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Research Article

Seismic Response of Cellwise Braced Reinforced Concrete Frames

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Abstract

This paper present an elastic seismic response of reinforced concrete frames with reinforced concrete braces in K or inverted – A or V – braced pattern which are analyzed numerically for twelve storey building with 5-bay structures. The responses of braced frames of different patterns (bay, level and combinations thereof and particular cell braced) have been compared with each other and the same also have been compared with unbraced i.e. bare frame. With this view point all parameters in dimensionless form, to include geometry of frame, axial forces, shear forces, bending moments, displacements, location of bracing etc. have been used. Results and finding can be directly used to predict the behavior of real life structures which are concluded from graphs and comprehensive discussions.

Keywords: *Bare Frames, Baywise & Levelwise Braced Frames, Concentrically Braced Frames (CBF), Outriggers, Cellwise Braced Frames.*

1. Introduction

The paper includes analyzing the effect of concentrically braced RC frames (CBRF) on the behavior of the frame and the amount of drift. The behaviors of these frames with different brace pattern are evaluated through structural analysis. The structural analysis was done on structural models plotted in the STAAD- structural analysis and design commercial software. The frame shall be designed to resist the effect of gravity and earthquake loadings for strength and serviceability without aid of V-braces first, to ultimately represent a proposal of an introduction of V-braces having economical structure with good behavior and a convenient architectural distribution.

V-braced frames are one type of Concentrically Braced Frame (CBF) in which the arrangements of members form a vertical truss system to resist lateral forces. The main function of bracing system is to resist lateral forces. It is therefore possible in initial stage of design to treat the frame and the bracing as two separate load carrying system.

The inelastic seismic response of X and K braced concrete frames with intermediate bracing members is satisfactory (J. P. Desai, A. K. Jain and A. S. Arya, 1987). In braced frames, not only lateral resistance and stiffness enhanced, but also energy dissipation amount increased significantly (Shan – Hau Xu & Di – Tao Niu, Jan –Feb-2003). A rational design methodology was adopted to design the braced frame including the connections between the brace members and the concrete frame (M. A. Youssefa, H. Ghaffarzadehb, M. Nehdi**,** 23 October 2006).

Nonlinear seismic behaviour of RC Frames with RC Braces focuses on evaluation of strength, stiffness, ductility and energy absorption of reinforced concrete braced frames and comparison with similar moment resisting frames and frames with shear wall (A.R. Khaloo and M. Mahdi Mohseni, 2008).

Perhaps optimization is the most challenging class of problems in structural optimization because of an infinite number of iterations which are difficult to classify and quantify. At the same time, such optimization is of considerable importance because it leads to significant material savings. Cross-sectional dimensions are the simplest design variables. Cellwise braced frame was tried to combine the advantages especially regarding the economy of tried pattern and to provide an obstruction free/ hindrance free openings. This helps the frame discharge the function more elegantly.

2. Description of study building structures

In order to study the behavior of moment resisting V-braced frames (bare frames, fully, partially bay and partially level braced frames, outrigger frames and cellwise braced frames) 5 bay 12 storey structures (for 350 mm beam depth) are modeled and analyzed numerically.

In case of bare frames sections of columns are reduced from top to bottom which is same for every 3 storey (1-3, 4-6, 7-9, and 10-12) in order to achieve an

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economy in bare frames itself. In all cases, span length and storey elevation are 4 and 3 meters, respectively. A typical frame of this type is shown in Fig. 1 below (a & b). The responses of braced frames of different configurations (baywise, levelwise, partially and cellwise braced frames) have been compared with bare frame and the same also have been compared with each other.

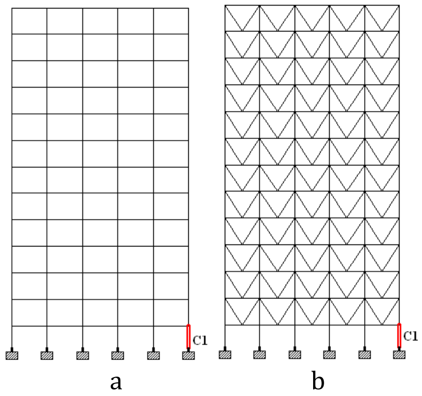


Fig.1 The specific worst loaded member considered for the analysis of various frames

The following Table 1 shows total number of cases for Baywise and Levelwise braced Frames tried for considered structures. In case of levelwise braced frames it is wise to restrict ourselves up to for higher level combinations since it will not going to procure any economy.

