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Seismic Analysis of Multi-Storey Irregular Building with Different Structural Systems

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***Abstract**: Most of the multi-storey buildings are analysed based on an assumption that the structure is subjected to whole load after modelling the entire structure. But in reality, each storey is subjected to some assumed loads to act during construction period itself as they are constructed in stages as storey wise. Sequential analysis in a structure is ignored by many structural engineers while analysing the structure. Because of this ignorance, variation may occur in structural members in the below storey with respect to above storey as the construction proceeds which leads to incorrect distribution of forces in the member. So, analysis has to be done only by sequential application of loads in each storey for the safety of the structure and cost-effectiveness. In order to study the structural behaviour of a 20-storey building with vertical setback irregularity has been modelled and analysed by response spectrum method considering with and without Construction Sequence Analysis (CSA) using different structural systems in CSI ETABS V16 as per BIS 1893:2016 (Part 1). Finally, results such as axial force, shear force, bending moment are drawn for the structural members and response such as storey displacement, storey shear and storey drift are plotted and compared for each structural system.*

***Keywords:** Construction Sequence Analysis, Multi-storey building, Response spectrum method, Seismic Analysis, Vertical setback irregularity.*

I. INTRODUCTION

Usually multi-storey building frames are modelled and analyzed based on an assumption that the structure is subjected to all kinds of load acting at a single instant. But in reality, they are constructed in stages as storey by storey. Self-weight is one of the important governing factors while constructing a multi-storey building. Nearly 85% of dead load acts as vertical load due to its own weight of structural member at the stage of construction itself. As in reality, structural members are added in stages as the construction proceeds and the load acting in each storey is carried by the members which is already constructed below. Due to this, there will be some variation in structural member as storey level increases. The displacement and stress at any instant during construction is independent of the storey which are to be constructed above. Accumulation of correct distribution of stress and displacement can be obtained only when it is analyzed in sequential manner. Ignoring this effect may lead to incorrect analysis results. Based on incremental loading, CSA considers the residual stress of each storey as step wise separately to view the final responses as in Fig. 1. CSA is a type of nonlinear analysis and the results obtaining from it without consideration might vary significantly. Therefore, it is always necessary to perform CSA for a multi-storey building.

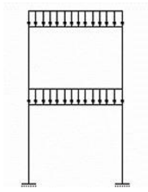

Fig. 1. Conventional analysis

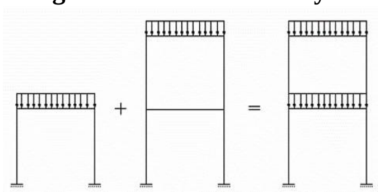

Fig. 2. Construction Sequence Analysis

A. Objective

To study the structural behaviour of a 20-storey vertical setback irregular building by response spectrum method with and without considering CSA for different structural systems.

Structural response such as axial force, shear force, bending moment and response such as storey displacement, storey shear and storey drift are plotted and compared.

B. Scope

A reinforced concrete frame is considered for the analysis. Column is assumed to be fixed at base. Structural systems which is considered are Moment frame system, Dual system and Braced frame system.

II. REVIEW OF LITERATURE

Panigrahi et al. (2019) have made an experimental investigation on a realistic structure to study the effect of construction sequence.

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Building with three different height was considered to study the effect of beam and column with different structural parameters. The results obtained from the analysis showed that the construction sequence analysis was higher than conventional analysis in terms of shear force and bending moment. Hence, CSA method has to be adopted while analysing the structure to avoid failure of structural members.

Surwase et al. (2018) have carried out the work in G+4 multi-storey residential building for regular and irregular building as per IS 1893-2002 and IS 1893-2016 seismic load recommendations in zone III & IV. The scope behind the work was to learn how relevant Indian Standard codes are used for design of various building elements in Etabs. Both lateral loads are considered to act in the structure. For regular and irregular building, the analysis carried was equivalent static method. The results such as bending moment, shear force and storey displacement were compared. It has been concluded that the results obtained by IS 1893-2016 codal provision was found to be more when compared to IS 1893-2002 because of new revision on IS code.

Rahman and Salik (2018) investigated the proportion of wind and seismic forces evolved in each storey level due to change in vertically irregular structures. Static analysis and dynamic analysis were used to calculate the response of structure in the form of storey response such as shear, displacement and drift. From the results concluded, frames which are irregular in shape are susceptible to more damage in earthquake lying zone and this type of irregularity has to be avoided. But if the irregularities are to be introduced, they must be properly designed and detailed as per IS 1893(Part1):2016 and IS 456-2000 and joints should be made ductile as per IS 13920:1993 for taking care of dynamic behaviour.

Kathrotiya et al. (2018) have done a study on flat slab frame for G+10 building which was modelled and analysed for nonlinear analysis under seismic zone IV for a medium type soil considering the sequential construction followed by time history analysis and construction sequence analysis. From the analytical results, the time period of structure analysed with construction stage analysis was more than the time history analysis when compared. Hence it is worthwhile to analyse the structure with construction stage analysis.

Subash (2017) studied the influence of P-delta effect in tall structures with irregularity. Presence of irregularities in buildings are harmful in some cases. Buildings are constructed as irregular one because of architectural requirements. For this purpose, a 30-storey building having vertical geometric irregularity was modelled and analysed in Etabs. The assumed building model has 5 bays of 5m span in both directions. It has been concluded that as the vertical irregularity increases the time period and storey drift also increase due to P-delta effect. Hence it is necessary to consider p-delta effect while designing both regular and irregular buildings.

Naxane et al. (2017) studied the effect of sequential construction on a rigid frame for different configuration. These structures are analysed for the sequential loading and the results were compared with the single step analysis having same configuration. The variation in axial force, axial deformation, shear force and bending moment were calculated. The structural results obtained from construction sequence analysis was more when compared to linear static analysis. This is probably because of stage wise construction. Thus, from the above conclusion it is necessary to do sequential analysis in multi-storeyed building than the conventional design.

