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# Seismic Retrofitting of RC Buildings with Soft Storey and Floating Columns

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***Abstract*****—**Open ground storey with floating columns is a typical feature in the modern multistory constructions in urban India. Such features are very much undesirable in buildings built in seismically active areas. The present study proposes a feasible solution to mitigate the effects caused due to non-uniformity of stiffness and discontinuity in load path and to simultaneously hold the functional use of the open storey particularly under the floating column, through a combination of various lateral strengthening systems. An investigation is performed on an example building with nine different analytical models to bring out the importance of recognising the presence of open ground storey and floating columns. Two separate analyses on various models of the building namely, the equivalent static analysis and the response spectrum analysis as per IS: 1893-2002 were performed. Various measures such as incorporation of Chevron bracings and shear walls, strengthening the columns in the open ground storey, and their different combinations were examined. The analysis shows that, in comparison to two short ones separated by interconnecting beams, the structural walls are most effective when placed at the periphery of the buildings and used as one long structural wall. Further, it can be shown that the force transfer from floating columns becomes less horizontal when the Chevron Bracings are placed just below them, thereby reducing the shear forces in the beams on which the floating column rests.

***Keywords*****—**Equivalent static analysis, floating column, open ground storey, response spectrum analysis, shear wall, stiffness irregularity.

## I. Introduction

TODAY many multi-storey buildings located in urban areas have an open ground storey with floating columns as an unavoidable feature. This structural feature is primarily being adopted to accommodate parking or reception lobbies in the ground storey. However, poor performances of such buildings worldwide have been known for almost a century. However, there must be compelling reasons (e.g., aesthetics and functionality) other than safety that continues to push the construction of such buildings even today. When all unreinforced masonry (URM) infills are removed in the ground storey, the building is significantly weakened in the ground storey, but it is strong in the upper storeys owing to a large contribution to lateral stiffness by the URM infills. Open ground storey buildings are inherently poor systems because of stiffness irregularity and strength discontinuity along the height of the buildings. If the columns are weak, they may be severely damaged, which may even lead to the collapse of the building.

For seismic retrofitting of Reinforced Concrete (RC) buildings, a recent survey of methods and techniques used such as concrete jacketing of columns of ground floor, brick masonry infill in the ground floor, X and V bracing, shear wall, FRP of beams and columns, was conducted [1]. Also, the soft first story irregularity condition of buildings was reviewed [2], and various retrofitting measures were found effective to reduce storey drift [3]-[5], increase strength and lateral stiffness of the columns in the soft storey [6]. According to a study, introduction of the X-plate energy dissipater (XPD) connection at ground storey also overcomes the global deficiency of the open storey [7]. Moreover, it was observed that in the soft storey of a building, when stiffer columns were provided, there was reduction in the lateral drift demand on the soft-storey columns, and when a concrete service core was provided, there was a reduction in the drift as well as the strength demands on the soft storey columns [8]. In a study, when an equivalent static analysis was performed for the seismic response of Reinforced Cement Concrete (RCC) building with soft storey, it was concluded that minimum displacement for corner column was observed in the building in which a shear wall was introduced in X-direction as well as in Z-direction [9]. In another seismic analysis of a multistoried building with soft first storey, shear wall and cross bracings helped in reducing the stiffness irregularity and bending moment in the columns [10].

Another strengthening measure like retrofitting the existing columns was also studied to achieve ductile performance, and for that, the use of FRP wrapping was suggested for the retrofitting of the deficient columns [11]. The behaviour of multi-storey building with and without floating column was also studied under different earthquake excitations where the compatible time history and Bhuj earthquake data were considered and it was concluded that, by increasing the column size, the maximum displacement and inter-storey drift values were reduced [12].

The present study attempts to explore different alternatives to strengthen the existing open ground storey buildings with floating columns, to prevent them from collapsing during strong earthquake shaking. The methodology envisages that stiffness regularity and continuity in load path is maintained to

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increase seismic safety of the buildings.

The present study has been organized into sections. Stiffness irregularity and discontinuity in load path is dealt in Sections II and III, respectively. Section IV describes the characteristics of the building studied and nine different analytical models. Section V discusses about the static and dynamic analysis performed on the various models of the building. Section VI presents the results and their discussions and Section VII deals with the conclusions of the study.

## II. Stiffness Irregularity: Open Storey

Open ground storey RC frame buildings are very common in Indian urban cities. Today, they have become the prevalent set of urban buildings. When the glass is used as an infill material in the open ground storey for outlook instead of brick masonry infill walls, the building becomes very weak or flexible in that storey [13]-[16]. This happens usually in buildings where shops and restaurants prevail in their ground storey.

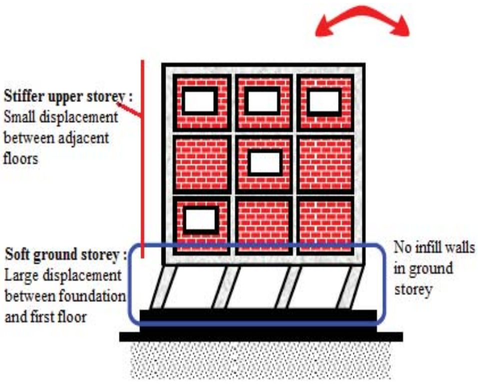


Fig. 1 Stiffness irregularity due to absence of infill walls in open ground storey

Irregularity with respect to lateral stiffness occurs when the sizes of the lateral load resisting members in the building are varied along the building height, and extra members are added or the existing ones are removed. The markdown of the lateral stiffness leads to the increase in the deformation demand in storeys with less stiffness, thereby, called the soft or weak or flexible storey (Fig. 1).

