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Effect of Building Configuration on Seismic Response Parameters

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SYNOPSIS To contribute to the available information on the inelastic performance of irregular structures, the investigation of four building characteristics on it seismic response was initiated. These characteristics are column height, beam-to-column capacity, stiffness distribution in elevation and set-backs and non-symmetric elevation configuration. The parametric study presented in the paper is intended to be more indicative than comprehensive, since simplifications in the modeling of structures were necessary.

INTRODUCTION

The assessment of the effect of building characteristics on its overall response is important for both the design of new buildings and the evaluation of existing ones. In this paper a parametric study, aiming at investigating the effect of four building characteristics on its seismic performance, is presented. The studied parameters are column height, beam-to-column capacity, stiffness distribution in elevation and setback and non symmetric elevation configuration.

A brief description of the performed analysis and the obtained results are demonstrated in this paper. Discussion of the results and final conclusions are presented at the paper end

COLUMN HEIGHT

The effect of column height on building performance as well as the force distribution and the predicted mode of failure, i.e. shear or flexural failure, are investigated. A one bay one story plane frame is analysed under the effect of a horizontal static load (P), laterally applied at the top. The position of one of the two supports of the frame is changed so that the ratio of the column height (H_{SC}) to the frame height (H_C) changes from 1.0 to 0.25.

Fig. 1 shows the relation between the ratio of the forces attracted by the two columns (V_{SC}/V_C) versus the column height ratio (H_{SC}/H_C), where V_C and V_{SC} are lateral reactions of the long and short columns, respectively.

From this figure it can be seen that the shear force attracted by the shorter column (V_{SC}) increases as its height decrease until it reaches 19 times the corresponding value of the longer column (V_C) when H_{SC}/H_C is 0.25. This reflects the increase in the shear stress, required to be accommodated by short columns and explains the frequently observed damage of these columns.

Fig 2 shows the effect of column height on its mode of failure

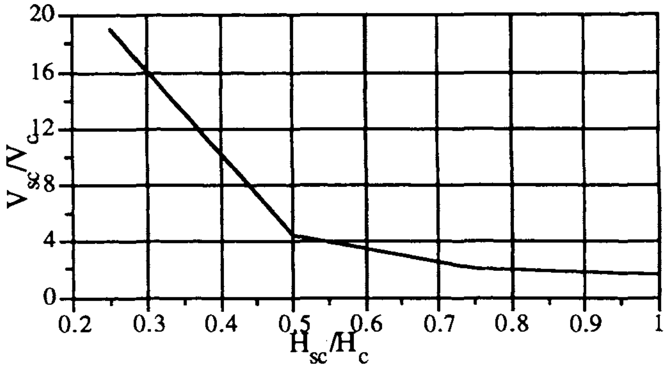


Fig. 1 Effect of Column Height on Lateral Reactions.

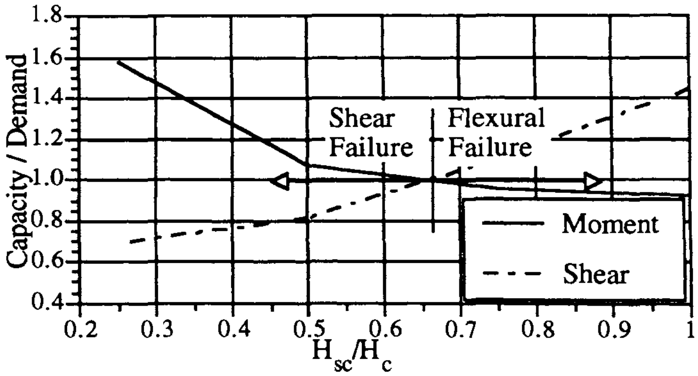


Fig. 2 Column Height Effect on its Mode of Failure.

It can be concluded that when the ratio (H_{SC}/H_C) is less than 0.65, the shear capacity/demand ratio becomes less than 1 reflecting that the unfavourable shear failure is expected.

