systems of E and A frames have been transferred to frames D and B from storeys 17 to 24. According to the lack of extending the lateral load-bearing elements of D and B frames to the foundation, the model is considered irregular.
A3 Model: in this model, the resistant lateral load-bearing systems of E and A frames have been transferred to frames D and B from storeys 9 to 24. According to the lack of extending the lateral load-bearing elements of D and B frames to the foundation, the model is considered irregular.
A4 Model: in this model, the resistant lateral load-bearing systems of E and A frames have been generally transferred to frames D and B. In the meantime, no displacement of the lateral load-bearing elements can be seen neither in-plane nor out-of-plane.
A5 Model: in this model, the lateral load-bearing system of A and E frames have been transferred to B and D frames from storeys 9 to 16. According to the lack of extending the lateral load-bearing elements of D and B frames to the foundation and also considering the discontinuity and non-integration of the lateral load-bearing elements of A and E frames , the model is considered irregular.

B) Group B: the set of models for investigating the effect of out-of-plane displacement of lateral load-bearing elements with fixed and braced frames:

The models in this group are similar to all of the states in group A with the difference being that the group possesses fixed and braced frame. According to the large amount of upward thrust in the columns for the models' lateral loading, the models of this group have been analyzed assuming fixed and braced frames in all 24 storeys. However, to perform a more precise investigation of the effect of displacement, a series of models, also mentioned in group A, have been analyzed without this fixed and braced frame.

Results

1. **Results related to models having out-of-plane lateral load-bearing displacement without fixed and braced frame in 24-storey building (group A)**
   A) Relative Drift of the Storeys:

Amongst group A's models, it seems that A3 has the lowest and, in the meantime, the most appropriate amount of relative drift in the storeys. Therefore, the model outperforms the rest of the models in this group. The trivial difference between the relative drift of the storeys in models A1 and A4 from the 8th storey to the top is due to the difference in the cross-section types of the elements (beam, column and bracing) (figure 4). The order of the models in terms of the low and appropriate relative drift is as shown below:

$$A_3 > A_2 > A_5 > A_4 > A_1 \text{ or } A_2 > A_3 > A_5 > A_4 > A_1$$

In A2, the out-of-plane displacement of the lateral load-bearing elements from 16th storey to the top brings about a considerable reduction in the relative drift that can be enumerated as an advantage of this model.

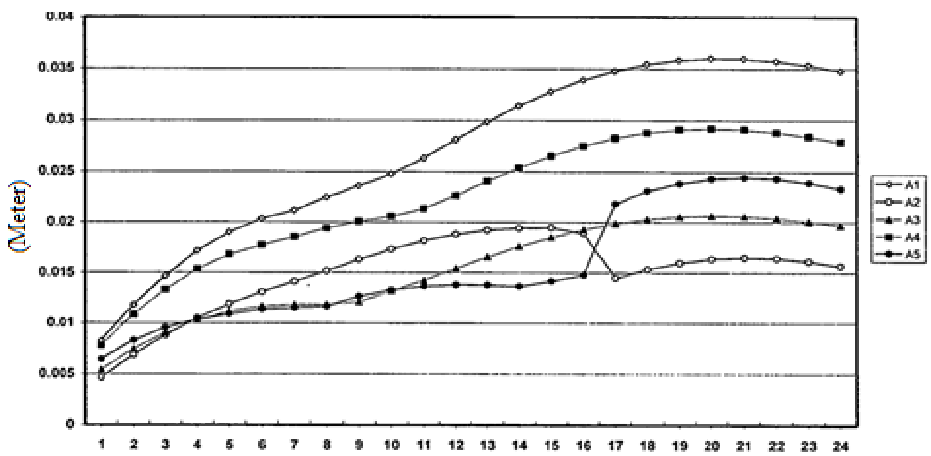

Figure 4: relative drift of the floors in 24-storey models (group A)

B) Storeys' Displacement:

Maximum displacement amongst the models in group A belongs to A1 and A4. The lowest displacement amongst the majority of the storeys belongs to A2, A5 and A3. The amounts of the storeys' displacement are close to one another in lower floors and their differences become more evident in higher floors (figure 5). In terms of the low and appropriate displacement, the models take the following order:

A3>A5>A2>A4>A1

It is worth mentioning that the amounts of the storeys' displacement in A2, A5 and A3 models are very close and similar to one another in such a way that the storeys' displacement can be considered equal to one another:

A2≅A5≅A3

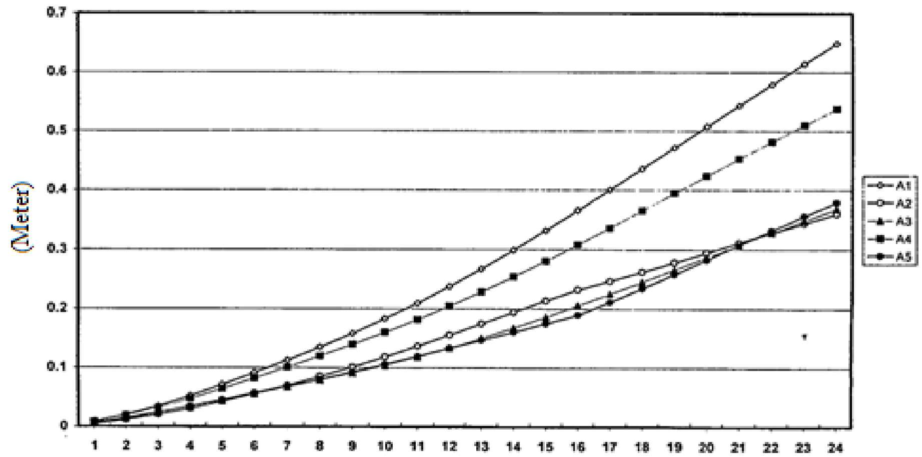

Figure 5: storeys' displacement in 24-storey models (Group A)

C) Distribution of the Axial Force in A, B and C Frames' Columns:

Frames A and E: model A1 has the highest compressive axial force and the highest upward thrust in the columns subject to the combined effect of seismic load. Model A4 that lacks any lateral bracing in A and E Frames also features the lowest axial force of the columns subject to the combined effect of seismic load (figure 6).