Shelke and Ansari (2017) studied the importance of seismic analysis in irregular structure by response spectrum method. Type of irregularity which were considered are mass, stiffness and vertical geometry. Comparison has been made for regular with irregular structure. The mass irregular structure was observed to experience large base shear than similar regular structures. Base shear was found to be more in mass irregular when compared to stiffness irregular which experienced lesser base shear. Displacement was found to be more in irregular structure than the regular structure. The change in displacement variation was found to be more due to presence of irregularities. From the overall study and observation, it is concluded that, base shear and displacement will increase as the seismic intensity increases which indicates structure should be designed to meet the seismic demand.

Meghana and Murthy (2016) has carried out a comparison between linear static and construction sequence analysis in RC building of G+5 with floating column placed in exterior position where the RC transfer girder is replaced by steel-concrete composite transfer girder. Finally, results of both transfer girder are compared for the moment and deflection. From the analysis results, composite transfer girder showed better results compared to RC transfer girder. The results also showed the necessity of construction sequence analysis in multi-storey building.

Umamaheshwara and Nagarajan (2016) determined the optimum location of shear wall in multi-storey building. Four models have been created with no shear wall, shear wall at corner, shear wall parallel to X- axis and parallel to Y-axis. A 15-storey residential building having zero eccentricity with mass centre and hardness centre have been analysed and designed in Etabs subjected to gravity and lateral loading by static analysis and dynamic analysis. The results of storey displacement, inter-storey drift and base shear were compared for the models. The model with shear wall placed at corners of the building shows better results than any other location.

Rajesh et al. (2015) has carried out a work in linear and dynamic analysis of plan irregularity of reinforced concrete building. Four models of G+15 building is modelled as one regular and the remaining as L-shape, I-shape and C-shape plan was modelled and analysed in Etabs 9.5. Various response like lateral force, base shear, storey drift and storey shear were compared. Since irregular building gets affected severely during earthquake especially in high seismic zone it has to be designed carefully. From the analysis results it has been concluded that the dynamic analysis needs to be done for high rise building and in irregular building the deformation and base shear was found to be more in both regular and irregular building. Considerably the storey drift was also more in regular building.

Soni et al. (2015) have made a calculation on performance of RC building with irregularity. An effort has been made to find the influencing parameters such as storey displacement, drift of adjacent stories, excessive torsion and base shear in vertical irregular RC building frame.

Frame with one regular building, two mass irregularity and two stiffness irregularity at different storey level were modelled and analysed by equivalent static method in Etabs. From the results concluded the displacement and storey drift was maximum in irregular building when compared to regular building.

Tanaji and Shaikh (2015) made a study on seismic analysis of RC building with bracings. Provision of bracing to the system improves not only the stiffness and strength capacity but also the displacement capacity. Different types of bracing made in concrete and steel such as diagonal, V-type, Inverted-V type, combine V-type, K-type and X-type were used. Position of bracing in model are located in peripheral column and two parallel sides of building model. Among all the bracings considered X-type concrete bracing has more stiffness and also reduces the drift of storey.

Suresh and Yadav (2015) studied the optimum location of shear wall in high rise reinforced concrete building. Three different model such as regular structural system and dual type with central core and corner shear wall were modelled. The analysis is done in Etabs for equivalent static method. Various structural parameters such as displacement, storey drift and storey displacement were determined. It was found that the building with no shear wall is critical than the building with shear wall provided at the corner. Thus, provision of shear wall at corner can reduce structural response with increase in strength and stiffness of the structure.

Dinar et al. (2014) studied the consequence of linear static and construction sequence analysis for rigid frame concrete and steel model using different configurations. Six different storey heights have been considered for both steel and concrete structures. The study reveals that performing non-linear static analysis becomes important with increasing height while each additional floor creates a significant load to act on the column. It was found that for long term loading, steel frame performed good over concrete frame when analysed in sequential manner. It has been observed that steel structures take maximum moment with less displacement than RC structures and construction sequence causes higher moment in structures.

Gaur et al. (2014) has analysed irregular building for horizontal loading to check the stability of the structure. Multi-storey irregular building was modelled in STAAD-PRO program as 20-storey. Building with irregular plan such as L-shape, H-shape and U-shape were considered for the study. Assessment is done for internal forces and roof displacement on the basis of lateral length ratio for each shape. Results were plotted for internal forces and roof displacements in critical members.

III. METHODOLOGY

A. Buildings

Buildings are formed by different structural elements made of concrete or steel standing more or less permanently in one place. They can also be constructed as single or multi-storey for residential, commercial and industrial building. As per IS 1893 (Part 1): 2016, buildings are classified into two types as regular and irregular based on various size, shape and function as per architectural requirements. The conceptual framework adopted for this research is illustrated in Fig. 2.

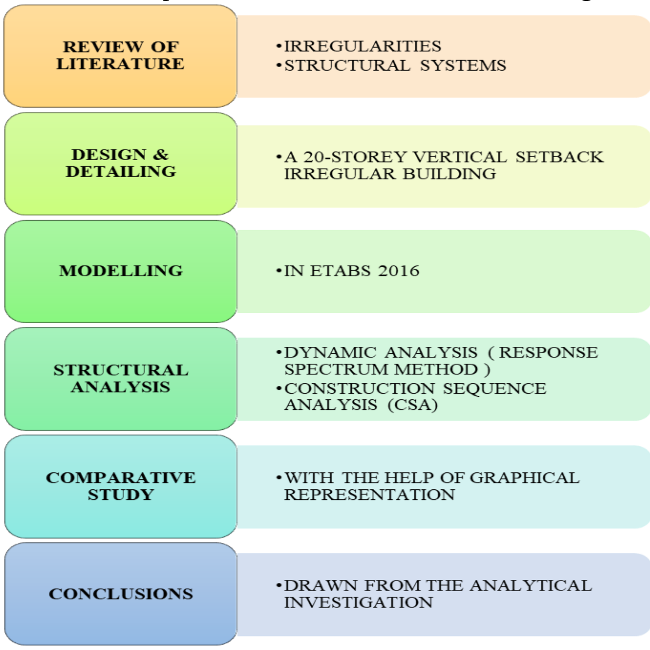

Fig. 3. Conceptual framework of this research

1) Regular building

Buildings with simple regular geometry and uniformly distributed mass and stiffness in plan and elevation are said to be regular building. This type of building suffers much less damage during earthquake.