A building with open ground storey, with only columns in its soft storey and both partition walls and the columns in its upper storeys have generally two distinct features:

a) It is very flexible in open ground floor, which leads to the increase in the relative displacement in horizontal direction as compared to that of the upper stories.
b) It is very weak in the open storey which leads to the reduction in the capacity of resistance against earthquake forces as compared to that of the upper stories.

## III. Discontinuity in Load Path

Another mundane feature comes with a floating column, which is the discontinuity in its load path in RCC moment frames. When an RCC column coming from top of a building is terminated at an intermediate level, generally at the ground floor, then the load path does not remain vertical as it is not continuous till foundation. It rather transfers its load to a horizontal member which has not been designed to take them [17]-[19]. This leads to the impairment of that member on which the floating column rests (Fig. 2). The floating column is used for the purpose of architectural view and site situations.

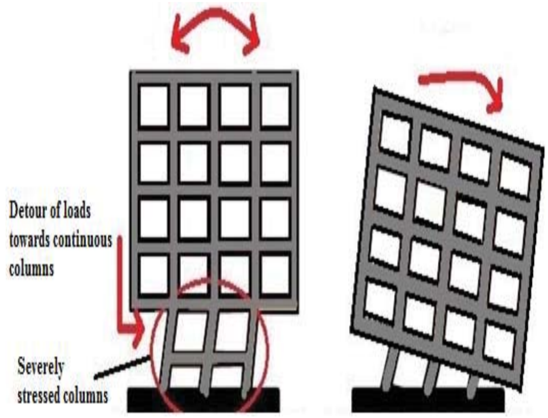


Fig. 2 Overloading of columns in ground storey cause failure during strong earthquake shaking

## IV. Building Studied

The layout plan and elevation of the RC moment resisting frame building with open ground storey having floating columns and unreinforced brick infill walls in the upper storeys, which is chosen for this study is shown in Figs. 3 and 4, respectively. Further, the columns are taken to be square to keep the discussion focused only on soft storey and floating column effect, without being distracted by the issues like orientation of columns. The building is considered to be located in seismic zone V. The soil conditions are medium stiff, and the entire building is supported on isolated footings. The RC frames in the upper storeys are infilled with brick masonry. The stiffness of the infills is represented in the structural model by Equivalent Diagonal Struts [20]. The lumped weight due to dead loads is 12 $kN/m^2$ on floors and 10 $kN/m^2$ on the roof. The floors are to cater for a live load of 4 $kN/m^2$ on floors and 1.5 $kN/m^2$ on the roof. The elastic moduli of concrete and masonry are taken as 21718.5 MPa and 3500 MPa, respectively, and their Poison's ratio as 0.17 for concrete and 0.2 for brick masonry. The unit weights of concrete and masonry are taken as 25 $kN/m^3$ and 20 $kN/m^3$. In the seismic weight calculations, only 50% of the floor live load is considered.

The columns used in the building are of size 400x400 mm. However, the four columns adjacent to the middle floating columns have been kept of size 500x500 mm (Fig. 5). The beams used are of size 230x450 mm, whereas some of the open ground storey roof beams (or stilt roof beams) on which floating columns rest, are taken as deep beams of size

400x900 mm (Fig. 6).

The concrete bracings used from the floating columns to the adjacent vertical columns (either end joints or mid-span) are taken of size 400x400 mm. Wherever used in the model, the bracings have been incorporated into the strengthened set-back columns of size 600x600 mm and the strengthened columns, adjacent to the middle floating column, of size 700x700 mm. The structural walls used in the open ground storey are of thickness 230 mm. The incorporation of shear walls and the strengthening of columns have been continued up to the foundation level.