Table 1 Number of cases considered for Baywise & Levelwise braced Frames for 12 storey structures

No. of Bays Braced	**No. of Bays Braced at a time**					
	One	Two	Three	Four	Five	Total
5-bay	5	10	10	5	--	30
No. of Levels Braced	**No. of Levels Braced at a time**					
	One	Two	Three	Four	Five	Total
5-bay	12	66	220	--	--	298
Total No. of Cases Studied						**328**

2.1 Check digit algorithms

Natural logarithm of reference number 'N' as dimensionless parameter has been used as abscissa with respect to various considered parameters. The reference number used here is pure number, which is uniquely specified for the frame and bracing pattern tried.

The check digit special algorithms are used for alpha and/or alphanumeric character fields. Each character is assigned a numeric equivalent. The numeric equivalents are weighted and the products are summed. The total is divided by the modulus to determine the remainder. The remainder is compared to a pre-assigned index to determine the check digit.

Here dimensionless parameter (R_a) i.e. ratio of axial force which is the ratio of value of axial force in member C1 for all cases of bays braced to axial force in same member of bare frame as shown in Fig. 1 (a) above. Same is applicable to ratio of shear force (R_s) and to ratio bending moment (R_m). The value of internal forces in worst loaded column segment (C1) of bare frame as shown in Fig. 1 (a) above is chosen as reference value for ratio Ra, Rs and Rm.

3. Internal forces

Forces induced viz. axial force, shear force and bending moment in one particular worst loaded column segment is considered for this purpose as shown in Fig. 1 above. In order to facilitate the direct comparison between bare and fully and/or partially braced frames and cellwise braced farmes the latter have been analyzed for the same geometry of mutually perpendicular/orthogonal members for the same loading combination for which the bare frame yielded the maximum design force in the members so selected as shown in Fig. 1 (a & b) above. However, once the design forces are evaluated for fully and/or partially braced structures all individual segments are redesigned and the minimum required cross sections and steel percentage was calculated. Ultimately cost comparison is carried out to compute economy.

4. Optimum baywise and levelwise location for bracing frames

4.1 Optimum baywise location for bracing frames 5 bay 12 storey structures

Fully braced frames when analyzed, exhibit the values of forces and displacements which are changing with the variation of number of parameters. However, it was noticed that the frames underwent a very small lateral displacement than was permissible. It is but obvious that, when such frames are partially braced i.e. braced all along the height in a particular or a combination of number of bays which is less than total numbers of bays for the frame, similarly when braced all along the level or a combination of number of levels concerned, will produce a larger displacement compared to bare and fully braced frames but within permissible limit i.e. 0.004H.

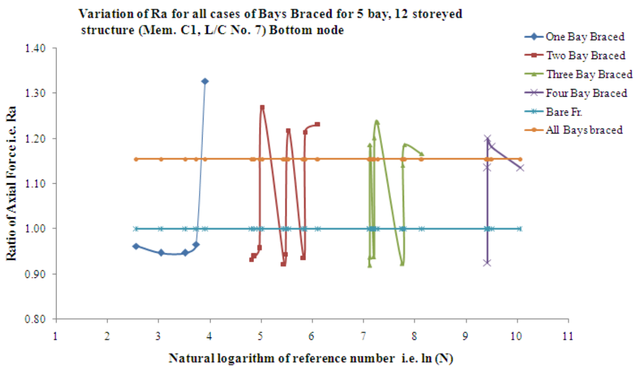
Hence it was decided to find out such possibility of developing a particular pattern for partially braced frames, which would produce smaller forces for worst load combinations. It goes without saying that the bracing pattern tried always satisfied strength as well as serviceability criterion.

It seen clearly that every graph shows two lines parallel to the x-axis as shown in Fig. 2 below. If these are considered as the upper and the lower limits as may be appropriate to a particular dimensionless parameter, one finds that many a times in case of partially braced frames the dimensionless parameters observed exceeds the upper limits and/or is less than the lower limit so considered. From which it concludes that some of the braced frames may allow reduction in effect of considered parameters hence; it would be advantageous to suggest certain working range from specified/accepted minimum to maximum for various internal forces concerned within which a number of bracing patterns/cases produce the force being considered for different cases. However, a number of cases may be found common to all of them are the optimum cases as far as force levels are concerned. The frames which appear between those acceptable ranges were further taken into account for the analysis and design purpose. Often symmetrical cases are taken into account and tried in case of baywise bracings only.