Frames D and B: the lowest axial force in these frames belongs to model A1 and the highest compressive and tensile axial force was evidenced Model A4. The upward thrust created in the columns of D and B frames, as compared to the upward thrust created in the columns of A and E frames are more increasingly lower and trivial (figure 7).

Frame C: the highest axial force of the columns was found for A4 and the lowest axial force of the columns was documented for A1. Of course, because the frame lacks the lateral bracing, upward thrust is accordingly not seen in A1, A2, A3 and A5 models and there is only a slight amount of upward thrust in A4 (figure 8).

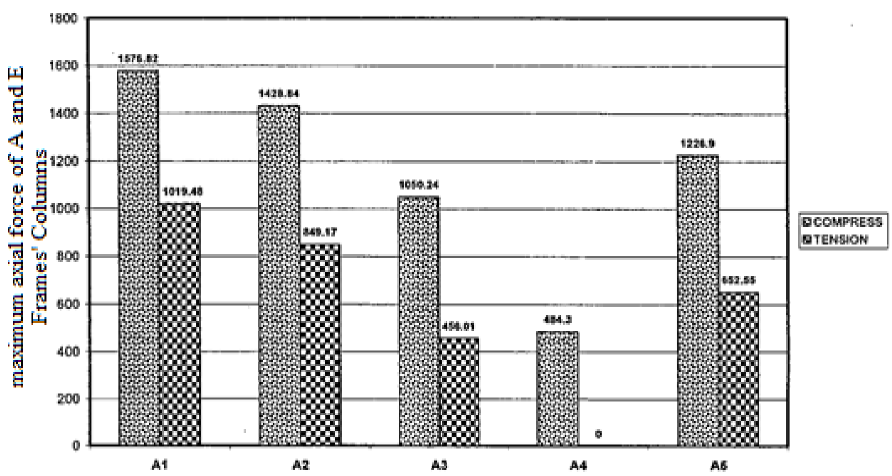

Figure 6: distribution of the axial force of A and E frames' columns in 24-storey models (Group A)

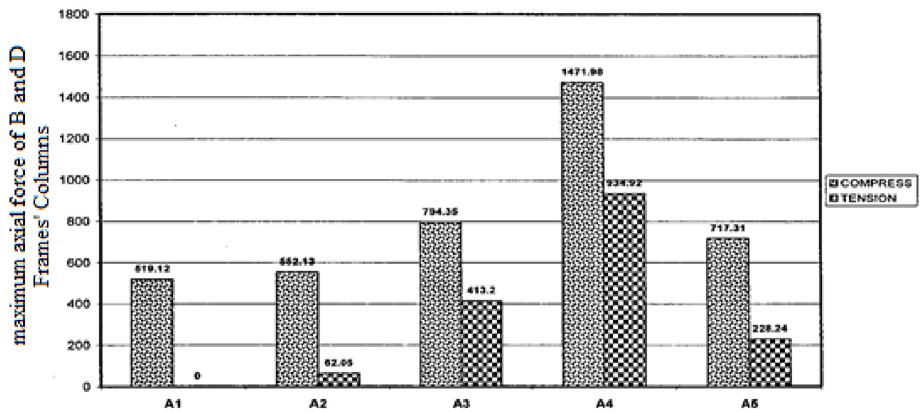

Figure 7: distribution of the axial force in B and D frames' columns in 24-storey models (Group A)

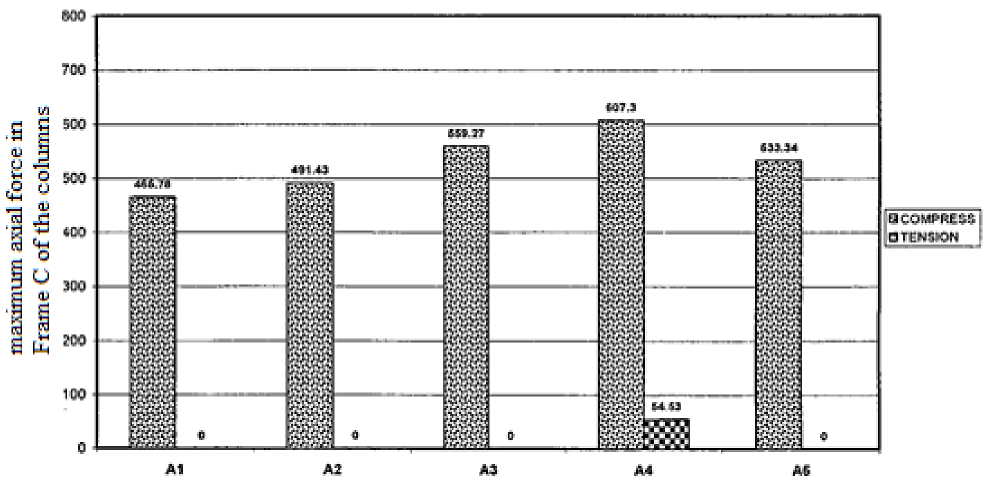

Figure 8: distribution of the axial force in C frames' columns in 24-storey models (Group A)

D) Calculation of Structure Hardness Along y-Axis Using Dynamic Analysis (Time History):

According to the fact that three modes are the dominant and determinant ones in analysis and design, the second mode is presumed for calculating the model's hardness:

$$T = 2\pi\sqrt{{}^{m}/_{k}} \Rightarrow k = \frac{4\pi^2 m}{T^2}$$

1) A1 Model:

$$T = 4.3019\ s \quad , \quad m = 270.49\ ton \qquad \Rightarrow k = 574.86\ \ {}^{ton}/_{s^2}$$

2) A2 Model:

$$T = 3.3419\ s \quad , \quad m = 171.54\ ton \qquad \Rightarrow k = 603.46\ \ {}^{ton}/_{s^2}$$

3) A3 Model:

$$T = 3.1714\ s \quad , \quad m = 202.34\ ton \qquad \Rightarrow k = 789.94\ \ {}^{ton}/_{s^2}$$