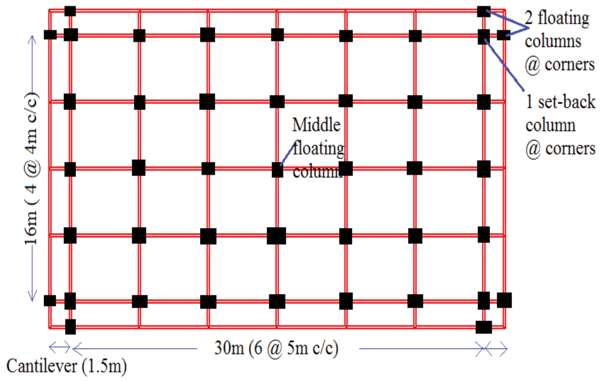


Fig. 3 Building Plan

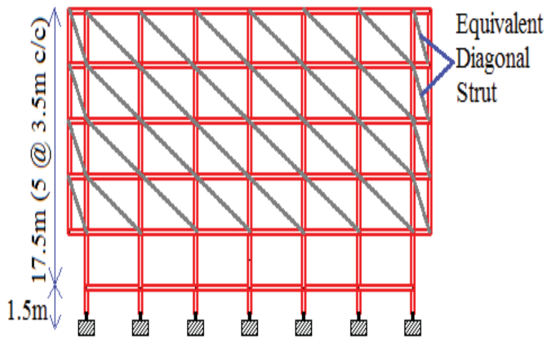


Fig. 4 Distribution of height of the building

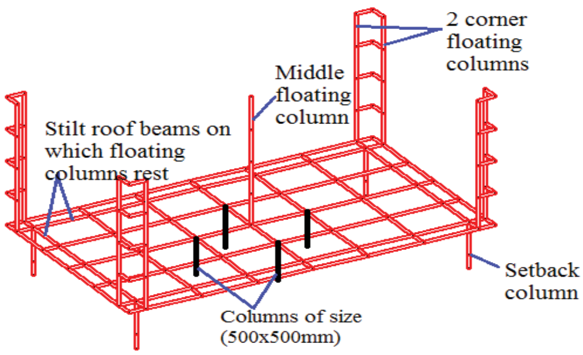


Fig. 5 Positioning of floating columns resting on ground roof beams

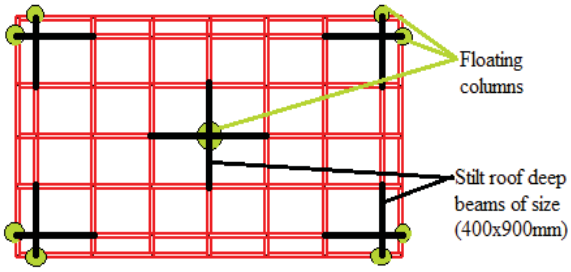


Fig. 6 Beams on which floating columns rest

The nine different models of the building studied are:

- Model 1: Building has neither shear walls nor lateral bracings in the ground storey and half brick masonry wall (115 mm) in the upper storeys (Fig. 7).
- Model 2: Building has four shear walls (in inner bays) in the ground storey (Fig. 8).
- Model 3: Building has four shear walls (at periphery) in the ground storey (Fig. 9).
- Model 4: Building has six shear walls (one wall in each strong direction and two separate walls in each weak direction) in the ground storey (Fig. 10).
- Model 5: Building has four shear walls (one wall in each strong direction and two combined structural walls in each weak direction) in the ground storey (Fig. 11).
- Model 6 (i): Building has concrete bracing (in weak direction only) from the middle floating column to the end joints of adjacent vertical columns which have also been strengthened (Fig. 12).
- Model 6 (ii): Building has concrete bracing from all the corner floating columns to the end joints of respective set-back strengthened columns (Fig. 13).
- Model 7 (i): Building has concrete bracing (in weak direction only) from the middle floating column to the mid-span of adjacent vertical strengthened columns (Fig. 14).
- Model 7 (ii): Building has concrete bracing from all the corner floating columns to the mid-span of respective set-back strengthened columns (Fig. 15).
- Model 8: Combination I (Model 3+Model 7) (Fig. 16).
- Model 9: Combination II (Model 5+Model 7) (Fig. 17).