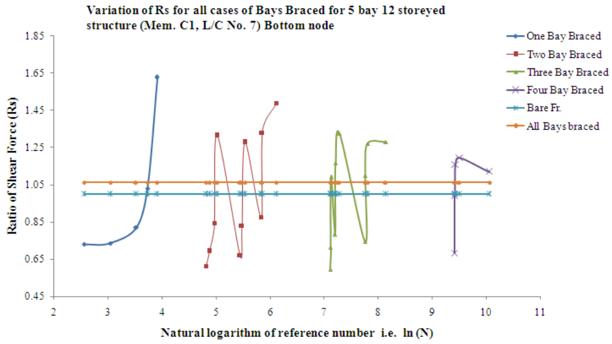
Table 2 Showing percentage of economy achieved in optimum baywise and levelwise location of bracings

Case No.	5 bay 12 storey structures	Percentage of Saving
a	B 3	**6.13%**
b	B 2+ B 4	**2.35%**
c	L 2 + L 5	**7.41%**
d	L 1	**6.30%**

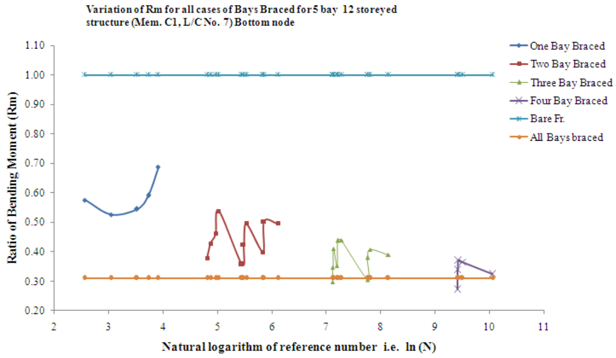
All members of the frame are designed and saving in material is found out. Amongst all the so called best choices there is only one or more than one choice/choices is made available which reduce the total cost of structures compared to a bare frames, when all members are designed to carry the most critical combination of the largest developed forces. This bracing pattern/ these bracing patterns is/are the optimum solution/solutions. It is found that such bracing pattern is most economical than fully braced one. Following Fig. 2 shows the variation of internal forces of 5 bay 12 storey structures and Fig. 3 shows examples of optimum baywise braced frames for 5 bay 12 storey structures and the economy is tabulated in Table 2 above.



(a) Variation of Axial Force i.e. R_a of 5 bay 12 storey structures



(b) Variation of Shear Force i.e. R_s of 5 bay 12 storey structures



(c) Variation of Bending Moment i.e. R_m of 5 bay 12 storey structures

Fig.2 Variation of internal forces of 5 bay 12 storey structures for baywise combinations

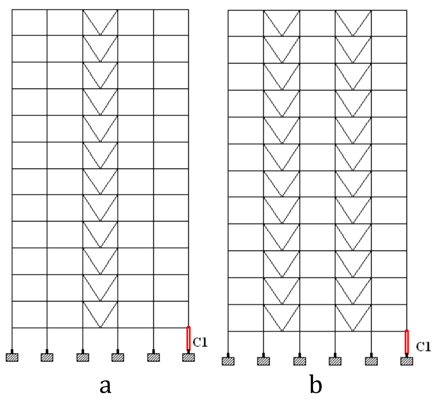


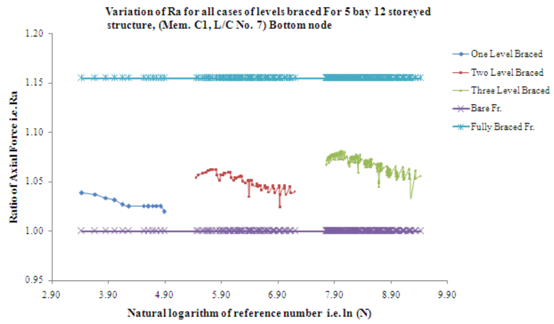
Fig.3 Optimum bay bracing pattern for 5 bay 12 storey structures

4.2 Optimum levelwise location for bracing frames 5 bay 12 storey structures

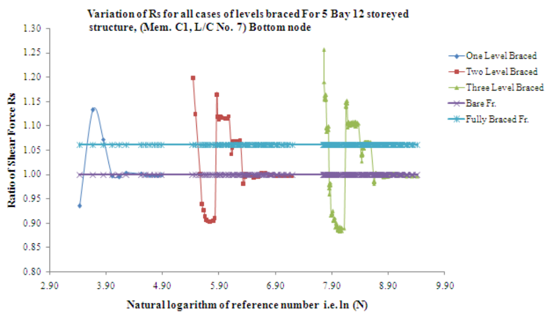
The same is repeated for levelwise bracing for previously mentioned structures and is represented in the Fig. 4 below. The graphs show variation of axial force, shear force and bending moment in member C1 as the bracing pattern changes. Overall, these graphs show the increment in the values of ratios of R_a as the bracing level and combinations of floor increases, Fig. 4

(b) show step variation except the cases which lie below and above the limit of bare and fully braced frames respectively, and Fig. 4 (c) show the step variation except the cases which lie below the limit of bare frames.