2) Irregular building

Buildings with different plan and in geometry will come under the category of irregular. Building is considered as an irregular when any of the conditions given in Table 5 and 6 of IS 1893 (Part 1):2016 satisfies. Irregular building is further classified into two types as,

Plan irregularity: Plan irregularity is further classified into five types as torsional irregularity, re-entrant corners, diaphragm discontinuity, out-of-plane offsets and non-parallel lateral force system.

Vertical irregularity: Vertical irregularity is further classified into six types as stiffness irregularity, mass irregularity, vertical geometric irregularity, strength irregularity-weak storey, floating or stub column and irregular modes of oscillation in two principal plan directions.

B. Structural system

Building with structural systems are usually designed to cope up with vertical gravity loads and lateral forces caused by wind and earthquake load. The structural system which is used to resist the lateral force is known as lateral load resisting system. Different structural system used for lateral resisting load systems are classified into,

- Braced frame structural system

- Rigid frame structural system
- Shear wall-frame system (Dual system)
- Shear wall system
- Core and outrigger structural system
- Infilled frame structural system
- Flat plate and flat slab structural system
- Tube structural system
- Coupled wall system
- Hybrid structural system

C. Structural analysis

a. Equivalent static method: Equivalent static method is a simplest method of analysis which requires less computational effort. The design seismic base shear (V_B) along horizontal direction is determined by

$$V_B = A_h * W \quad\text{------ (1)}$$

and for vertical direction as

$$V_B = A_v * W \quad\text{------ (2)}$$

The design horizontal seismic coefficient is computed by,

$$A_h = \left(\frac{Z}{2} * \frac{Sa}{g} * \frac{I}{R}\right) \quad\text{------ (3)}$$

The design vertical seismic coefficient is computed by,

$$A_v = (2/3)\left(\frac{Z}{2} * 2.5 * \frac{I}{R}\right) \quad\text{------ (4)}$$

Distribution of base shear:

The design base shear (V_B) computed is distributed along the height of the building as, $Q_i = V_B \dfrac{W_i * h_i^{\,2}}{\sum_{j=1}^{n} W_j * h_j^{\,2}}$ ------------ (5)

b. Dynamic method: Linear dynamic analysis is performed to obtain the seismic lateral force for all buildings other than regular building lower than 15m in seismic zone II. Usually dynamic analysis is done for the building with unusual configuration like irregularities in the building. Dynamic analysis is performed either by response spectrum or time history method. Response spectrum method is done using design acceleration spectrum method and time history method by appropriate ground motion. When either of the methods are used, the design base shear V_B estimated shall not be less than design base shear V_b calculated using a fundamental time period T_a.

The calculation of design lateral force is done by,

Modal mass of mode k, $M_k = \dfrac{\sum_{i=1}^{n} [W_i * \varphi_{ik}]^2}{g * \sum_{i=1}^{n} W_i * \varphi_{ik}^{\,2}}$ ------------- (6)

Modal participation factor of mode k, $P_k = \dfrac{\sum_{i=1}^{n} W_i * \varphi_{ik}}{\sum_{i=1}^{n} W_i * \varphi_{ik}^{\,2}}$-- (7)

Design lateral force at each floor in each mode, $Q_{ik} = A_k * \varphi_{ik} * P_k * W_i$ ------------ (8)

Storey shear force V_{ik} in each mode acting in storey i of mode,

$$V_{ik} = \sum_{j=i+1}^{n} Q_{ik} \quad\text{------ (9)}$$

Lateral force F_{roof} at roof level and F_i at level of floor i shall be obtained as, $F_{roof} = V_{roof}$, $F_i = V_i - V_{i+1}$ --------------------- (10)

c. Construction Sequence Analysis (CSA): CSA is a nonlinear analysis approach in which the structure is analysed at various stages corresponding to the construction sequence and the partial required loads are applied sequentially at every stage. This analysis will provide more reliable results and hence this method should be adopted in usual practice while analysing the structure.

IV. PARAMETRIC STUDY

The detailed analogy of the parameters considered for this research are tabulated in Tables I, II & III.

Table I. Building configuration data

Specification	Multi-storey building (G+19)		
Type of building	Vertical setback irregular building		
Type of system	Moment frame	Dual	Braced frame
Building dimension	35m x 36m		
Bay length in X-direction	5m (7 bays)		
Bay length in Y-direction	6m (6bays)		
Bottom storey height	4m		
Typical storey height	3.5m		
Total height of the building	71m		
Size of beam	400mm x 400mm		
Size of column	500mm x 500mm		
Thickness of slab	200mm		
Thickness of shear wall	250mm		
Size of X-bracing	200mm x 200mm		
Material for concrete and steel	M40, Fe 415, Fe 500		

Table II. Seismic and wind parameters

Software used	ETABS
Type of analysis	1) Response Spectrum Analysis 2) Construction Sequence analysis
Seismic parameters (IS1893 :2016)	
Seismic zone	IV
Zone factor, Z	0.24
Type of soil	Medium soil (Type 2)
Importance factor, I	1.2
Response reduction factor, R	5.0
Wind parameters (IS875:2015)	
Design wind speed, V_b	39 m/s
Terrain category	3
Probability factor, k_1	1.07
Terrain factor, k_2	Category 3
Topography factor, k_3	1