COLUMN-TO-BEAM-CAPACITY

In the present study, 4-story one and two-bay plane-frame models with variable column-to-beam capacity ratio (M_c/M_b) are analysed. A lateral load (P) is applied at frame top. The load is increased proportionally with pseud time domain through ten steps. Loads corresponding to the first plastic hinge (P_y) and to the formation of failure mechanism (P_u) are utilized to indicate the frame yielding and ultimate capacities, respectively. The corresponding displacements (δ_y) and (δ_u) are utilised as yielding and ultimate displacements.

Fig. 3 shows curves plotted for the ratio (P/P_{max}) versus the parameter (δ_4/H_s) for different column-to-beam capacity ratio (M_c/M_b) where :

P : applied load.
P_{max} : maximum load carried by the frames.
δ_4 : inter-story drift of the fourth story.
H_s : story height

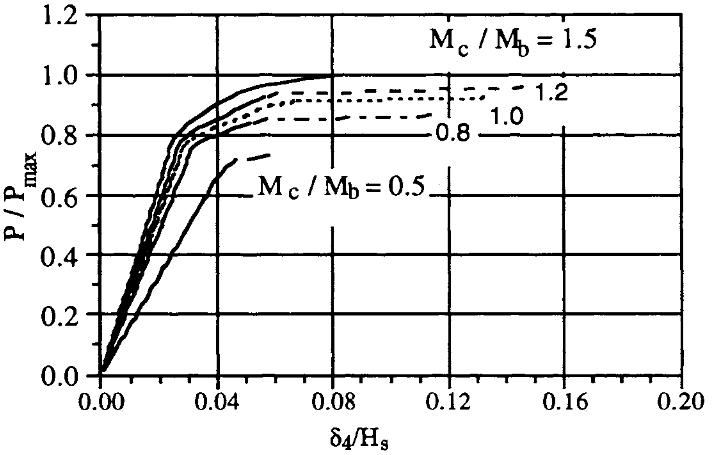


Fig. 3 Inter-Story Drift at the Fourth Story of the One-Bay Frame.

Fig. 4 shows the effect of column-to-beam capacity ratio (M_c/M_b) on the frame ductility, measured by the ratio (δ_u/δ_y).

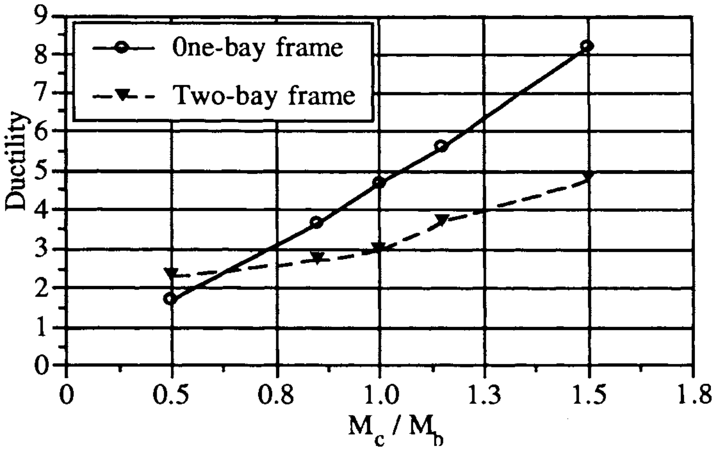


Fig. 4 Effect of Column-to-Beam Capacity on Frame Ductility

From the obtained results and the above figures, the following remarks are concluded :

i. For the one-bay frame, 9 out of 10 plastic hinges are formed in columns rather than in beams when (M_c/M_b) = 0.5. In the case of (M_c/M_b) = 1.5, only the final two plastic hinges in the mechanism take place in the bottom of the ground floor columns.
ii. For the two-bay frame, in the case of (M_c/M_b) = 0.5, 16 out of 18 plastic hinges are formed in columns reflecting the unfavourable mode of failure expected in buildings with such configuration. In the case of (M_c/M_b) = 1.5, only four plastic hinges are formed in columns.
iii. The effect of the ratio (M_c/M_b) on the frame ductility is significant where the ductility ratio increases by 482% (one-bay frame) and 209% (two-bay frame) when the ratio (M_c/M_b) increases from 0.5 to 1.5.
iv. The energy consumed (indicated by the area under the curves) increases as the ratio (M_c/M_b) increases. This reflects the increase in the building ability to absorb and dissipate the input earthquake energy.