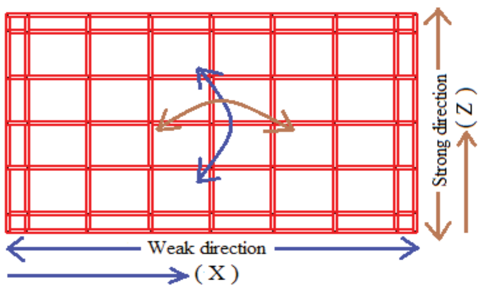


Fig. 7 Model 1

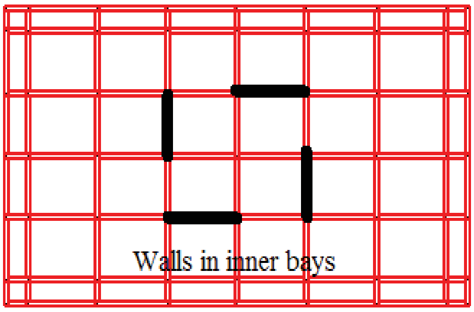


Fig. 8 Model 2

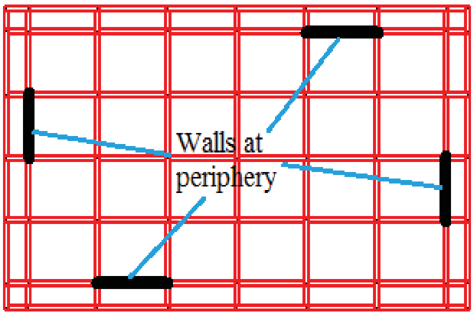


Fig. 9 Model 3

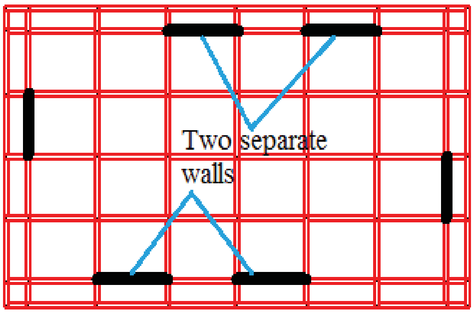


Fig. 10 Model 4

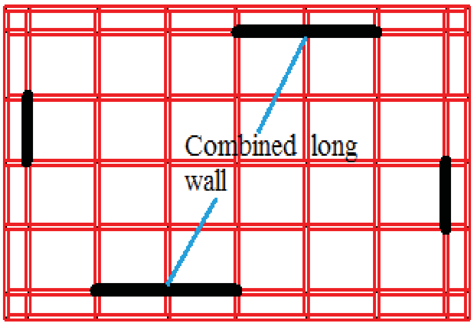


Fig. 11 Model 5

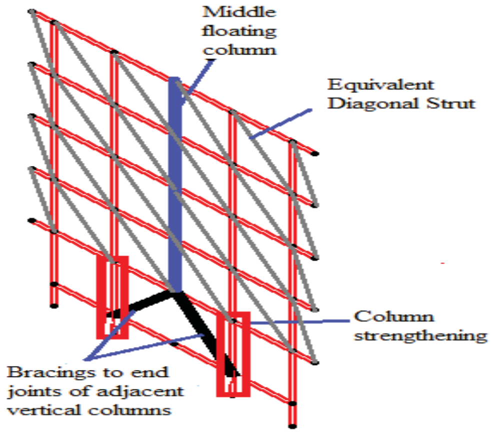


Fig. 12 Model 6(i)

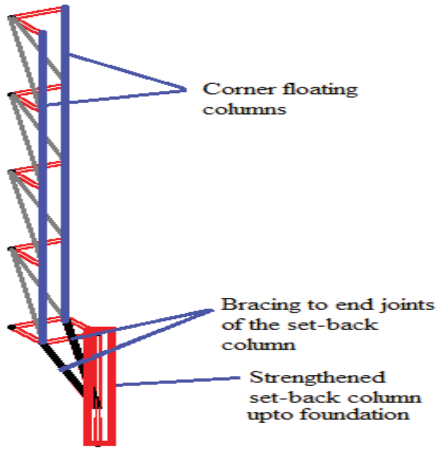


Fig. 13 Model 6(ii)

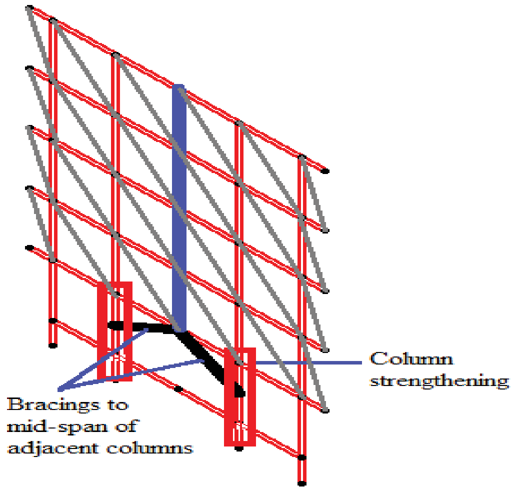


Fig. 14 Model 7(i)

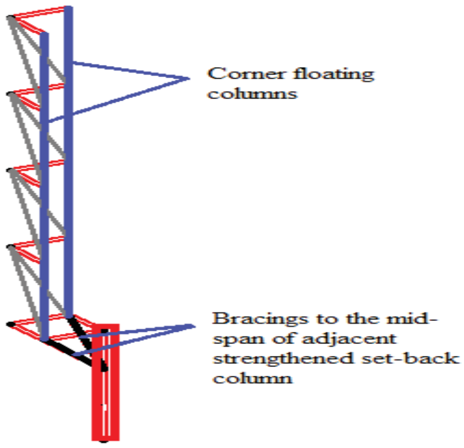


Fig. 15 Model 7(ii)

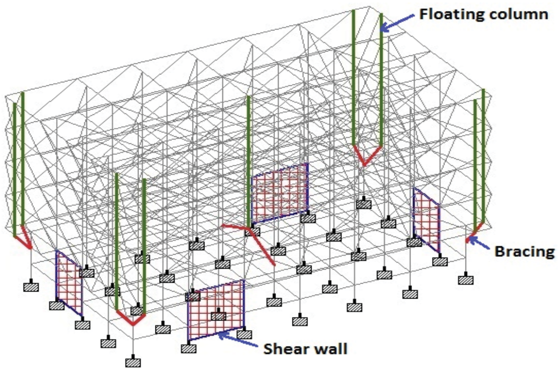


Fig. 16 Model 8 (combination I: Model 3 + Model 7)

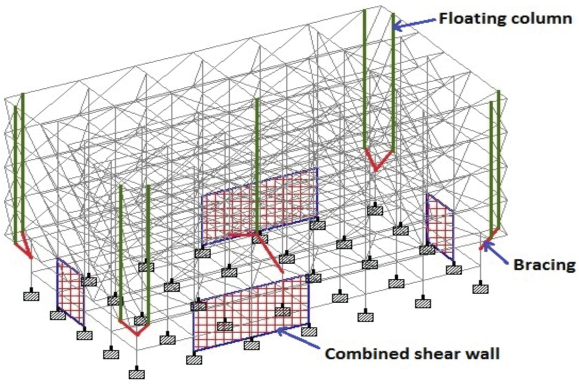


Fig. 17 Model 9 (combination II: Model 5 + Model 7)

## V. Analysis of the Building

The two different analyses performed on the various models of the building considered in this study are the equivalent static analysis and the response spectrum analysis, as per IS:1893-2002 [21]. These analyses are performed by using STAAD.Pro [22].