4) A4 Model:

$$T = 3.6956\ s \quad , \quad m = 200.28\ ton \qquad \Rightarrow k = 577.57\ \ {}^{ton}/_{s^2}$$

5) A5 Model:

$$T = 3.0414\ s \quad , \quad m = 168.81\ ton \qquad \Rightarrow k = 716.43\ \ ^{ton}/_{s^2}$$

Amongst the Group A's models, A3 features the highest hardness and A1 has the lowest hardness. Thus, Group A's models take the order demonstrated in the following inequality in terms of hardness:

A3>A5>A2>A4>A1

2. **Results related to models having out-of-plane displacement of lateral load-bearing elements with fixed and braced frames in all 24 storeys (Group B):**

   A) Relative Drift of the Floors:

Amongst the Group B models, B2 seems to have the lowest and, in the meantime, the most appropriate relative drift of the floors. Thus, the model outperforms the rest in this regard. The trivial difference between the floors' relative drifts in B1 and B4 models occurs from 9^{th} storey to the top due to the differences in the cross-section types of elements (beam, column and bracing) (figure 9). The models take the following order in terms of their low and appropriate relative drift:

B2>B5>B3>B4>B1

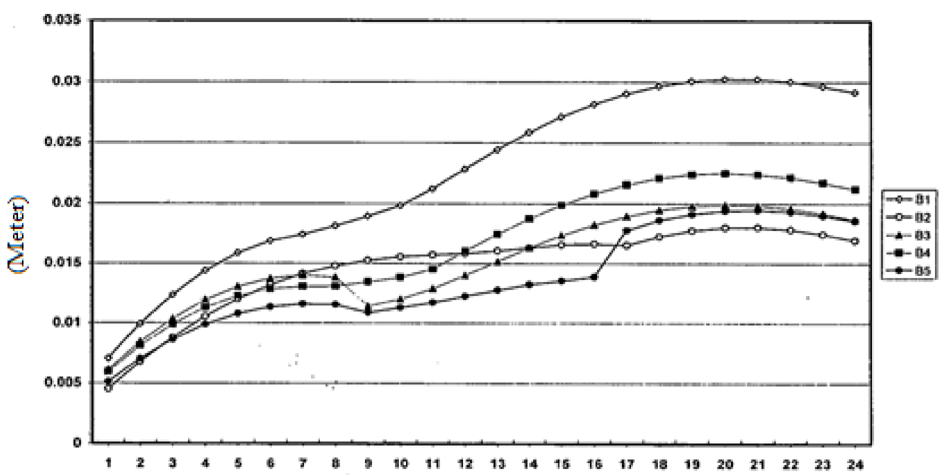

Figure (9): relative drift of the floors in 24-storey models (group B)

B) Storeys' Displacement:

The highest displacement between the Group B's models pertains to B1 and B4. The lowest displacement of all the floors belongs to B2, B3 and B5. The storeys' displacements are close to one another in lower floors and their differences become clearer in higher floors (figure 10). The models take the following order in terms of the low and appropriate displacement:

B5>B3≅B2>B4>B1

In the meanwhile, it has to be pointed out that due to the existence of fixed and braced frames in all 24-storeys, the floors' displacements have undergone considerable reductions in B1 and B4 models in contrast to their counterparts in Group A (A1 and A4).

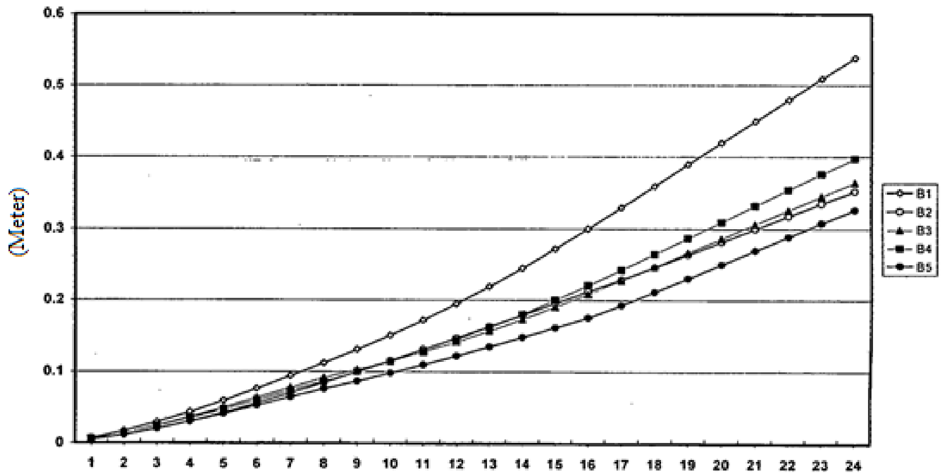

Figure 10: storeys' displacement in 24-storey models (Group B)

C) Distribution of Axial Force in A, B and C Frames' Columns:

Frames A and E: B1 has the highest compressive axial force and the highest upward thrust in the columns subject to combined seismic load. Model B4 that lacks any lateral bracing in Frames A and E features the lowest axial force in the columns subject to combined seismic load (figure 11).

B and D Frames: the lowest axial force in these frames was found belonging to B1and the highest rates of compressive and tensile axial force were scored for B4. The amount of the upward thrust created in B and D frames is a lot lower and trivial in comparison to the upward thrust of A and E frames and the reason for such a high difference is the larger load-incurring surface of the columns in these frames in comparison to the columns of frames A and E (figure 12).

Frame C: the highest axial force of the columns was found belonging to B1 and B4 models and the lowest axial force was evidenced for B2, B3 and B5 models. Of course, the upward thrust is a little lower in B2 than that in B3 (figure 13).