STIFFNESS DISTRIBUTION IN ELEVATION

Distribution of stiffness in building elevation is one of the important parameters that affects the building seismic response. The significance of this parameter for the building performance is investigated in this section. Seismic response of buildings exhibit stiffness irregularity in the first or second story is studied. A brief description of the studied cases as well as discussion of the results are presented hereafter.

The response of a hypothetical four story steel building is investigated. The building is modelled by a lumped mass model and analysed using the modal analysis method. The earthquake record considered in the analysis is the Morgan Hill earthquake of 24 April, 1984. The peak ground acceleration of the record is 0.2 g. The first 8 modes are considered in the analysis and the total response is obtained by the square root of sum of squares.

Two building sets are investigated. In the first set (set I), the stiffness of the first story is changed while fixing the other story stiffnesses. In the second set (set II), the stiffness of the second story is changed while keeping the other story stiffnesses constant.

The mode shapes and their contribution in the total response are firstly investigated. Tables 1 and 2 present the effective modal mass of the first four mode shapes of set I and set II, respectively. These tables help to investigate the effect of changing the stiffness distribution on the contribution of the different mode shapes in the overall response. From these tables, it can be concluded that :

i. Stiffness distribution in building elevation significantly affects the contribution of mode shapes in the building overall response.
ii. In set I, reducing the first story stiffness to 0.2I increases the participation of the first mode shape by about 11% and reduces the contribution of the other modes by a ratio between 88% and 97.5%.
iii. In the case of I_1/I = 0.2 (set I), about 99% of the response comes from the contribution of the first mode shape.
iv. In set II, reducing the stiffness of the second story to 0.2I reduces the contribution of the first and fourth mode shapes by 8.1% and 97.5%, respectively, and increases the participation of the third mode shape by 360%.

Table 1 Effective Modal Mass - Set I

I_1/I	First Mode (%)	Second Mode (%)	Third Mode (%)	Fourth Mode (%)
1	89.29	8.33	2.08	0.40
0.8	91.55	6.99	1.28	0.18
0.6	94.03	5.18	0.70	0.19
0.4	96.63	3.04	0.30	0.03
0.2	98.92	1.00	0.07	0.01

Table 2 Effective Modal Mass - Set II

I_2/I	First mode (%)	Second Mode (%)	Third Mode (%)	Fourth Mode (%)
1	89.29	8.33	2.08	0.40
0.8	88.63	8.33	2.80	0.24
0.6	87.52	8.33	4.04	0.21
0.4	85.58	8.33	6.81	0.08
0.2	82.10	8.33	9.56	0.01

Fig. 5 shows curves plotted for the inter-story displacement of set-I versus the story stiffness ratio (I_1/I).

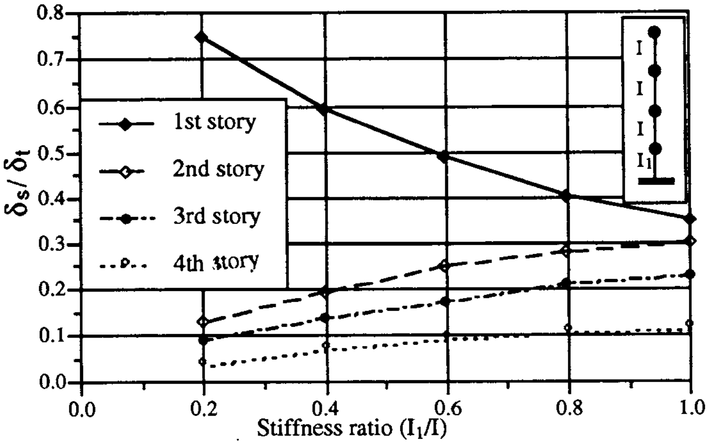


Fig. 5 Inter-Story Drift of Set I

Fig. 6 shows curves plotted for story forces versus the story stiffness ratio ($I_2/$ I) of set II.