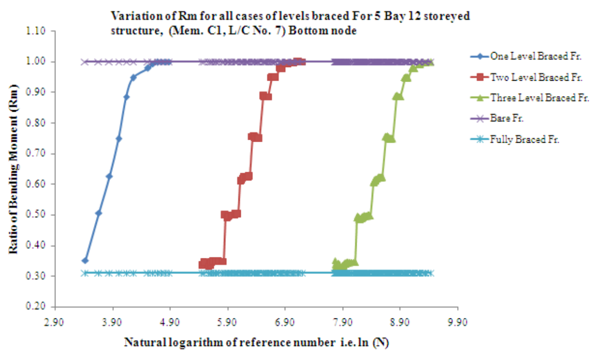
Hence, it seems reasonable to accept certain working range for axial force; shear force and bending moment from specified/accepted minimum to maximum for various internal forces concerned within which a number of bracing patterns/cases produce the force being considered for different cases. However, a number of cases may be found common to all of them. These are most optimum cases as far as force levels are concerned. Fig. 5 shows examples of optimum levelwise braced frames for 5 bay 12 storey structures and the economy is tabulated in table and the respective combinations are shown in Table 2 above.



a) Variation of Axial Force i.e. R_a of 5 bay 12 storey structures

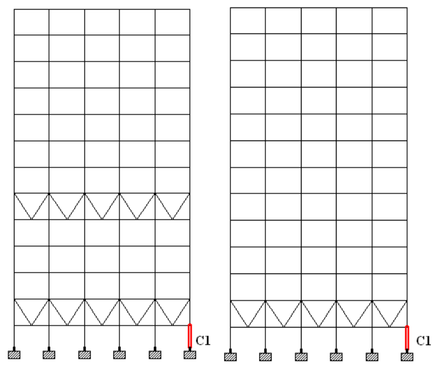


b) Variation of Shear Force i.e. R_s of 5 bay 12 storey structures



c) Variation of Bending Moment i.e. R_m of 5 bay 12 storey structures

Fig.4 Variation of internal forces (R_a, R_s, and R_m) of 5 bay 12 storey structures for levelwise combinations

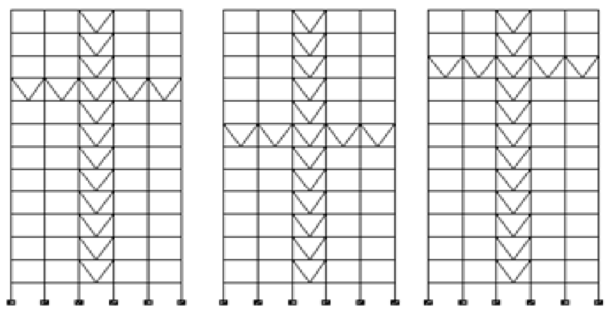


a b

Fig.5 Optimum level bracing pattern for 5 bay 12 storey structures

4.3 Optimally braced frames with outriggers

To begin with and to arrive at the outrigger orientation, a combination of optimum cases of baywise bracing and levelwise bracing pattern are tried. It may be noted that when a number of bays or levels braced simultaneously are increases then normally the cost effectiveness is lost, as the number of members increase which compensate the saving claimed due to reduction in the internal forces induced in the structures and the reduced cross sections commensurate with the same.



a b c

Fig.6 Optimum bracing patterns for 5 bay 12 storey structures

In order to reduce the material cost, optimum combinations of baywise and levelwise braced frames are considered and the section sizes are reduced to get minimum material cost and yet displacement remain within permissible limits.

Table 3 Showing percentage of economy achieved in optimally braced frames with outriggers

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
B (3) + L (9)	**6.00%**
B (3) + L (7)	**5.72%**
B (3) + L (10)	**5.70%**

The Fig. 6 (a, b & c) shows the partially braced frame for the combination of specific bays and levels braced. The respective combinations and economy is tabulated as shown in Table 3 below.