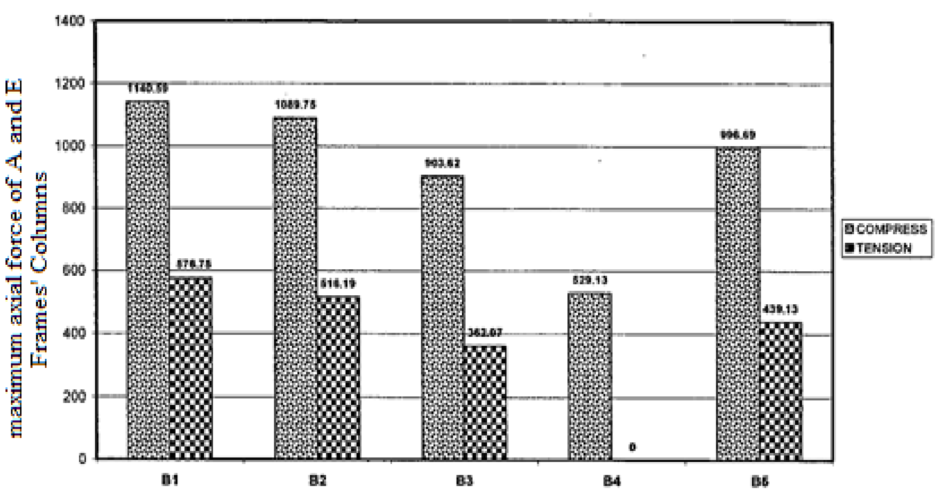

Figure 11: axial force distribution in the columns of A and E frames in 24-storey models (Group B)

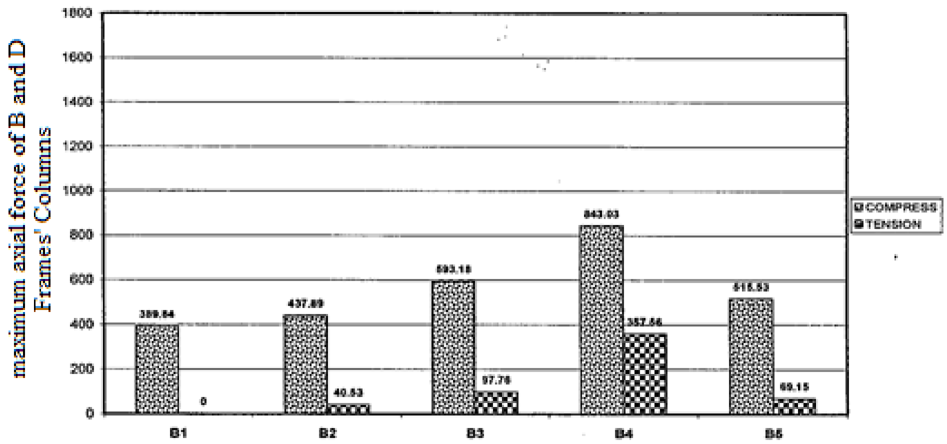

Figure 12: axial force distribution in the columns of B and D frames in 24-storey models (Group B)

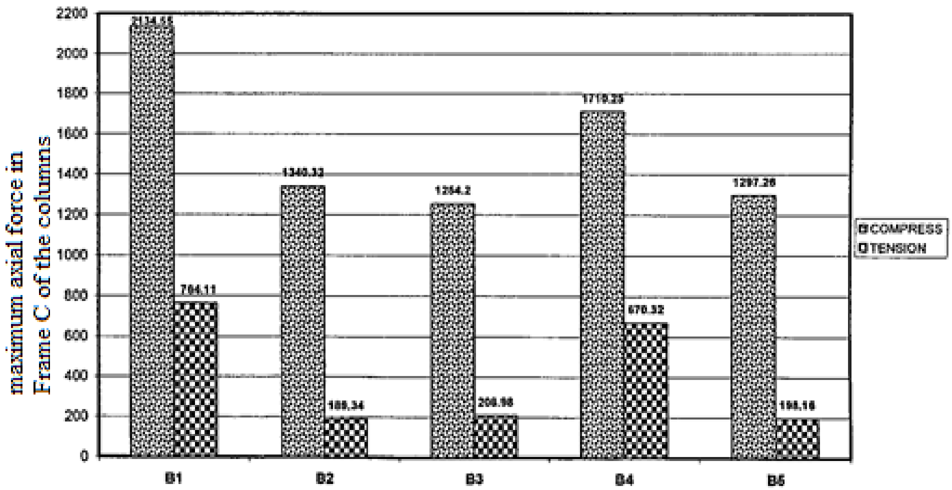

Figure 13: axial force distribution in the columns of frame C in 24-storey models (Group B)

D) Calculation of the structure's hardness along y-axis using dynamic analysis (time history):
According to the determinative role of the three first modes in analyzing and designing the structure, the second mode is presumed for computing the hardness:

$$T = 2\pi\sqrt{\frac{m}{k}} \Rightarrow k = \frac{4\pi^2 m}{T^2}$$

1) ModelB1:

$$T = 4.3117 \ s \quad , \quad m = 247.61 \ ton \qquad \Rightarrow k = 523.80 \ \ {ton}/{s^2}$$

2) Model B2:

$$T = 3.4856 \ s \quad , \quad m = 219.10 \ ton \qquad \Rightarrow k = 710.14 \ \ {ton}/{s^2}$$

3) ModelB3:

$$T = 3.0448 \ s \quad , \quad m = 215.43 \ ton \qquad \Rightarrow k = 914.27 \ \ {ton}/{s^2}$$

4) ModelB4:

$$T = 3.3458 \ s \quad , \quad m = 154.52 \ ton \qquad \Rightarrow k = 543.57 \ \ {ton}/{s^2}$$

5) ModelB5:

$$T = 2.9659\ s \quad , \quad m = 217\ ton \qquad \Rightarrow k = 971.28\ \ ^{ton}/_{s^2}$$

Amongst group B's models, B5 has the highest hardness and B1 has the lowest hardness. Thus, the Group B's models take the order shown in the following inequality in terms of hardness:

B5>B3>B2>B4>B1

3. 18-Storey Buildings with Height above 55.30m (below 50m):

3.1. Results related to models having out-of-plane displacement without fixed braced frame in all 18 floors (Group A):

A) Floors' Relative Drift:

The models take the following order in terms of their low and appropriate relative drift:

A5>A3>A4>A2>A1

The following order of the models can also be mentioned instead of the above:

A5>A3>A2>A4>A1

In A2, considerable reduction is brought about in the floors' relative drift with the out-of-plane displacement of the lateral load-bearing elements from 12th storey on and this can be recounted as an advantage of this model.