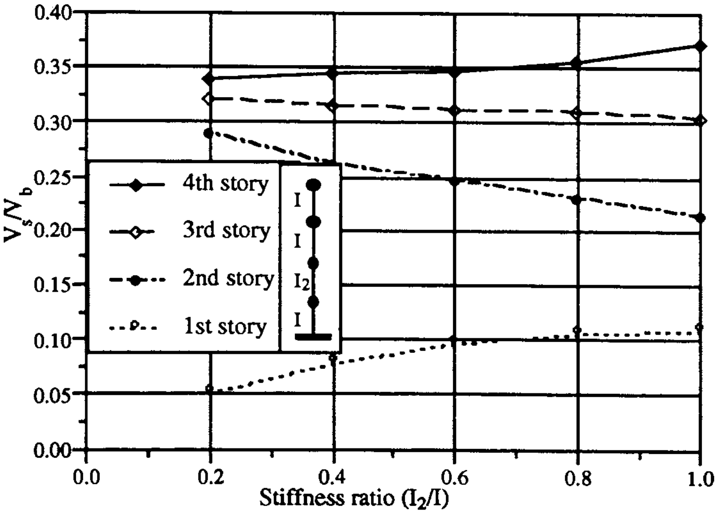


Fig. 6 Shear Force Distribution of Set II

From the obtained results and the presented figures, the following remarks are demonstrated :

i. Stiffness distribution in elevation is one of the characteristics which have a significant effect on the building response. This effect increases as the difference in the stiffness ratio of the successive stories increases.

ii. Stiffness distribution affects the period of vibration and mode shapes.This effect depends on the position and the ratio of the stiffness change.

iii. Stiffness change has a remarkable effect on the participation of mode shapes in the overall response. This effect depends mainly on the story stiffness ratio (I_s/I) and the position of the softer story.

iv. Stiffness distribution significantly affects the distribution of the inter-story drifts as follows :
   - Ductility demand increases considerably as the stiffness ratio decreases. It is obtained that as the story stiffness ratio reaches 0.2, 75% and 70% of the total drift are concentrated at the first and the second stories for sets I and II respectively.
   - In set I, when the stiffness ratio changes from 1.0 to 0.2, the displacement ratio of the first story becomes 2.14 times the corresponding ratio of the control case.
   - In set II, the displacement ratio of the second story becomes twice the corresponding value of the control case as the stiffness ratio changes from 1.0 to 0.2.
   - The displacement ratio of soft story is inversely proportional to stiffness ratio. The drift of soft stories can be determined from the following relationship :

$$\delta_s = F_d \times \delta \qquad (1)$$

$$F_d = 2.5 - 1.5\ I_r \qquad (2)$$

where :

δ_s : drift of soft story.

δ : story drift of the regular case.

F_d : factor of soft story drift.

I_r : story stiffness ratio = (I_s/I), ≤ 1 and ≥ 0.2.

v. Story forces are remarkably affected by stiffness distribution. From the obtained results the following remarks can be demonstrated :
   - An increase in shear forces of 91% and 35% is observed in the first story (set I) and second story (set II), respectively, when the stiffness ratio decreases from 1 to 0.2.
   - Shear forces of soft story is inversely proportional to the stiffness ratio. The following relationship relates the shear forces of the soft story to the corresponding value of regular stiffness distribution condition :

$$Q_s = F_f \times Q \qquad (3)$$

$$F_f = 2.25 - 1.25\ I_r \quad \text{Set I} \qquad (4\text{-a})$$

$$F_f = 1.5 - 0.5\ I_r \quad \text{Set II} \qquad (4\text{-b})$$

where :

Q_s : soft story force.