4.4 Optimally cellwise braced frames

To make the structure reasonably more flexible and simultaneously requiring a least number of bracing elements, braces are provided at suitable, predetermined, well thought selected locations on the cells occupied by the so called outriggers. It also provides the more flexibility for architectural provisions and offers the space to accommodate the openings/doors and windows. So it is advantageous to try cellwise bracing in these floors with symmetrical cases beyond which the economy is going to decrease. Hence it is decided to do cellwise bracing in two ways.

a) In those structures which offer maximum economy in levelwise bracing and
b) In those structures which offer maximum economy in baywise bracing

4.4.1 Cellwise bracing – moving levelwise

For 5 bay 12 storey structures case number 03 i.e. whole central bay braced structure offer 6.13% economy as compared to bare frame. Hence it is decided to provide single cellwise bracing pattern that is moving levelwise in respective levels to find out such a cell braced frame which gives more economy as compared to bare frame as well as optimally (central bay) braced frame i.e. case number 03. So it is tried to find out more economical solution by way of the provision of single cell brace rather than providing whole central bay bracing.

The hidden advantage behind the provision of cellwise bracing is that, the speedy construction which is faster than other bracing patterns utilized previously. The same logic is applied for the combinations of cells braced more than one i.e. two and/or three cells braced at a time and so on.

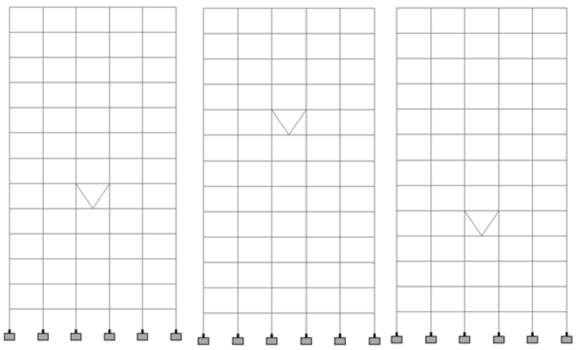
a) Single Cell Braced at a Time

To get the deep insight about savings to achieve in cellwise braced frames, it is decided to do cellwise bracing in 5 Bay 12 storey structures for central bay braced i.e. case number 03 in the same structure.

Table 4 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
4	**9.29%**
7	**9.26%**
3	**9.17%**

Above table shows the economy obtained for one cell braced frame which offer more economy as compared to bare frame as well as other single cellwise braced combinations of the same frame. The results are tabulated in the following Table 4 and the patterns of bracing which gives an optimum result is also shown in Figure 7.



a b c

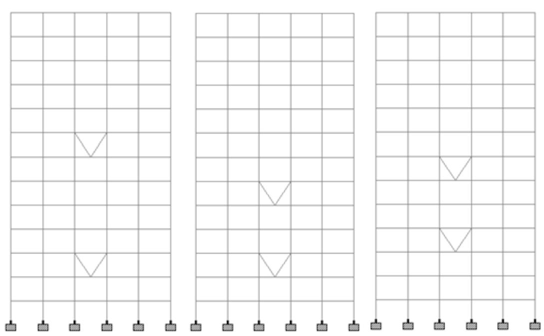
Fig.7 Optimum cellwise bracing patterns for 5 bay 12 storey structures

b) Two Cells Braced at a Time

It is seen from following table 6 that the combination of 1st & 6th floor cell gives 9.28% economy which is 51.39% more than central bay braced throughout, but comparing to single cell braced it gives slightly less economy and as we move towards upper floor cellwise bracing combinations the economy is going to reduce by 1.72% and 2.15% for 1st & 4th floor cell and 2nd & 5th floor cell braced combinations respectively as compared to 1st & 6th floor cellwise bracing combination of the same structure. The results are tabulated in the following Table 5 and the patterns of bracing which gives an optimum result is also shown in Figure 8.

Table 5 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
1+6	**9.28%**
1+4	**9.12%**
2+5	**9.08%**



a b c

Fig.8 Optimum cellwise bracing patterns for 5 bay 12 storey structures *c) Three Cells Braced at a Time*

It is seen from following table 7 that the combination of 2nd, 5th and 8th floor cell gives 8.94% economy out of other combinations of three cells braced, which is 45.84% more than central bay braced throughout, but comparing to single cell braced it offers less economy and as we move towards upper floor cellwise bracing combinations the economy is going to reduce. The results are tabulated in the following Table 6 and the patterns of bracing which gives an optimum result is also shown in Figure 9.