Table III. Load details

DESCRIPTION	LOAD DATA
Live load	Floor – 4 KN/m^2
Floor finish (including interior wall load)	2 kN/m^2
Exterior wall load	4.5 kN/m^2

Parapet wall load	2 kN/m^2

A. Load combination

As per IS 1893:2016 clause 6.3.3, when a structure is located in seismic zone IV or V and has vertical or plan irregularities the structure has to be designed for vertical earthquake effects also. When effects due to vertical earthquake shaking are considered, the design vertical force shall be calculated for vertical ground motion as detailed in Clause 6.4.6. When responses from the three earthquake components are considered, the response due to each component may be combined using the assumption that when the maximum response from one component occurs, the responses from the other two components are taken as 30 percent. All possible combinations of three components (EL_X, EL_Y and EL_Z) including variation in sign should also be considered. Thus, while designing the structure the following sets of load combination should be considered for both horizontal and vertical earthquake load is as follows,

- $\pm$ ($EL_X \pm 0.3\ EL_Y \pm 0.3\ EL_Z$)
- $\pm$ ($EL_Y \pm 0.3\ EL_Z \pm 0.3\ EL_X$)
- $\pm$ ($EL_Z \pm 0.3\ EL_X \pm 0.3\ EL_Y$)

V. STRUCTURAL ANALYSIS

Fig. 4 to 8 shows the plan of the structure for considered building. Black colour box denotes the lift area and red colour box denotes the staircase area. Staircase and lift are provided at two different location separately for storey 1 to 12 and other connecting between storeys 1 to 20 for easy access in the building.

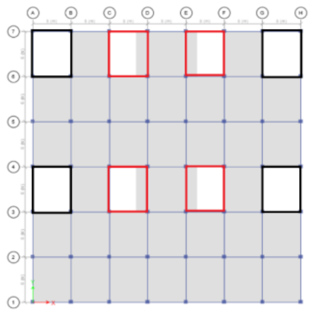

Fig. 4. Storey 1 to 4

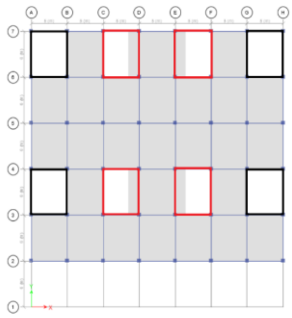

Fig. 5. Storey 5 to 8

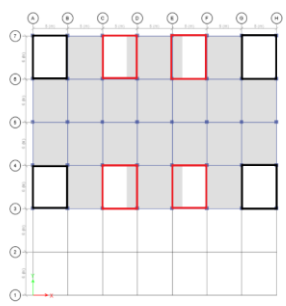

Fig. 6. Storey 9 to 12

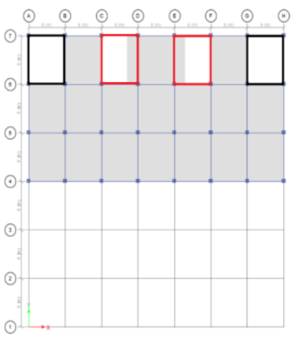

Fig. 7. Storey 13 to 16

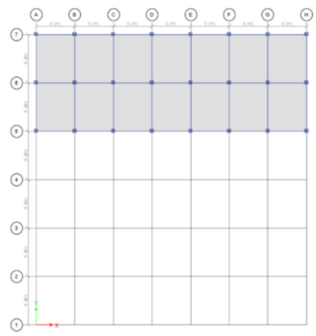

Fig. 8. Top view of Storey 20

A. Moment frame system

It is a rectilinear assemblage of beams and columns, with the beams rigidly connected to the columns as in Fig. 9.

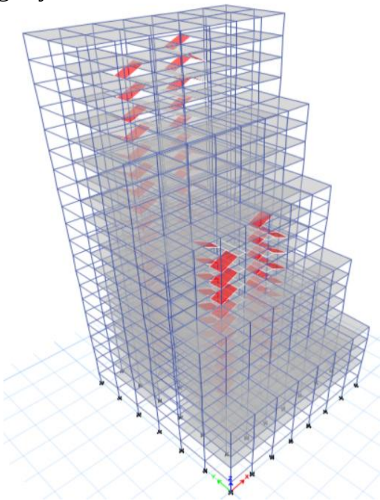

Fig. 9. 3D view of moment frame system

B. Dual system

Dual system is the combination of shear wall and frame system as in Fig. 10. These walls have a positive impact on the performance of the building under lateral loads. Dual systems are mainly used to increase the stiffness of the building and to resist the lateral loads.

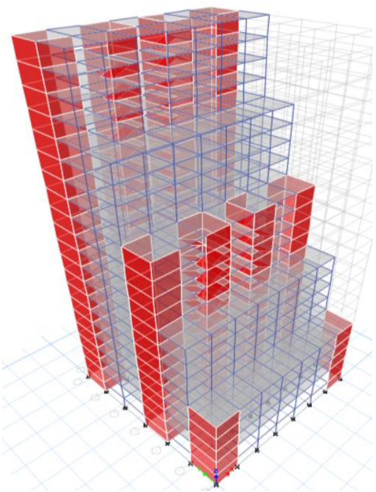

Fig. 10. 3D view of dual system

C. Braced frame system

Braced frame structural system is suitable for multi-storey building from low to mid height range to resist the lateral load as in Fig. 11. To increase the strength and stiffness of the building, use of bracing can be a best solution to improve the earthquake resistance. In this system shear wall provided at peripheral outer side is replaced by X-shaped bracing.