### A. Equivalent Static Analysis

The fundamental natural period of vibration ($T_a$), in seconds, of moment resisting frame buildings with brick infill panels is estimated by the empirical expression:

$$T_a = \frac{0.09h}{\sqrt{d}} \quad (1)$$

where, h = height of the building, in m, d = base dimension of building at the plinth level, in m, along the considered direction of the lateral force.

The design lateral force shall first be computed for the building as a whole. It shall then be distributed to the various floor levels. The total design seismic base shear ($V_b$) along any principal direction is determined by:

$$V_b = A_h * W \quad (2)$$

where, $A_h$ = design horizontal acceleration spectrum value, using the fundamental natural period $T_a$ in the considered direction of vibration, W = Seismic weight of the building.

### B. Response Spectrum Analysis (Dynamic Analysis)

Based on various ground motion records, the response spectrum represents an envelope of upper bound responses.

The design lateral force at each floor in each mode is computed according to:

$$Q_{ik} = A_k * \Phi_{ik} * P_k * W_i \quad (3)$$

where, $A_k$= design horizontal acceleration spectrum value using the natural period of vibration ($T_k$) of mode k. $\Phi_{ik}$= mode shape coefficient at floor i in mode k, $P_k$=modal participation factor of mode k, $W_i$= seismic weight of floor i.

The peak storey shear force in storey i due to all considered modes is obtained by combining those due to each mode in accordance with using Square Root of Sum of Square (SRSS) combination given by:

$$\lambda = \sqrt{\sum_{k=1}^{r} (\lambda_k)^2} \quad (4)$$

where, $\lambda_k$ = absolute value of peak response quantity in mode k, r = number of modes being considered.

## VI. Results and Discussion

### A. Fundamental Periods

The static and dynamic (IS:1893-2002) natural periods of the building models are shown in Table I. It is observed that the fundamental natural period is reduced when shear walls are introduced in the building (Model 2, 3, 4, 5).

Interestingly, it is seen that torsion has become the first mode of oscillation in the Model 2, due to a drastic increase in the fundamental natural period in torsion. The Building Models 2 and 3 have the same number and the size of the shear walls but at separate locations such as, shear walls in the inner bays and at the periphery of the building (Figs. 8 and 9), respectively. Generally, by keeping the same shear walls near the centre of the building, the tendency of the building to undergo torsion is indirectly led. This unwanted torsion occurred because of an eccentricity between the centre of mass and centre of rigidity. Hence, the shear walls are the most impressive when usually kept at the periphery of the buildings.

TABLE I
FUNDAMENTAL NATURAL PERIOD

| Model | Fundamental Natural Period (s) | | | | |
|---|---|---|---|---|---|
| | X-Direction | | Z-Direction | | Torsion |
| | Static | Dynamic | Dynamic | Static | |
| 1 | 0.312 | 0.389 | 0.428 | 0.426 | 0.389 |
| 2 | 0.312 | 0.348 | 0.428 | 0.380 | 0.988 |
| 3 | 0.312 | 0.373 | 0.428 | 0.413 | 0.384 |
| 4 | 0.312 | 0.357 | 0.428 | 0.408 | 0.383 |
| 5 | 0.312 | 0.311 | 0.428 | 0.409 | 0.382 |
| 6 | 0.312 | 0.381 | 0.428 | 0.417 | 0.388 |
| 7 | 0.312 | 0.381 | 0.428 | 0.418 | 0.388 |
| 8 | 0.312 | 0.354 | 0.428 | 0.406 | 0.382 |
| 9 | 0.312 | 0.307 | 0.428 | 0.402 | 0.380 |

### *B. Lateral Deformation*

The lateral displacement profiles of the various models for the two different analyses performed in this study are shown in Fig. 18. In these figures, the abrupt changes in the slope of the profile stipulate the stiffness irregularity. The displacements at ground and first floor level are shown in Tables II and III. It is observed that the displacements are reduced when shear walls are introduced (Model 2, 3, 4, and 5).

TABLE II
LATERAL DEFORMATION (STATIC ANALYSIS)

| Model | Displacement (mm) | | | |
|---|---|---|---|---|
| | X-Direction | | Z-Direction | |
| | Ground Floor | First Floor | Ground Floor | First Floor |
| 1 | 6.297 | 42.901 | 5.975 | 41.401 |
| 2 | 1.901 | 13.386 | 2.337 | 18.337 |
| 3 | 3.086 | 16.632 | 3.620 | 20.314 |
| 4 | 2.305 | 12.480 | 4.205 | 22.637 |
| 5 | 2.808 | 14.922 | 3.603 | 20.071 |
| 6 | 4.497 | 27.938 | 3.599 | 22.649 |
| 7 | 4.703 | 29.339 | 4.157 | 25.779 |
| 8 | 2.815 | 15.198 | 2.890 | 15.743 |
| 9 | 2.579 | 13.785 | 2.744 | 14.952 |

When Models 4 and 5 are compared, it is observed that the lateral displacement of the building in the X-direction has been considerably decreased in Model 5. The building Models 4 and 5 have same the size of the shear walls but at separate locations in the X-direction at the periphery such as two short shear walls (Fig. 10) and one combined long shear wall (Fig. 11), respectively. Since, the concerned wall area is nonetheless the same in both buildings, but the building with longer shear wall is more unyielding than the others, and thus, allows the building to be more resistant against the lateral motion, and hence, the lateral deformation has been tremendously reduced by properly using the double length shear walls. Therefore, it is beneficial to keep one long shear wall instead of the two short walls having separated by the interrelated beams.