Q : story force of the regular case.

F_f : factor of soft story force.

BUILDINGS WITH SETBACK

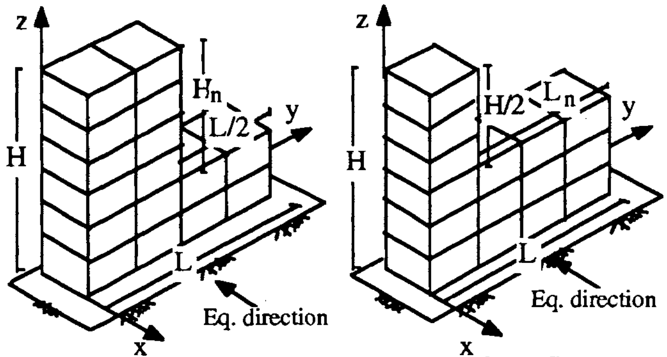
Investigation of the behaviour of setback-type buildings is seriously needed to get more information for seismic design of this kind of buildings. In order to assess the effect of setback irregularity on the seismic response, a set of buildings exhibiting setbacks is studied. A building with regular configuration served as a control model. A brief description of the studied cases and the obtained results is presented.

Model Used in the Analysis

The model used in this study is a 6-story hypothetical steel building whose typical frame consists of columns spaced at 4 meters on centre in both the transverse and longitudinal directions with interconnecting floor girders in each direction. The considered building is modelled as a space frame with one element per member. The analysis is performed by the finite element program ADAPTIC [1]. The element used is a quartic elastic 3-dimensional beam–column element. Concentrated mass elements are used to model the building mass. Typical solid square sections are used for beams and columns. The used material model is elastic with strain hardening.

Case Studies

In this study, several setback configurations are considered to investigate the effect of the asymmetry setbacks on the building seismic performance. Two groups of setback configurations are used. In Group I, the setback length is fixed at the building mid length (L/2) while its height (H_n) is changed (Fig. 7-a). Five cases are included in this group where the setback height is changed from one to five stories, (case studies B, C, D, E and F). In Group II, the setback is fixed at the building mid height (H/2) while changing its length (L_n) (Fig. 7-b). Three cases are considered in this group where the setback length is changed from one to three bays, (case studies G, D and H).



(a) Group I (b) Group II

Fig. 7 Setback Configurations Considered in the Analysis

Eigenvalue Analysis

The effect of setback dimensions on mode shapes and periods of vibration is illustrated in this section. From the obtained results, the following remarks are concluded :

i. The first five mode shapes of all the studied cases are as follows :
   - Mode 1 : sway in x direction.
   - Mode 2 : sway in y direction.
   - Mode 3 : rotation.
   - Mode 4 : sway in x direction, second mode.
   - Mode 5 : sway in y direction, second mode.

ii. The first sway mode shape in x direction is significantly affected by the presence of setbacks where torsional movements take place in this mode in all the cases of setback.

iii. The setback effects on the torsional vibrations is more pronounced at the setback level.

iv. Torsional vibrations increase as the setback dimensions (height and length) increase.

Time History Analysis

The pre-shown 3-dimensional model is analysed under the acceleration excitation of the Morgan Hill earthquake of 24 April, 1984, which has a peak ground acceleration of 0.2g. The acceleration excitation is applied synchronously at the ten supports fixing the structure in the x direction. The Newmark's beta method with beta value of 0.25, gamma value of 0.5 and integration step of 0.001 sec. are used for the numerical integration.

Displacement response

The significance of setback configuration for the distribution of inter-story drifts and torsional movements is illustrated in this section.