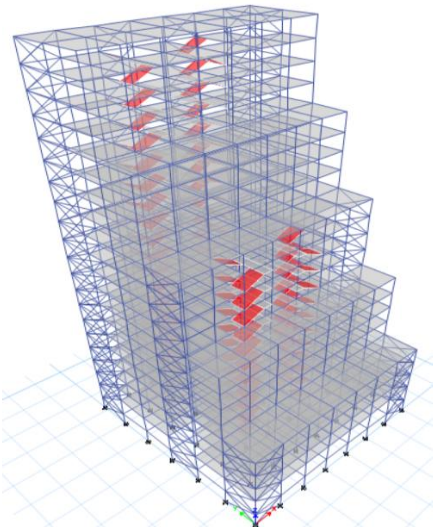

Fig. 11. 3D view of braced frame system

VI. RESULTS AND DISCUSSION

Figs 12-18 shows the structural systems such as Moment frame system, Dual system and Braced frame system are named as Modal-1, Modal-2 and Modal-3 respectively and the related structural behaviour and inference (Kannan 2017).

A.*Storey displacement* Storey displacement is defined as the displacement of a storey with respect to the base of the structure.

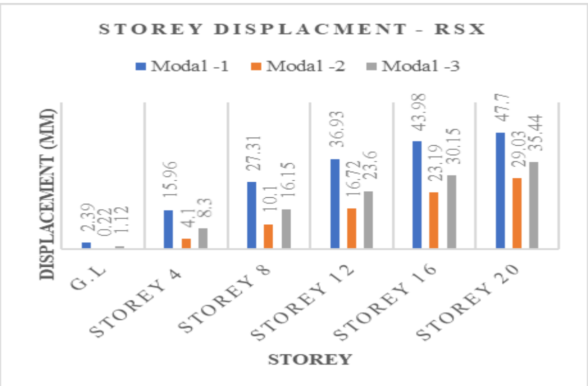

Fig. 12(a). Storey v/s Storey displacement in X- direction

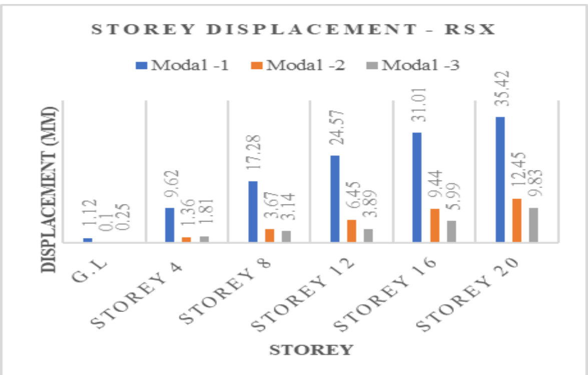

Fig. 12(b). Storey v/s Storey displacement in Y- direction

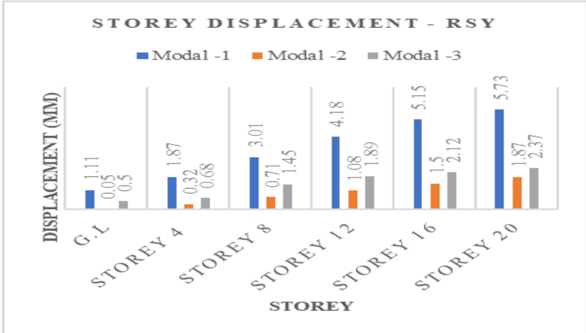

Fig. 13(a). Storey v/s Storey displacement in X- direction

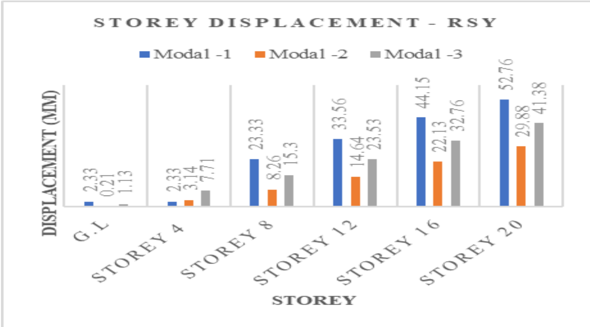

Fig. 13(b). Storey v/s Storey displacement in Y- direction

B.*Storey shear* Storey shear is the sum of design lateral forces at all levels above the storey under consideration. Graphs are plotted for ground floor, 4th, 8th,12th,16th and 20th storey where the setback level exist in the irregular building. Higher the stiffness greater the base shear.

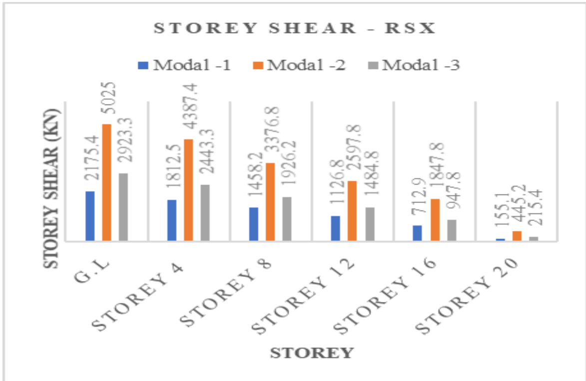

Fig. 14. Storey v/s Storey shear in X- direction

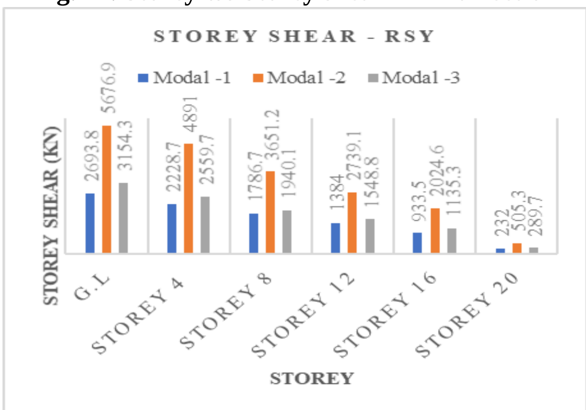

Fig. 15. Storey v/s Storey shear in Y- direction

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C. ***Storey drift*** Storey drift is calculated as the relative horizontal displacement of two adjacent floors in a building. As per IS 875, storey drift limitation with partial safety factor of 1 shall not exceed 0.002 times the storey height or H/500.