Further, it is seen that the lateral deformation is also reduced when the Chevron Bracings are incorporated (under the floating column) in the strengthened columns of soft storey of the building (Model 6 and 7).

TABLE III
LATERAL DEFORMATION (DYNAMIC ANALYSIS)

| Model | Displacement (mm) | | | |
|---|---|---|---|---|
| | X-Direction | | Z-Direction | |
| | Ground Floor | First Floor | Ground Floor | First Floor |
| 1 | 6.343 | 43.169 | 6.611 | 46.852 |
| 2 | 2.210 | 17.966 | 2.978 | 24.937 |
| 3 | 3.502 | 18.378 | 4.179 | 23.281 |
| 4 | 2.719 | 14.474 | 5.074 | 26.573 |
| 5 | 3.346 | 17.322 | 4.264 | 23.492 |
| 6 | 4.742 | 28.766 | 3.971 | 24.989 |
| 7 | 5.070 | 30.965 | 4.518 | 27.722 |
| 8 | 3.305 | 17.341 | 3.500 | 18.769 |
| 9 | 3.157 | 16.389 | 3.312 | 17.721 |

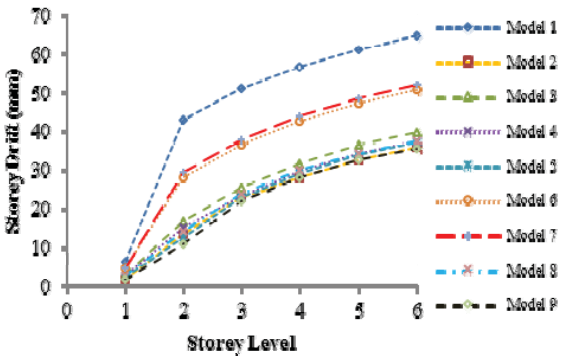


Fig. 18 (a) Lateral displacement profile by static analysis in X-direction

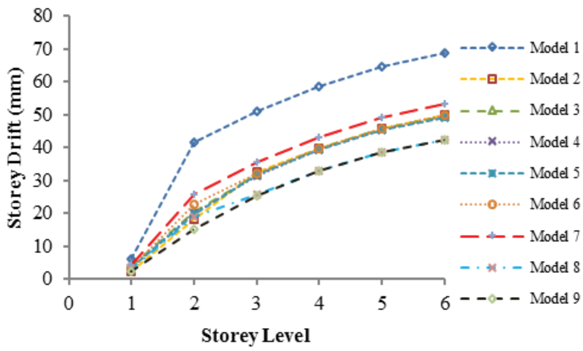


Fig. 18 (b) Lateral displacement profile by static analysis in Z-direction

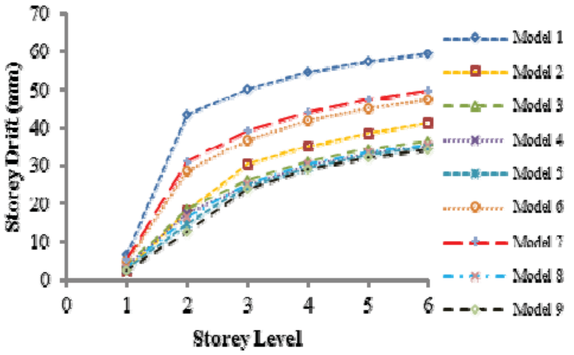


Fig. 18 (c) Lateral displacement profile by dynamic analysis in X-direction

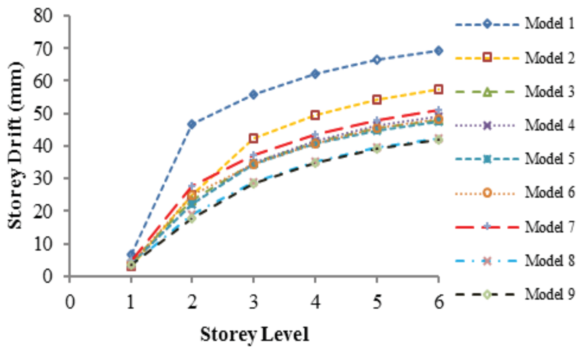


Fig. 18 (d) Lateral displacement profile by dynamic analysis in Z-direction

### *C. Shear Force in Beams on Which the Floating Columns Rest*

From Table IV and V, it is clear that the shear force demands in the beams (both the intermediate and overhang) on which floating columns rests have been exceptionally reduced in Model 6.

Introduction of the Chevron bracings, in the soft ground storey, has greatly helped in globally reducing the lateral deformation of building. In Model 1, without the braces, the transfer of forces is not vertical, which leads the beams (on which the floating columns rest) to carry the forces horizontally to the continuous columns, and get heavily stressed in shear (Fig. 19). But, after the ingression of the chevron braces in the Model 6, the transfer of forces has become less horizontal. The forces have been transferred to the beams and the columns through the brace, thereby relieving the girder beams on which the floating column rests. Therefore, for a soft ground storey, the bracings should be kept in relevant bays under the floating column so as to reduce the discontinuity in the load path of the vertical forces in a building.