Group I (variable setback height)

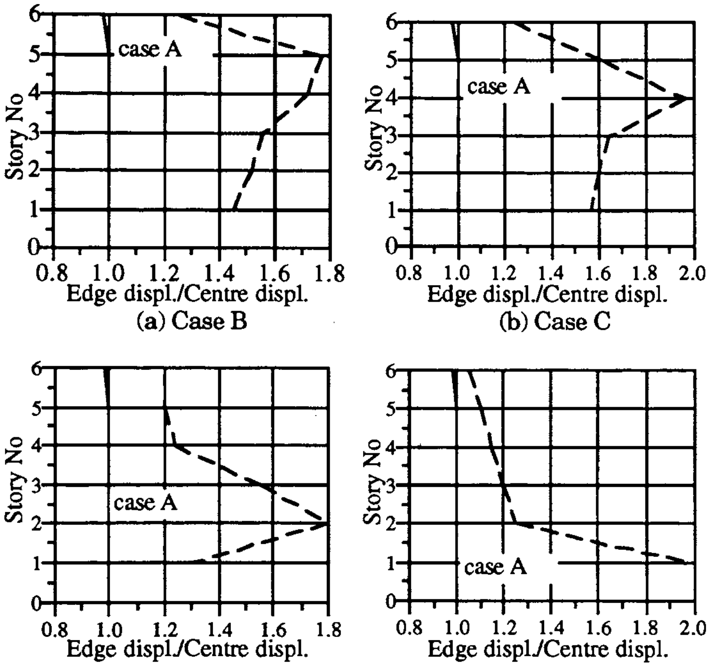
The effect of setback height on building torsional response is illustrated in Fig. 8. In this figure, curves are plotted for the displacement ratio of corner nodes and centre nodes (δ_e/δ_c) at each floor level of cases B, C, E, and F. The figure shows that the presence of setbacks causes severe torsional movements which increase the displacements of corner nodes and lead to a corresponding increase in the ductility demand of perimeter elements. This effect is more pronounced at the setback level where the displacement of corner nodes are about 1.6-2.0 times the displacement of centre nodes at that level.

Group II (variable setback length)

The ratio of the maximum displacement of corner and centre nodes (δ_e/δ_c) for the first three stories is plotted in Fig. 9. From this figure, it can be concluded that the torsional effect of setbacks increases as the setback length increases where the ratio (δ_e/δ_c) reaches 2.2 in case H (setback length ratio = 0.75).

Resulting forces

The effect of setback configuration on the distribution of story forces in the two principal directions are presented in this section.