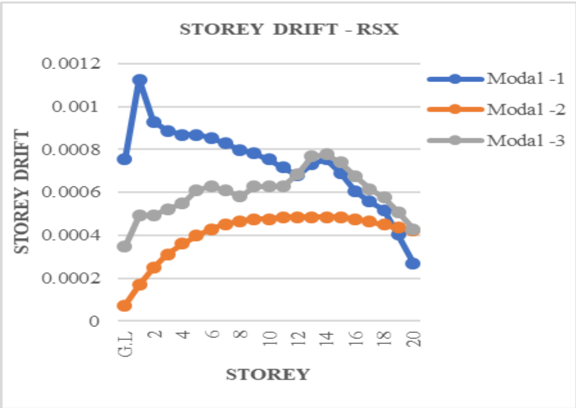

Fig. 16(a). Storey v/s Storey drift in X- Direction

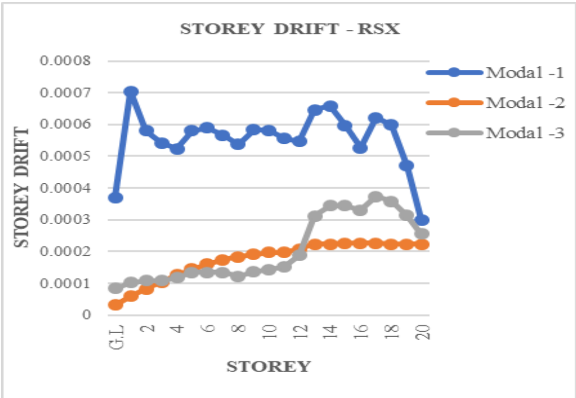

Fig. 16(b). Storey v/s Storey drift in Y- Direction

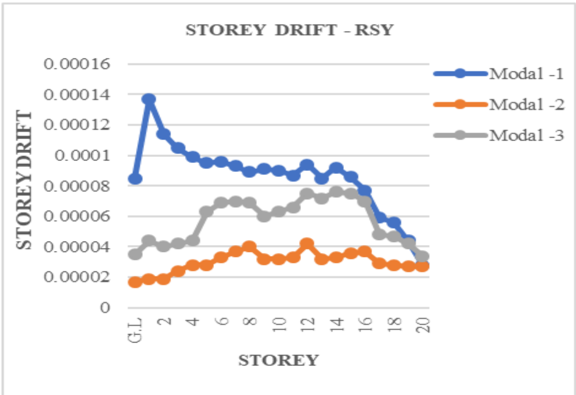

Fig. 17(a). Storey v/s Storey drift in X- Direction

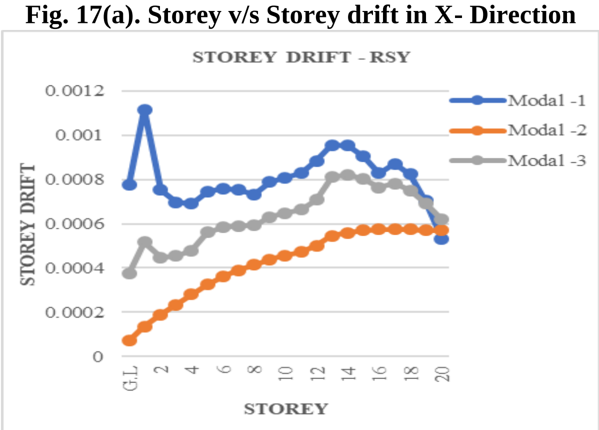

Fig. 17(b). Storey v/s Storey drift in Y- Direction

D. ***Mode shape***

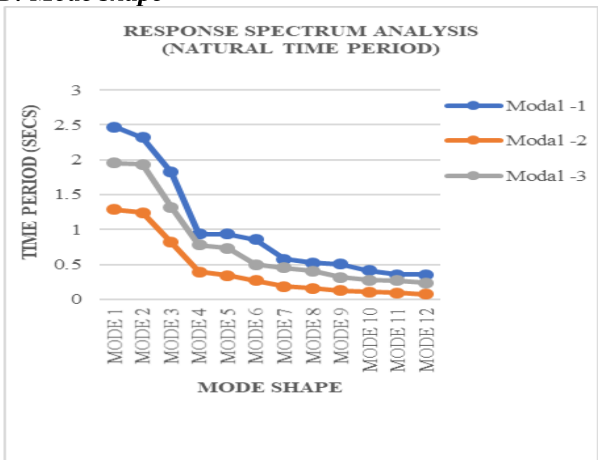

Fig. 18. Time period v/s Mode shape

Table IV provides the time period for first 12 mode shapes for different structural system.

Table IV. Natural Time Period

RESPONSE SPECTRUM ANALYSIS			
TIME PERIOD (SECS)			
MODE SHAPE	MODAL-1	MODAL-2	MODAL-3
MODE 1	2.47	1.289	1.953
MODE 2	2.318	1.241	1.937
MODE 3	1.822	0.819	1.319
MODE 4	0.939	0.394	0.777
MODE 5	0.933	0.342	0.735
MODE 6	0.858	0.272	0.5
MODE 7	0.575	0.185	0.453
MODE 8	0.525	0.156	0.405
MODE 9	0.505	0.129	0.315
MODE 10	0.414	0.104	0.275
MODE 11	0.357	0.091	0.269
MODE 12	0.354	0.076	0.238

The other structural behaviour of the hybrid framed structures (Naidu and Kannan, 2015; Kannan 2017) are illustrated in the Figs. 19-31.