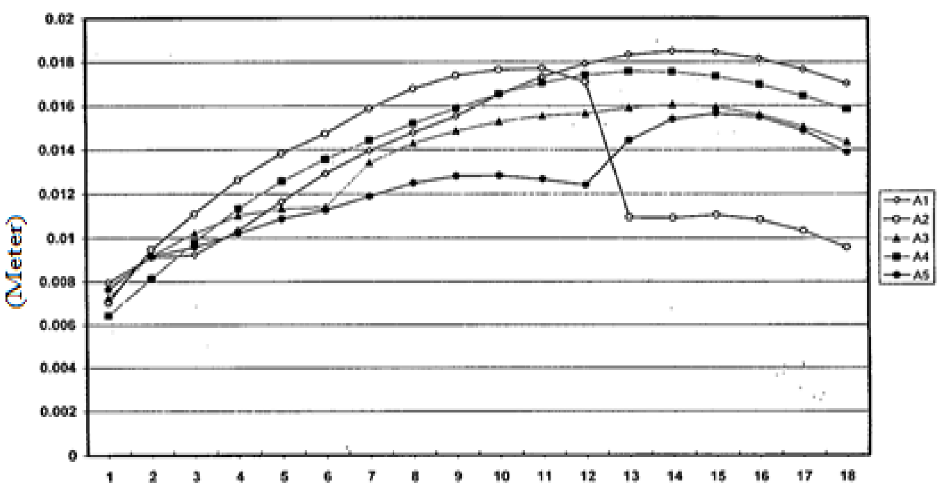

Figure 14: floors' relative drift in 18-storey models (group A)

B) Storeys' Displacement:

The highest displacement of the models in Group A goes to A1 and A4. Model A2 features the highest displacement in the first 12 storeys of Group A's models and the displacement is reduced from the 12th storey to the top. The lowest displacement in the entire storeys has been scored for A3and A5. The amounts of displacement are close to one another in the lower floors and the distance enlarges in the higher floors. The models take the following order in terms of the low and appropriate displacement of the storeys:

A5>A3>A2>A4>A1

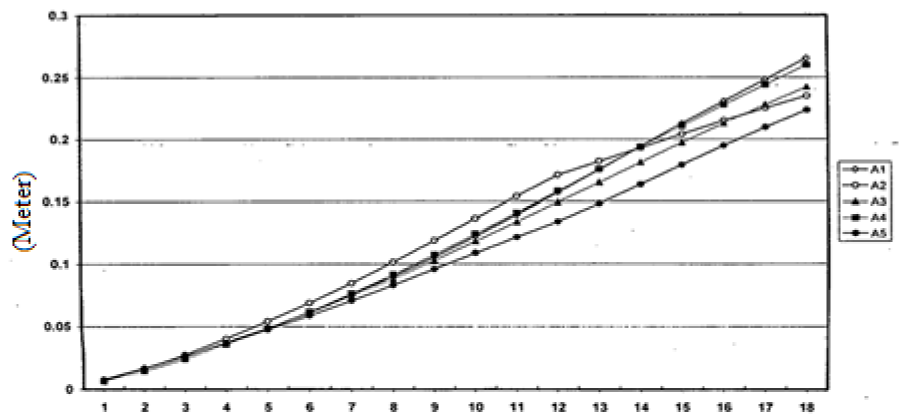

Figure 15: floors' displacement in 18-storey models (group A)

C) Distribution of Axial Force in Columns of A, B and C Frames:

Frames A and E: A1 has the highest compressive axial force and the highest upward thrust in the columns subject to the combined effect of seismic load. Model A4 that lacks any lateral bracing in A and E frames features the lowest axial force of columns subject to the combined effect of seismic load (figure 16).

D and B Frames: the lowest axial force of these frames was found belonging to A1 and the highest compressive and tensile axial force rates were scored for A4. The upward thrust created in columns of D and B frames are increasingly lower and trivial as compared to that created in the columns of E and A frames. This vivid difference originates from the largeness of the load-bearing surface in columns of frames D and B in contrast to the columns of A and E frames (figure 17).

Frame C: the highest axial force of the columns pertains to A4 and the lowest axial force of the columns belongs to A1. Of course, since the frame lacks the lateral bracing, upward thrust is not seen in A1, A2, A3 and A5 models and a trivial amount of upward thrust only exists in A4 (figure 18).

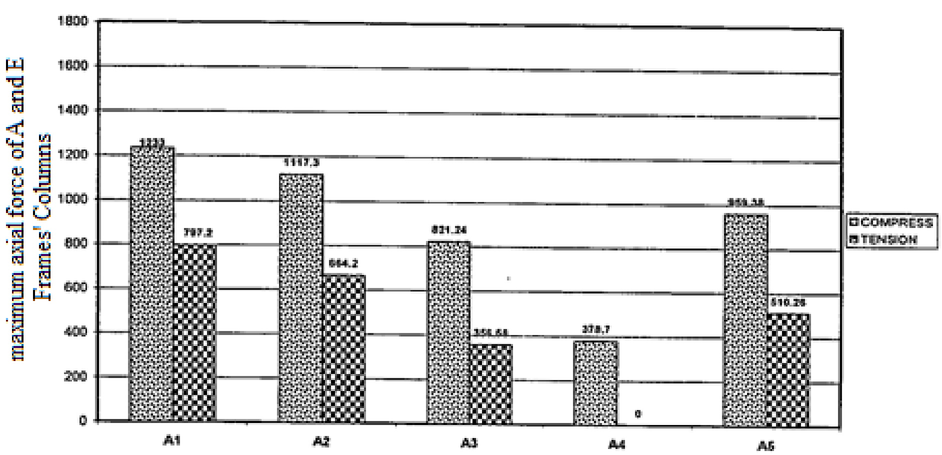

Figure 16: distribution of axial force in columns of A and E frames in 18-storey models (group A)