(a) Case B (b) Case C

(c) Case E (d) Case F

Fig.8 Displacement Ratio of Edge and Centre Nodes-Group I

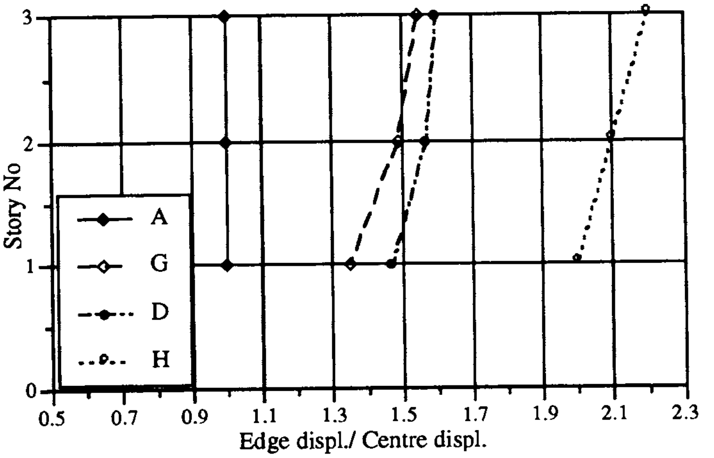


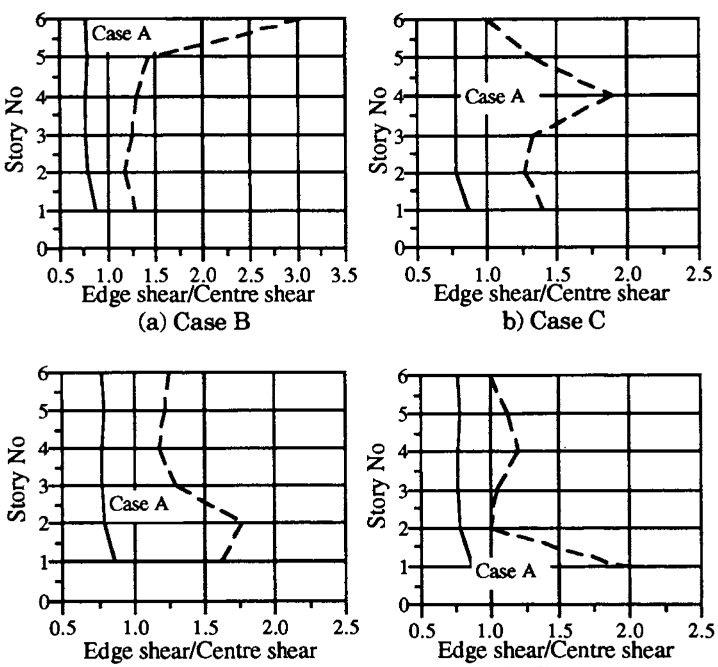
Fig. 9 Displacement Ratio of Edge and Centre Nodes-Group II

Group I (variable setback height)

The effect of setback height on the strength demand of perimeter elements is shown in Fig. 10 where curves are plotted for the force ratio of edge and centre elements (V_e/V_c). This figure reflects the pronounced effect of setbacks on the force distribution among the story members where the ratio of the forces created in corner and centre elements is between 1.75 and 3.

Group II (variable setback length)

The ratio of the maximum forces of edge and centre elements (V_e/V_c) for the first three stories are plotted in Fig. 11. This figure shows that the increase in strength demand of the perimeter elements is proportional to setback length.



(a) Case B b) Case C

(a) Case D b) Case E

Fig. 10 Shear Ratio of Edge and Centre Elements-Group I

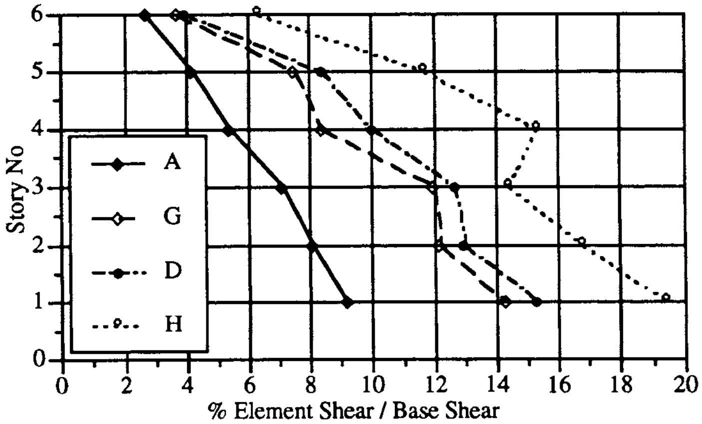


Fig. 11 Shear Ratio of Edge and Centre Elements-Group II

Fig. 12 illustrates the effect of setback length on the force distribution in elevation. From this figure it can be concluded that increasing the setback length (L_n) increases the forces created in corner elements while it slightly affects force distribution in elevation.

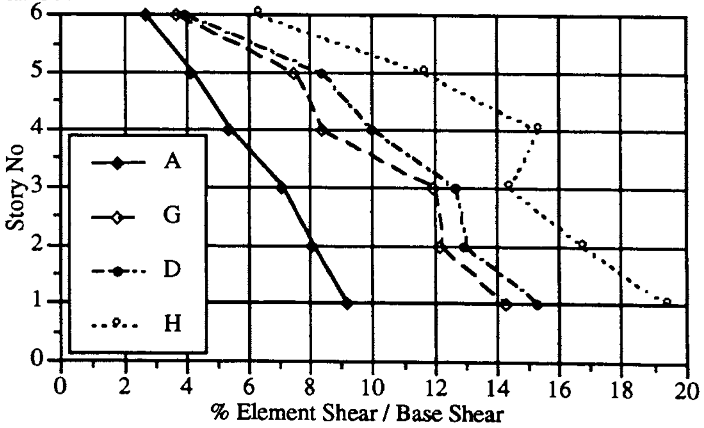


Fig. 12 Shear Distribution of Corner Elements-Group II

Discussion of results

From the obtained results and the shown figures the following remarks and conclusions are presented :