E. Moment frame system

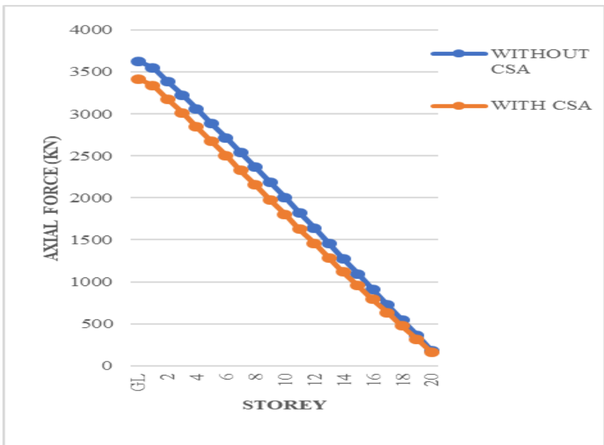

Fig. 19. Axial force in Exterior column – C23

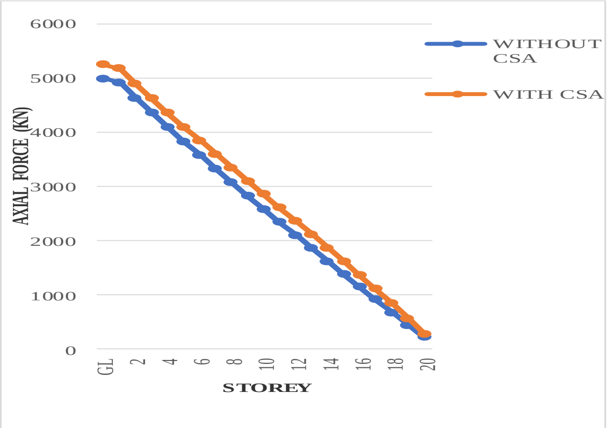

Fig. 20. Axial force in Interior column – C20

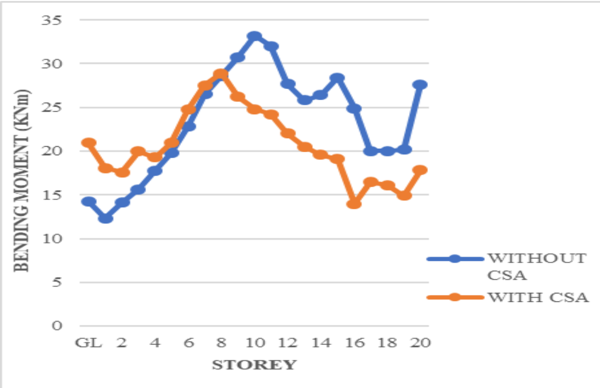

Fig. 21. Bending moment of beam – B16

Fig. 22. Shear force in critical column at setback level

Fig. 23. Bending moment in critical beam at setback level

F. Dual system

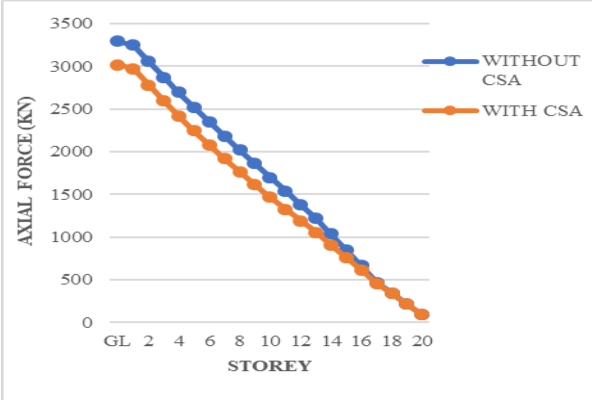

Fig. 24. Axial force in Exterior column – C22

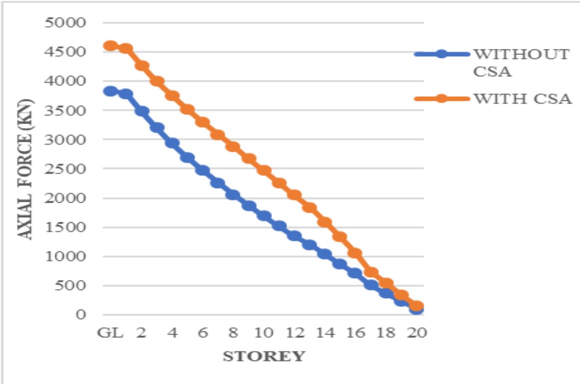

Fig. 25. Axial force in Interior column – C19

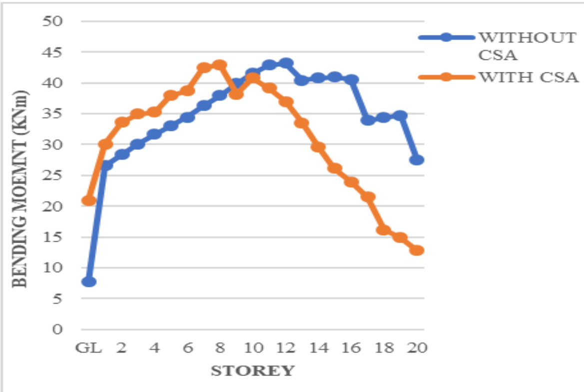

Fig. 26. Bending moment in beam – B15

G. Braced frame system

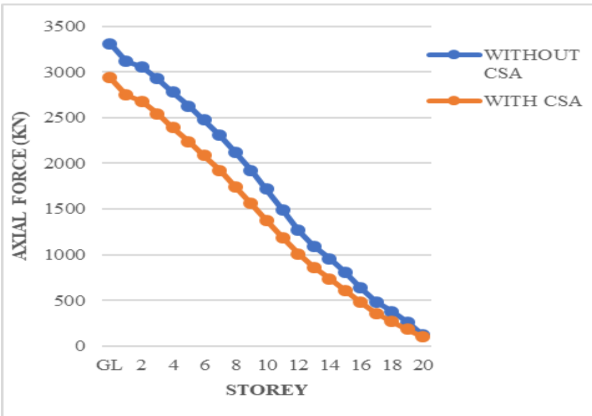

Fig. 27. Axial force in Exterior column – C24

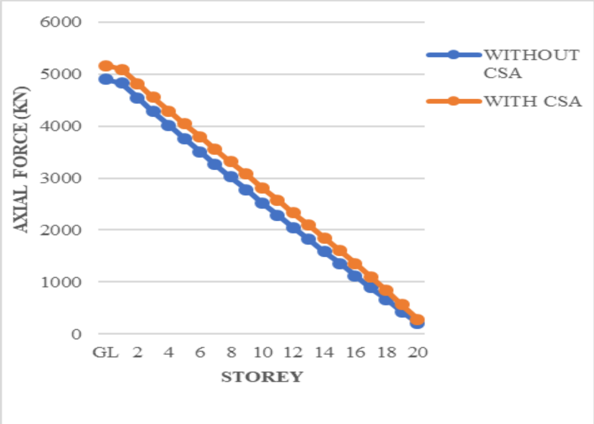

Fig. 28. Axial force in Interior column – C20

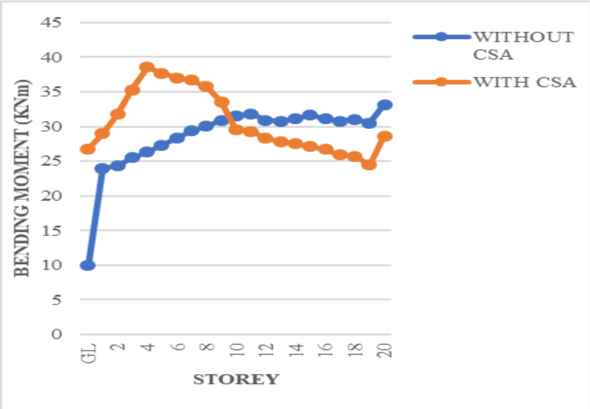

Fig. 29. Bending moment of beam – B14

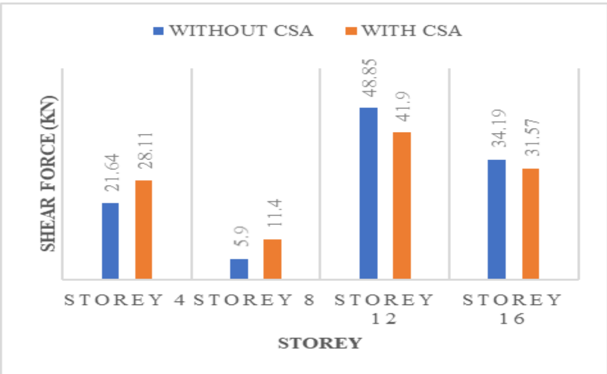

Fig. 30. Shear force in critical column at setback level

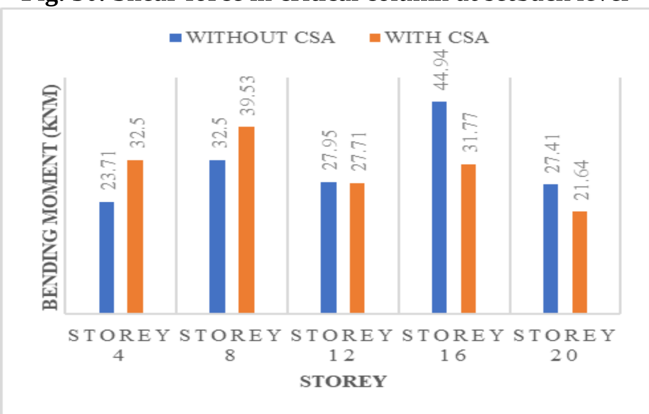

Fig. 31. Bending moment in critical beam at setback level

VII. CONCLUSION

For a vertical setback irregular building, dynamic analysis was carried out by response spectrum method with and without CSA using different structural systems and the following conclusion were drawn from it.

1) For response spectrum in X-direction, maximum displacement at top storey is decreased by 49% for dual system and by 30% for braced system similarly for response spectrum in Y-direction, maximum displacement at top storey is decreased by 55% for dual system and by 24% for braced system when compared with moment frame system.

2) Higher the stiffness greater the base shear. Dual system has performed well in both horizontal direction for response spectrum. Base shear at the ground level was found around 75% more in dual system and 55% more in braced system when compared with moment frame system.

3) Provision of shear wall and bracings to the building has considerably reduced the drift of storey which is also within the permissible drift limitation.

4) Time period obtained from mode shape of dual system was 1.25 seconds which is nearly half than that of moment frame system which proves will act safe during earthquake excitation.

5) For all the three structural systems, axial force in exterior column was found to be more in conventional analysis than CSA and for in interior column the axial force was more in CSA than the conventional analysis.

6) Bending moment in beam has shown a gradual increase from bottom storey to 2/3rd of the building height and thereafter the value has decreased considerably when analyzed in Construction Sequence Analysis. This may be due to the fact that bottom storeys are involved in numerous cycles of analysis in CSA than the conventional method.

7) The column shear force from the bottom storey is more in CSA and it gradually decreased at the top by slight variation for all the structural systems.

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