Even though, the lateral deformation of the building and shear force in beams on which floating column rests, is less in Model 6 when compared with that in Model 7, the latter is preferred as it does not completely occupy the space under the floating column, and thereby, simultaneously holds the functional use of the open storey especially under the floating columns.

TABLE IV
INTERMEDIATE BEAM MAXIMUM SHEAR (KN)

| Model | Maximum Shear (kN) | | | |
|---|---|---|---|---|
| | Static Analysis | | Dynamic Analysis | |
| | SHEAR-Z | SHEAR-Y | SHEAR-Z | SHEAR-Y |
| 1 | 17.8 | 626.5 | 20.9 | 617.4 |
| 2 | 137.3 | 446.4 | 132.7 | 466.3 |
| 3 | 38.4 | 599.3 | 68.4 | 673.8 |
| 4 | 40.3 | 587.1 | 79.1 | 657.9 |
| 5 | 40.8 | 587.9 | 80.6 | 655.4 |
| 6 | 18.4 | 256.6 | 55.1 | 327.6 |
| 7 | 33.5 | 423.3 | 67.5 | 422.4 |
| 8 | 45.7 | 415.8 | 85.8 | 412.8 |
| 9 | 47.1 | 413.3 | 93.4 | 408.3 |

TABLE V
OVERHANG BEAM MAXIMUM SHEAR (KN)

| Model | Maximum Shear (kN) | | | |
|---|---|---|---|---|
| | Static Analysis | | Dynamic Analysis | |
| | SHEAR-Z | SHEAR-Y | SHEAR-Z | SHEAR-Y |
| 1 | 226.2 | 473.7 | 273.7 | 888.1 |
| 2 | 327.6 | 437.2 | 355.4 | 867.4 |
| 3 | 318.5 | 395.4 | 272.5 | 797.6 |
| 4 | 331.9 | 378.6 | 278.8 | 785.9 |
| 5 | 338.8 | 387.7 | 321.2 | 827.8 |
| 6 | 239.6 | 209.2 | 257.6 | 693.6 |
| 7 | 258.4 | 300.3 | 263.9 | 796.2 |
| 8 | 341.9 | 179.9 | 319.1 | 476.3 |
| 9 | 343.7 | 156.1 | 322.7 | 428.7 |

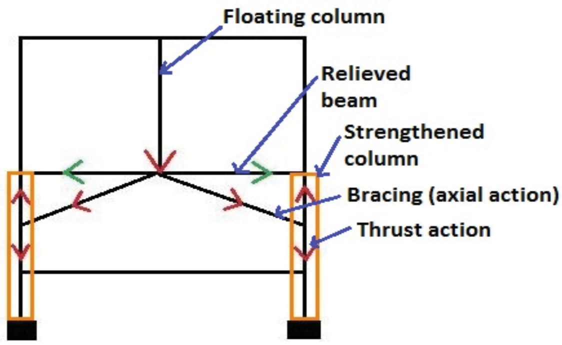


Fig. 19 Model 7 (axial and thrust action)

### *D. Maximum Forces in Ground Storey Columns (Braced Set-Back Columns and Braced Columns around Middle Floating Column)*

The maximum bending and shear forces in the columns (braced both set-back and middle) in the ground storey are shown in Tables VI, VII, VIII, IX. It is seen that the forces are reduced in the columns when the shear walls are introduced in the soft storey (Model 2, 3, 4, 5). These shear walls, because of their huge initial lateral stiffness, help in reducing the shear forces and the bending moments in the beams and columns, when provided along with the reinforced concrete moment resisting frames and by being the most crucial part of lateral load resisting system. They have also indirectly succeeded in reducing the stiffness irregularity in the building.

When Models 8 and 9 are compared, both models are combination of all the lateral strengthening techniques discussed. Both lateral strengthening techniques, i.e. the structural or shear walls and the Chevron braces under the floating column in the strengthened columns, are incorporated in the building to get the best structural configuration in terms of seismic resistance.

TABLE VI
BRACED SET-BACK COLUMN MAXIMUM MOMENT

| Model | Square Column Size (mm) | Maximum Moment (kNm) | | | |
|---|---|---|---|---|---|
| | | Static Analysis | | Dynamic Analysis | |
| | | MOM-Z | MOM-Y | MOM-Z | MOM-Y |
| 1 | 400 | 549.9 | 403.6 | 608.7 | 634.6 |
| 2 | 400 | 285.6 | 323.7 | 404.5 | 566.4 |
| 3 | 400 | 104.4 | 57.8 | 93.5 | 43.6 |
| 4 | 400 | 103.3 | 57.8 | 92.4 | 48.8 |
| 5 | 400 | 99.7 | 57.3 | 94.1 | 46.3 |
| 6 | 600 | 486.1 | 527.6 | 489 | 607.7 |
| 7 | 600 | 770.2 | 544.4 | 873.7 | 605.2 |
| 8 | 600 | 468.6 | 386.7 | 440.6 | 208.8 |
| 9 | 600 | 462.1 | 384.4 | 446.1 | 209.7 |