Displacement response

i. In all cases, the maximum torsional response is noticed at the setback level.
ii. Edge node displacements of 1.6-2.0 times centre node displacements take place at the setback level of Group I.
iii. In group II, displacements of corner nodes reach 1.6-2.25 times displacements of centre nodes.
iv. Lateral movements of 13 to 24 % of the longitudinal movements take place in buildings with setbacks while the corresponding value of the control case (case A) does not exceed 1 %.

Resulting forces

i. Setbacks alter the distribution of forces among story elements where forces of perimeter members increases substantially. It is obtained that shear forces of perimeter members reaches twice, or more in some case, the values of centre elements.
ii. The strength demand of perimeter members increases as the setback length increases. For setback length ratio of 0.25 and 0.75, the forces created in corner elements reach 1.5 and 2.25 times the corresponding forces of centre elements, respectively.
iii. The presence of setbacks creates forces in the lateral direction of values up to 0.6 the values in the loading direction.

SUMMARY AND CONCLUSIONS

The effect of column height on the building performance is investigated. The obtained results show that the shear forces attracted by short columns is too high to be accommodated. Short column effect becomes pronounced when the column height is less than 0.75 of the Story height. Beyond this limit, the column should be carefully designed and detailed so that it can accommodate the expected shear forces and achieve the demand ductility level.

The behaviour of 4-Story one and two-bay plane frames with variable column-to-beam flexural capacity ration are studied to quantify the significance of column-to-beam capacity for the failure mode and the ductility demand of buildings. It is obtained that the frame ability to absorb and dissipated the input earthquake energy increases as the column-to-beam capacity ratio (M_c/M_b) increases. Building ductility increases considerably by increasing the ratio (M_c/M_b). The ductility of the one and two-bay frames increases by 482% and 209%, respectively when the ratio (M_c/M_b) increases from 0.5 to 1.5.

The effect of stiffness distribution in elevation on the building seismic response is also investigated. Story stiffness ratio changes from 1.0 to 0.2 of the stiffness of the regular case is considered in the analysis. From this study, it is concluded that stiffness change has a remarkable effect on the participation of mode shapes in the overall response. Also, it affects the value and the distribution of inter-Story drifts and Story forces. This effect is pronounced at the softer story and is inversely proportional to the stiffness ratio

The seismic response of a six-Story steel building exhibiting setbacks of different configurations is investigated. The building is modelled as a space frame and analysed under an acceleration excitation using the time history analysis technique. From this study it can be concluded that :
i. The presence of setback, regardless its dimensions, leads to torsional vibration where the displacements of corner nodes reach 2.25 times the corresponding values of centre nodes.
ii. Setbacks alter the distribution of forces along the building elevation and among the Story elements. The shear forces of perimeter members reaches twice, or more in some case, forces of centre elements.
iii. The strength demand of perimeter members increases as the setback length increases. It is obtained that, for setback length ratio of 0.25 and 0.75 the forces created in corner elements reach 1.5 and 2.25 times the corresponding values of centre elements, respectively.
iv. The presence of setback creates forces and displacements in the lateral direction up to 0.6 and 0.23 of the corresponding values in the loading direction, respectively.
v. Torsional effect of setbacks can not be neglected even in cases of small setbacks. It is obtained that, for a 25% setback, which is allowed in most codes, an increase of 40 to 50% in the forces and drifts of perimeter members at the setback level must be considered in the design.

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