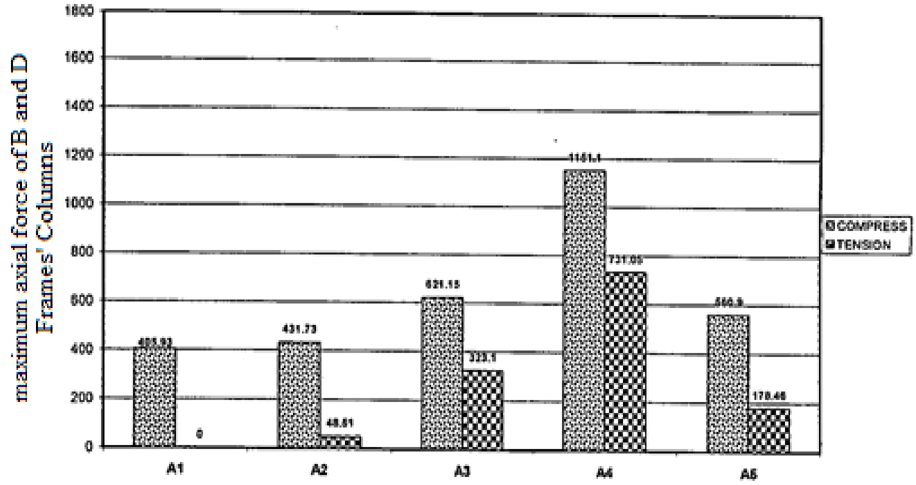

Figure 17: distribution of axial force in columns of B and D frames in 18-storey models (group A)

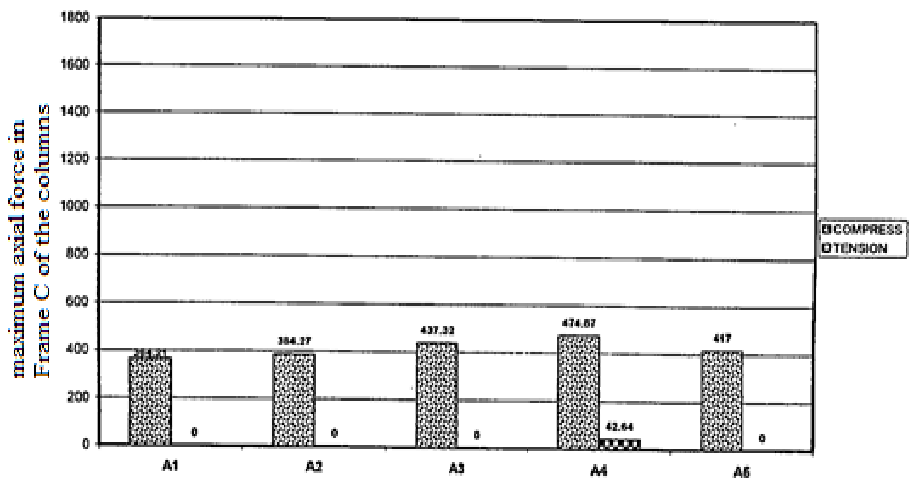

Figure 18: distribution of axial force in columns of Frame C in 18-storey models (group A)

D) Calculation of hardness along y-axis using dynamic analysis (time history):

Considering the fact that the three first modes are the dominant and determinant ones for the analysis and design, the second mode has been presumed for the computation of the models' hardness:

$$T = 2\pi\sqrt{\frac{m}{k}} \Rightarrow k = \frac{4\pi^2 m}{T^2}$$

1) ModelA1:

$$T = 2.9569\ s \quad , \quad m = 99.93\ ton \quad \Rightarrow k = 450.25\ \ {}^{ton}/_{s^2}$$

2) ModelA2:

$$\mathrm{T = 2.3188\ s} \quad , \quad \mathrm{m = 64.44\ ton} \quad \Rightarrow \mathrm{k = 472.65\ \ {}^{ton}/_{s^2}}$$

3) ModelA3:

$$T = 2.07198\ s \quad , \quad m = 61.50\ ton \quad \Rightarrow k = 561.12\ \ {}^{ton}/_{s^2}$$

4) ModelA4:

$$T = 2.2975\ s \quad , \quad m = 60.62\ ton \quad \Rightarrow k = 452.36\ \ {}^{ton}/_{s^2}$$

5) ModelA5:

$$T = 2.0079\ s \quad , \quad m = 63.02\ ton \qquad \Rightarrow k = 617.13\ \ {ton}/{s^2}$$

Amongst the Group A's models, A5 has the highest hardness and A1 has the lowest hardness. Thus, Group A's models take the order as demonstrated in the following inequality in terms of hardness:

A5>A3>A2>A4>A1

3.2. Results related to the models having out-of-plane lateral load-bearing elements' displacement with fixed and braced frames in all 18 storeys (Group B):

A) Floors' Relative Drift:

Amongst Group B models, it seems that B3 and B5 have the lowest and, in the meantime, the most appropriate relative drifts of the floors. Therefore, these models outperform the rest of the models in the group in terms of floors' relative drift. The reason for the trivial difference between the relative drifts of B1 and B4 from the 12th storey to the top is due to the differences in the cross-section types of the elements (beam, column and bracing) (figure 19). The models take the order shown beneath in terms of the low and appropriate relative drift of the floors:

B5>B3>B2>B4>B1

In B2, considerable reduction is seen in the floors' relative drifts in the displacement place of the lateral load-bearing elements in the distance from 12th storey to 13th storey and this can be considered as an advantage for this model.