TABLE VII
BRACED SET-BACK COLUMN MAXIMUM SHEAR

| Model | Square Column Size (mm) | Maximum Shear (kN) | | | |
|---|---|---|---|---|---|
| | | Static Analysis | | Dynamic Analysis | |
| | | SHEAR-Z | SHEAR-Y | SHEAR-Z | SHEAR-Y |
| 1 | 400 | 212.7 | 264.6 | 366.3 | 287.7 |
| 2 | 400 | 172.2 | 136.2 | 333.8 | 192.4 |
| 3 | 400 | 14.6 | 38.1 | 34.6 | 34.2 |
| 4 | 400 | 14.3 | 37.8 | 34.7 | 33.9 |
| 5 | 400 | 14.4 | 35.9 | 34.1 | 32.6 |
| 6 | 600 | 271.7 | 220.2 | 306.6 | 296.4 |
| 7 | 600 | 350.2 | 843.4 | 838.1 | 923.8 |
| 8 | 600 | 187.9 | 320.7 | 263.5 | 300.8 |
| 9 | 600 | 186.0 | 310.2 | 255.7 | 291.2 |

TABLE VIII
BRACED MIDDLE COLUMN MAXIMUM MOMENT

| Model | Square Column Size (mm) | Maximum Moment (kNm) | | | |
|---|---|---|---|---|---|
| | | Static Analysis | | Dynamic Analysis | |
| | | MOM-Z | MOM-Y | MOM-Z | MOM-Y |
| 1 | 400 | 813.6 | 1247.1 | 818.3 | 1237.4 |
| 2 | 400 | 50.2 | 527.8 | 21.5 | 648.6 |
| 3 | 400 | 506.5 | 1163.7 | 593.8 | 1490.8 |
| 4 | 400 | 478.3 | 1132.5 | 584.9 | 1439.2 |
| 5 | 400 | 480.1 | 1128.3 | 583.1 | 1434.7 |
| 6 | 700 | 1313.4 | 304.6 | 1402.4 | 188.3 |
| 7 | 700 | 1418.8 | 1694.6 | 1544.6 | 1675.1 |
| 8 | 700 | 1058.9 | 1640.7 | 1256.7 | 1933.9 |
| 9 | 700 | 1011.2 | 1630.4 | 1230.1 | 1918.6 |

For severe requirements, combination Model 8 can be preferred, where a single structural wall in each direction is placed along with the braces. Moreover, for moderate requirements, combination Model 9 can be preferred, where a long combined structural wall in a particular direction is placed along with the braces.

TABLE IX
BRACED MIDDLE COLUMN MAXIMUM SHEAR

| Model | Square Column Size (mm) | Maximum Shear (kN) | | | |
|---|---|---|---|---|---|
| | | Static Analysis | | Dynamic Analysis | |
| | | SHEAR-Z | SHEAR-Y | SHEAR-Z | SHEAR-Y |
| 1 | 400 | 597.7 | 450.4 | 592.6 | 474.2 |
| 2 | 400 | 244.5 | 11.8 | 302.3 | 14.3 |
| 3 | 400 | 556.6 | 281.6 | 715.5 | 347.9 |
| 4 | 400 | 538.1 | 265.1 | 687.9 | 340.1 |
| 5 | 400 | 536.4 | 267.5 | 685.1 | 343.6 |
| 6 | 700 | 30.3 | 637.2 | 29.3 | 727.2 |
| 7 | 700 | 1555.4 | 709.6 | 1535.4 | 816.4 |
| 8 | 700 | 1502.8 | 532.8 | 1787.2 | 674.3 |
| 9 | 700 | 1510.2 | 509.4 | 1779.6 | 654.7 |

## VII. CONCLUSION

RC frame buildings with open ground storeys and floating columns are known to perform poorly during strong earthquake shaking. In this paper, the seismic vulnerability of buildings with soft ground storey and floating columns is shown through an example building. The lateral deformation and the strength demands in the ground storey columns are very large for buildings with soft ground storeys. It is not easy to provide such capacities in the columns of the ground storey. Thus, it is clear that such buildings will exhibit poor performance during a strong earthquake shaking. This dangerous feature of Indian RC frame buildings needs to be recognized immediately, and necessary measures need to be taken to improve the performance of the buildings.

The soft ground storey has become a very important and useful requirement of almost every multi-storey building in the urban cities, and therefore, cannot be exterminated. Sometimes, the floating columns also become necessary to hold the purpose of open spaces in the ground storey. Various measures can help in overcoming these peculiar situations of an open ground storey along with the floating columns in a building. The under-lying principle of any solution to this problem is in (a) reducing the stiffness irregularity in the open ground, (b) reducing the discontinuity in load path due to floating columns. The possible schemes to achieve the above are (i) introduction of shear walls at proper positions in the soft storey, (ii) incorporation of lateral bracings under the floating column to the strengthened columns of the soft storey. These schemes have been found to considerably reduce the lateral drift demands, and thus the stress resultants, on the ground storey columns and the beams on which floating columns rest. A feasible combination of lateral strengthening techniques is proposed, which not only reduces the stiffness irregularity and discontinuity in load path but also retains the functional requirement of the open ground storey particularly under the floating columns.

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