Table 6 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
2+5+8	**8.94%**
1+4+6	**8.87%**
2+4+6	**8.44%**

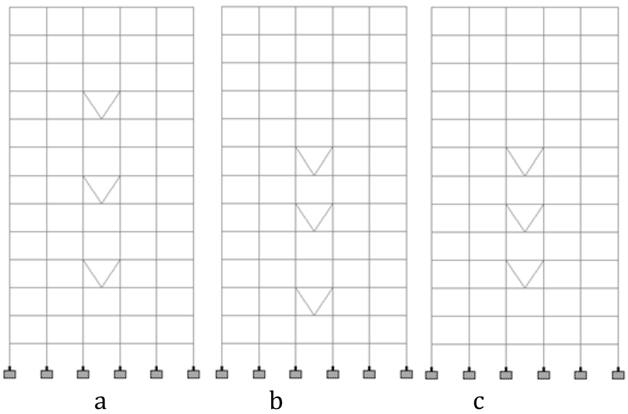


Fig.9 Optimum cellwise bracing patterns for 5 bay 12 storey structures

It is seen that single cell braced frames offer more economy as compared to bare and other cases of cell bracing combinations which concludes that, when an appropriately located single cell is braced makes a structure more rigid than other cases of combinations of bracings. Further it is seen that the economy of cellwise bracing configurations tried for other floors will reduce the economy gradually hence it is wise to restrict further combinations.

4.4.2 Cellwise bracing – moving baywise

The levelwise bracing combinations are restricted up to three levels only since because of the bracing combinations beyond third floor are not offering more economy and also such combinations are not feasible to do and represent them.

When ground floor is braced for 5 bay 12 storey structures throughout in levelwise such bracing pattern offers 7.41% economy and hence it is decided to provide cellwise bracing that is moving baywise in respective bays to yield more economy. So it is tried to find out more economy due to the provision of single cell braced (but placed geometrically similar) rather than providing whole level braced throughout from the conclusions which are recommended in above cellwise bracing combinations i.e. moving levelwise.

The same logic is applied for the combinations of cells braced more than one i.e. two and/or three cells braced at a time and so on for respective floors which offered more economy already.

a) Ground Floor Braced

When cellwise bracing is provided by moving baywise it is wise to consider symmetrical cases since they behave symmetrically in case of change in earthquake directions.

Table 7 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
Braced cell 3	**8.88%**
Braced cell 2+4	**8.67%**
Braced cell 1+3+5	**8.34%**

The single cell which is symmetrically placed in the ground floor is same as in the previous table offering an economy of 8.88%. Following Table 7shows the other cases of cell braced at ground floor only seeking the case of specific cell braced which debt more economy and the Figure 10 shows the cases tried.

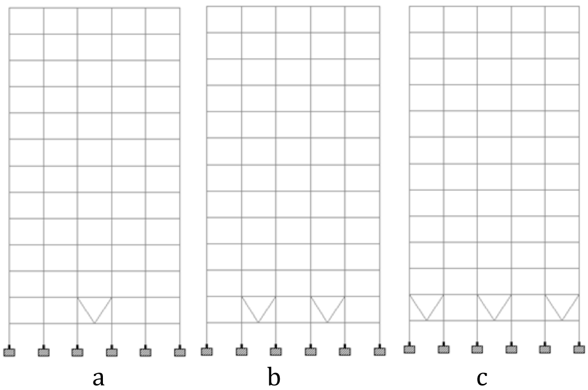


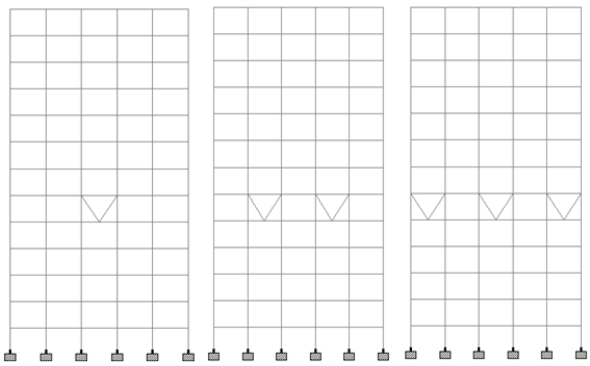
Fig.10 Optimum bracing pattern for 5-bay 12 storey structures, Ground floor level braced.

b) Fourth Floor Braced

Now for this case fourth floor is braced cellwise to see the frame with optimum economy. As discussed earlier, the cellwise bracing is provided by moving baywise and it is wise to consider symmetrical cases since they behave symmetrically in case of change in earthquake directions. Following *Table 8* shows the cases of cells braced and their combinations at fourth floor only with symmetry, offering more economy and the *Figure 11* shows the cases tried.