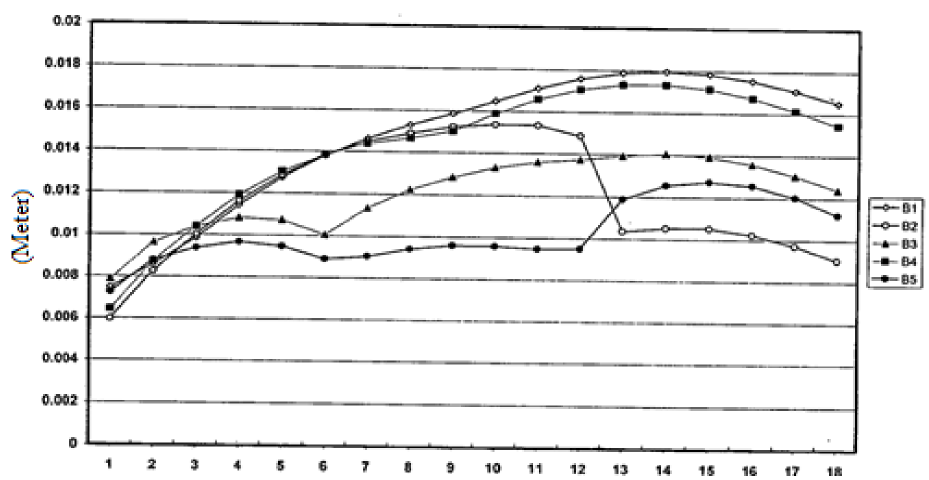

Figure 19: relative drift of the floors in 18-storey models (Group B)

B) Storeys' Displacement:

The highest displacement amongst the Group B's models pertains to B1 and B4. The lowest displacements in the entire floors were found respectively belonging to B5, B3 and B2. The Storeys' displacements are close to one another in lower floors and the differences become more vivid in the higher floors (figure 20). The models take the following order in terms of their low and appropriate displacements:

B5>B3>B2>B4>B1

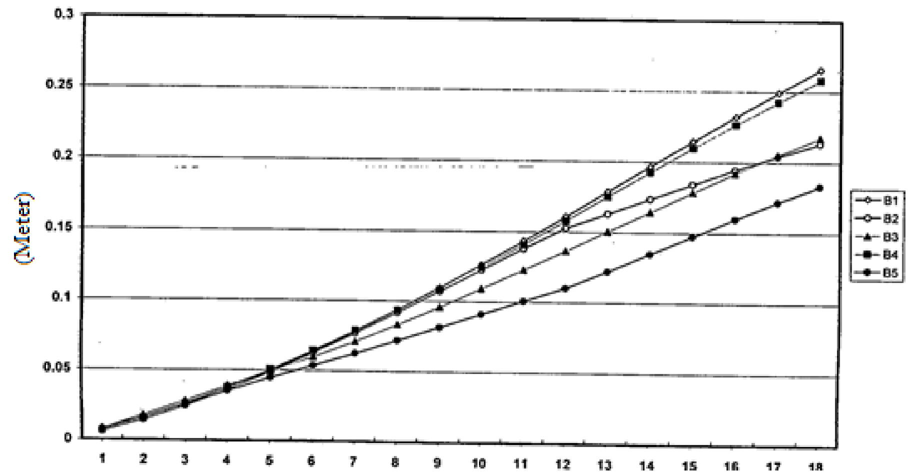

Figure 20: floors' displacement in 18-storey models (Group B)

C) Distribution of axial force in columns of A, B and C Frames:

Frames A and E: B1 has the highest compressive axial force and the highest upward thrust in the columns subject to the combined effect of seismic load. Model B4 that lacks any lateral bracing in Frames A and E has the lowest axial force rates in columns subject to combined effect of seismic load (figure 21).

B and D Frames: the lowest axial force of the frames was found belonging to B1 and the highest compressive and tensile axial force was found pertaining to B4. The amount of the upward thrust created in the columns of frames B and D is a lot lower and more trivial than that created in A and E frames and the reason for such a high difference is the larger load-bearing surface of the columns in the former frames as compared to that in the latter frame (figure 22).

Frame C: the highest axial force of the columns belongs to B1 and B4 models and the lowest axial force of the columns pertains to B2, B3 and B5 models. Of course, the upward thrust is a little lower in B2 in comparison to that in B3 (figure 23).

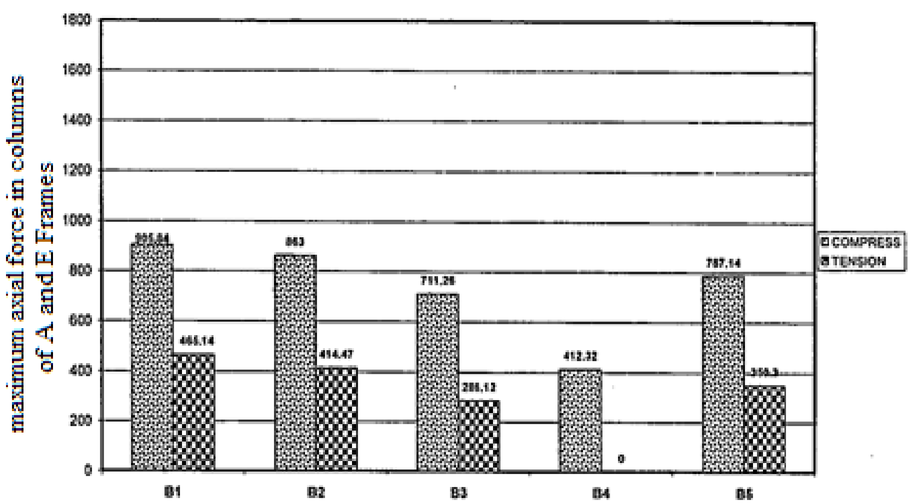

Figure 21: distribution of the axial force in columns of A and E frames in 18-storey models (group B)