Table 8 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
Braced cell 3	**9.29%**
Braced cell 2+4	**9.05%**
Braced cell 1+3+5	**9.31%**



a b c

Fig.11 Optimum bracing pattern for 5-bay 12 storey structures, Fourth floor level braced.

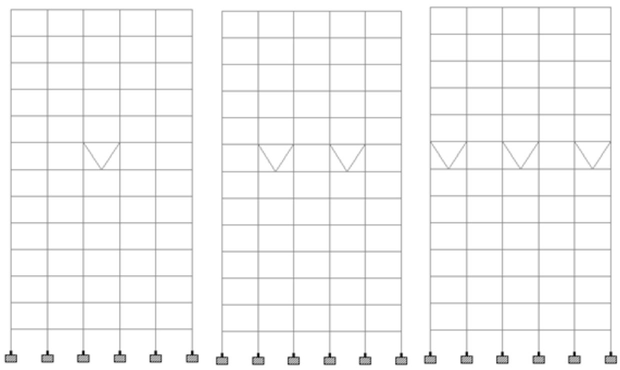
c) Sixth Floor Braced

In the same way symmetrical cases of cell bracing were tried for sixth floor braced to obtain more economy. Now these cases were tried with symmetry as mentioned above. The cases which offer more saving are presented in the following *Table 9* and *Figure 12* shows the cases tried.

Table 9 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
Braced cell 3	**9.26%**
Braced cell 2+4	**9.00%**
Braced cell 1+3+5	**9.00%**

Comparing the economy of all the different cellwise braced frames with respect to different floors overall it is seen that the economy is more in the case of cellwise braced frames that is moving levelwise as compared to cellwise braced frames that is moving levelwise . In fourth floor braced frame i.e. braced cell 1+3+5 offer 9.31% economy which shows that such configurations offer more stiffness to the frame as compared to other cases. Similarly in sixth floor braced frame i.e. Braced cell 3 offer 9.26% economy which is nearly equal to the cellwise braced frame.



a b c

Fig.12 Optimum bracing pattern for 5-bay 12 storey structures, sixth floor level braced.

It concludes that as we towards upper level with increased number of cell bracing combinations will offer savings which are nearly equal to single cell braced configuration when the braces are provided at equal spacing.

4.4.3 Combination if cellwise bracing – moving levelwise and baywise

Based on findings presented in above discussion it is observed that cellwise braces when provided by moving levelwise offer some more economy as compared to when braces are provided by moving baywise, particularly when we talk about single cell braced at a time which offer more economy as compared to bare and other cases of cellwise bracing i.e. two cells, three cells etc. braced at time in the structure. But it also shows that when bracing are provided at equi-spaced and at appropriate level will offer more economy as compared to single cell braced configurations.

Hence to obtain still more economy it is decided to use same strategy which is used in the case of partially braced frames i.e. to combine the economy obtained in baywise braced frames and levelwise braced frames throughout the bay and level respectively.

The combination comprises the case of cellwise bracing that is provision is made by moving either levelwise or baywise. When we consider the economy of single cell braced, in that, the cell braced by moving levelwise i.e. case number 04 gives 9.29% economy and the three cells braced at a time by moving baywise i.e. braced cell 1+3+5 case gives 9.31% economy which is more as compared to other combinations of cellwise bracing.

Hence it is again restricted to do the combinations for those cases which have more economy than other combinations of cellwise bracings which are provided either by levelwise or baywise for 5 Bay G+11 structure i.e. localizing the view over the cases which produce more economy than other, such as only bay braced or level braced throughout, combinations of them and cellwise braced with combination of them which is one cell less than the number of cells in either bay or level throughout.

Table 10 Showing percentage of Economy achieved in cellwise braced frames

Case no. (For 5 bay 12 storey structures)	Percentage of Saving
Trial 1	**9.04%**
Trial 2	**8.97%**
Trial 3	**8.88%**
Trial 4	**8.63%**

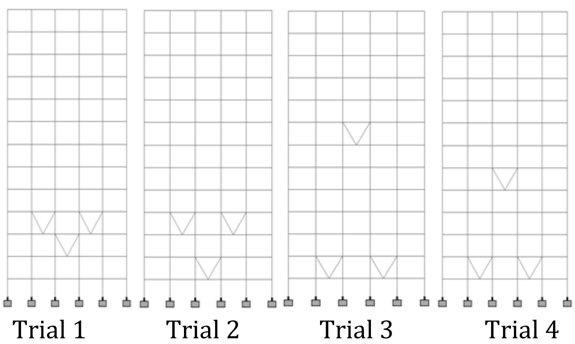


Fig.13 Optimum bracing pattern for 5-bay 12 storey structures with arbitrary bracing pattern

6. Storey drift

The lateral displacements of frames were observed at common point at specific position in 5 bay 12 storey structures. The comparison is made between bare, fully braced, partially braced i.e. optimum bay braced and level braced, outrigger and cellwise braced frames. It was checked whether the structure satisfies maximum permissible relative lateral drift criterion as per IS: 1893-2002 (Part-I) which is 0.004H.