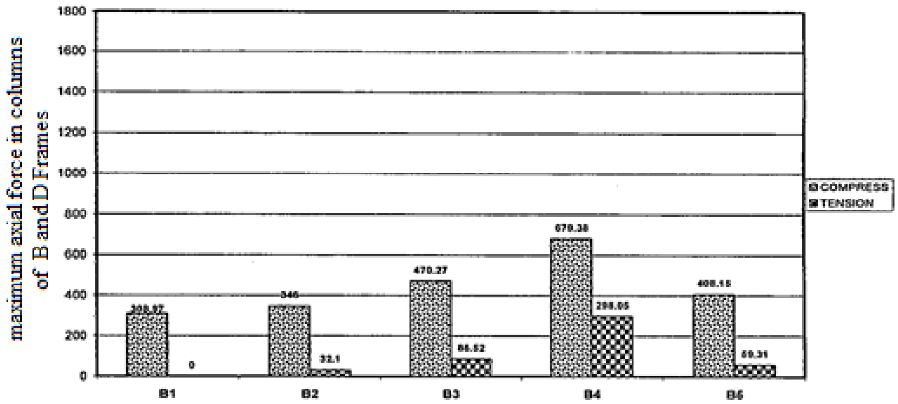

Figure 22: distribution of the axial force in columns of B and D frames in 18-storey models (group B)

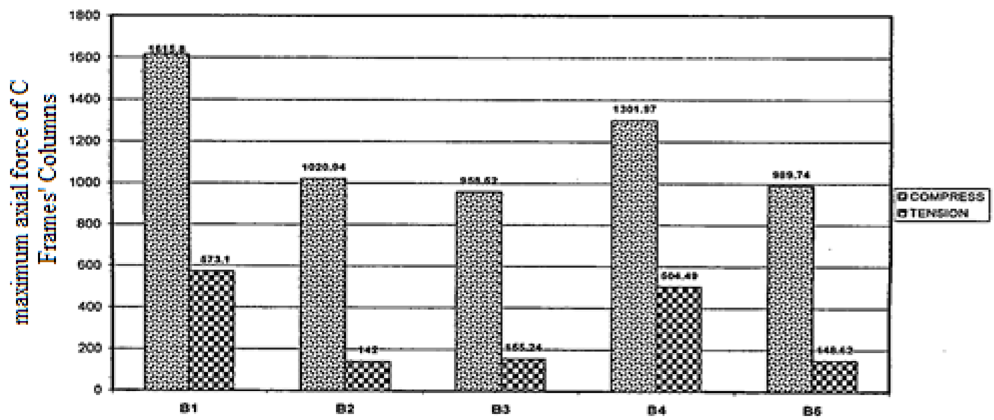

Figure 23: distribution of the axial force in columns of Frame C in 18-storey models (group B)

D) Calculation of the structure's hardness along y-axis using dynamic analysis (time history)

According to the first three modes' determinative role in analysis and design of the structure, the second mode was presumed for computing the models' hardness:

$$T = 2\pi\sqrt{\frac{m}{k}} \Rightarrow k = \frac{4\pi^2 m}{T^2}$$

1) ModelB1:

$$T = 2.3195\ s \quad , \quad m = 58.32\ ton \quad \Rightarrow k = 427.74\ \ ^{ton}/_{s^2}$$

2) ModelB2:

$$T = 2.1818\ s \quad , \quad m = 67.65\ ton \quad \Rightarrow k = 551.78\ \ ^{ton}/_{s^2}$$

3) ModelB3:

$$T = 2.0726\ s \quad , \quad m = 76.50\ ton \quad \Rightarrow k = 698\ \ ^{ton}/_{s^2}$$

4) ModelB4:

$$T = 2.9585\ s \quad , \quad m = 108.43\ ton \quad \Rightarrow k = 488.56\ \ ^{ton}/_{s^2}$$

5) ModelB5:

$$T = 1.90204\ s \quad , \quad m = 69.60\ \ ton \quad \Rightarrow k = 753.13\ \ ^{ton}/_{s^2}$$

Amongst Group B's models, B5 and B1 were found possessing the highest and the lowest hardness rates, respectively. Thus, the Group B's models take the order shown in the following inequality in terms of hardness:

$$B5>B3>B2>B4>B1$$

Conclusion

1) Out-of-plane and in-plane displacement lateral load-bearing elements cannot be generally considered harmful to the structure. Lateral load-bearing elements' displacement would be followed by benefits to the structure in case it is done carefully. The reduction in the relative drifts of the floor, reduction in the storeys' displacement, reduction in the columns' force and balanced distribution of the axial force in the columns, reduction and, in some of the cases, perfect elimination of the harmful upward thrust in the columns and increase in the hardness are amongst these advantages.
2) The force in the frame columns with displacement of an element is reduced upon the out-of-plane displacement of the lateral load-bearing elements and the force is subsequently increased in the frame columns to which an element is added.
3) The most favorable models in terms of balanced distribution of the axial forces, including compressive and upward thrust (tensile), reduction in the storeys' displacement, reduction in the floors' relative drift as well as the increase in hardness in each model of Groups A and B and the threefold building model (24-storey building (73.9m) and 18-storey building (55.3m)) are as outlined below:
   24-storey buildings, Group A: Model A3
   24-storey buildings, Group B: Model B5
   18-storey buildings, Group A: Model A5
   18-storey buildings, Group B: Model B5
4) The most appropriate models in Group A of the aforementioned buildings are A2, A5 and A3, respectively; the most appropriate models in Group B of the abovementioned buildings are B2, B3 and B5, respectively.
5) The existence of the fixed braced middle frame in the middle span exerts a notable effect on the reduction of the floors' relative drift in the threefold model. The reduction in the number of the storeys with braced middle frame in 18-storey building causes accentuation of this reductive effect.
6) The most inappropriate models in terms of balanced distribution of the axial force of the columns, including compressive and upward thrust (tensile), storeys' displacement, floors' relative drift and hardness are the frames and models the braced members of which are extended from the foundation to the roof (A1 and A4 models).
7) It can be concluded in a comparison of A1 with A4 and B1 with B4 that they would exhibit better performance if the lateral load-bearing elements are distributed in the middle and interior frames and the values of the aforesaid parameters would be found in a more acceptable range because in Group A and Group B of the threefold models, the results of A4 and B4 models are a lot more favorable than those of A1 and B1.
8) In A2 model of the aforesaid buildings, the floors' relative drift in the location of lateral load-bearing elements' displacement is considerably reduced. In the meanwhile, this amount of relative drift is found less in B2 for the existence of fixed braced frame in the entire elevation.

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