To insure the serviceability criterion, considering the lowest point as base of structure and highest point as top of the structure, maximum relative drift is found and simultaneously compared with the permissible one as well as with other analyzed structures such as fully braced, partially braced and outriggers and cellwise braced frames. The values are tabulated in Table 11 and the variation is shown in Fig. 14 below.

For bare frames the lateral drift is well within the permissible one, but it is increasing as one move towards the top most point of structure. Also the lateral displacements for fully braced frames are getting substantially reduced as compared with bare frame, but these are uneconomical structures from saving point of view.

For optimally bay braced frames and for outriggers the lateral displacements are getting reduced by near about half and more as compared to the bare frames. There is no valuable reduction in the lateral displacement for optimally levelwise braced frames.

Table 11 Showing variation of lateral displacement along height of structure for 5 Bay 12 storey structure with 350 mm beam depth

Analyzed Structures of 5 Bay 12 storey structures for 350 mm beam Depth						
Ht. From Base (m)	Bare Frame (mm)	Fully Braced Frame (mm)	Optimum Bay Braced (mm)	Optimum Level Braced (mm)	Frame with Outrigger (mm)	Cellwise Braced Frame (mm)
0	0	0	0	0	0	0
2.44	1.05	0.66	0.74	0.59	0.742	1.00
5.44	4.14	1.48	2.27	1.68	2.21	3.81
8.44	8.72	2.26	4.31	4.17	4.10	7.85
11.44	14.23	3.00	6.62	8.04	6.23	12.47
14.44	21.12	4.13	9.44	13.88	8.76	17.10
17.44	28.95	5.18	12.55	21.2	11.46	21.03
20.44	36.98	6.13	15.78	28.97	14.14	26.21
23.44	45.00	7.14	19.13	36.88	16.71	32.89
26.44	52.32	8.01	22.44	44.15	18.58	39.71
29.44	58.58	8.74	25.61	50.4	19.84	45.76
32.44	63.56	9.33	28.56	55.38	21.16	50.63
35.44	67.1	9.77	31.21	58.92	22.67	54.12
38.44	69.57	10.13	33.63	61.4	24.11	56.54

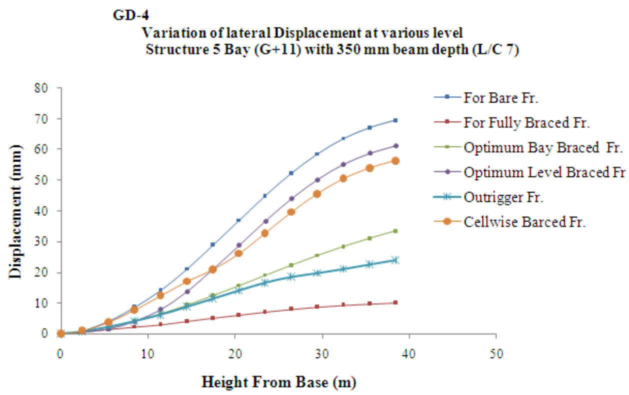


Fig.14 Variation of lateral displacement along height of structure for 5 Bay 12 storey, 350 mm beam depth for L/C 7 i.e. (1.5 D.L. + 1.5 E.Q.)

The graph shows the similar variation of lateral displacement for optimally cellwise braced frame which is less than that of bare frame but well within the permissible limit. In lateral displacement 18.73% decrement is found in the cellwise braced frame as compared to bare frame. Similarly for partially braced frame this amount is getting reduced by nearly half and more as compared to bare frame. Hence it is proved that for cellwise braced frame though the drift is larger than bare frame, but is well within the acceptable limit. In nutshell, it is advantageous to adopt such optimally cellwise braced frame to increase the economy.

Conclusions

1) Fully braced frames are very conservative in so far as lateral drift is concerned but uneconomical and at the same time optimally braced one have least forces induced in the structure and produce maximum displacement but within prescribed limit.
2) It is seen that maximum economy is obtained with less number of bracings are used with proper position and at the same time lateral drift is within acceptable range offering more economy as compared to bare frames.
3) Optimally (cellwise) braced frames are stiff, strong, and an economical structural system.

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