Analysis Outrigger Structural System Subjected to Lateral Loads

Paresh V. Patel and Jigneshkumar C. Patel
Department of civil engineering, Nirma University Ahmedabad.

Abstract— **The advances in structural systems and material technology made it possible to design light and slender structures satisfying economical and architectural requirements. In tall buildings, lateral loads caused by wind and earthquake actions are often resisted by a system of braced-frame and shear wall-frame. However, such structures face the problems of vibration induced by the wind load and inconveniences may be caused to the occupants of the building due to excessive deflection and acceleration. In order to limit the wind drift to acceptable limit and to maintain human comfort with optimum utilization of material, the core-outrigger and belt truss structural system is developed. The magnitude of the reduction in drift and core moment depends on the location of outrigger and relative flexural rigidities of the core, outriggers and columns.**

In the present paper simplified analysis of structure under lateral uniform wind pressure is presented to understand the behaviour of the outrigger structural system. Further effect of location of outrigger in tall building is illustrated. A 50-story reinforced concrete building is considered for study. Modeling and analysis of building is carried out using ETABS software. In present study an outrigger is provided at different level to obtain optimum location for the one outrigger structure system. Response of building under uniform lateral load in terms of displacement, drift, core moment are studied for building with and without outrigger.

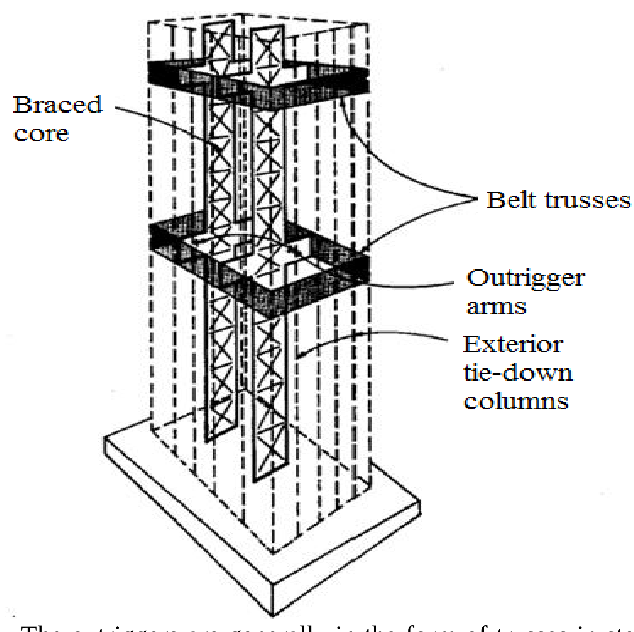
Index Terms-- **Tall building, Outrigger structural system, Optimum location, Top storey displacement and core bending moment.**

I. INTRODUCTION

Developing efficient structural systems for tall buildings pose great challenges for structural engineers. Along with strength and stability of structure, lateral drift and human comfort criteria are important factors for design of tall buildings. Significant savings in structural materials can be achieved in high-rise buildings if certain techniques are employed to utilize the full capacities of the structural elements. The outrigger and belt truss system is one of the lateral load resisting systems in which the external columns are tied to the central core wall with very stiff cantilevers, known as outriggers, and deep spandrel girder or belt truss around structure at one or more levels (Fig. 1). It is the one of the most efficient and economical systems for controlling drift in tall buildings.

The outrigger concept is in widespread use today in the design of tall buildings. In this concept, "outrigger" trusses (or, occasionally, girders) extend from a lateral load-resisting core to columns at the exterior of the building [2]. The core may consist of either shear walls or braced frames. Outrigger systems can lead to very efficient use of structural materials by coupling of the core and the perimeter column, enabling buildings to utilize its total width to resist lateral load and the critical overturning forces present in high rise building. The axial strength and stiffness of exterior columns are utilized to resist part of the overturning moment produced by lateral loading. The stiffness of outrigger and belt truss system is increased by 25 to 30% in contrast to a system without such outriggers. The core of a structure with outriggers will be subjected to 30 to 40% less overturning moment compared to a free cantilever [1]. In addition outrigger structural system experiences less drift. There are, however, some important space-planning limitations and certain structural complications associated with the use of outriggers in tall buildings.

Fig. 1 The outrigger and belt truss system



The outriggers are generally in the form of trusses in steel structures, or walls in concrete structures, that effectively act as stiff headers, which induce a tension-compression couple in the outer columns. Belt trusses are often provided to distribute these tensile and compressive forces to a large number of exterior frame columns. The belt trusses also help in minimizing differential elongation and shortening of columns [3].

II. Behavior of Outrigger Structural System

To understand the behaviour of an outrigger system, consider a building stiffened by a story high outrigger at top, as shown in Fig. 2(a). The building is subjected to uniformly distributed lateral load. Due to rotation of core rigidly connected outriggers cause tension in windward column and compression in leeward column. This tie-down action of the cap truss generates a restoring couple at the building top, resulting in a point of contra-flexure in its deflection curve. This reversal in curvature reduces the bending moment in the core and hence, the building drifts.

A. Advantages of Outriggers

Following are the advantages of outrigger structural system:

1. Lateral movement of the structure is decreased by using the exterior columns for the lateral resisting system. (Refer Fig. 2(b))
2. Overturning moment of the core is decreased. By using outriggers the effective width of the structure will increase from the core itself to almost the complete building. (Refer Fig. 2(d))
3. Since the exterior framing can consist of simple beam and column framing without the necessity for rigid connections the cost of the structure can decrease significantly compared to a structure made with rigid connections.
4. Significant reduction of uplift and reducing the cost of the foundation.
5. In rectangular plan buildings the outriggers incorporate even the middle gravity columns into the lateral load resisting system. This will lead to a much more economic structure.

The extent of the reduction in drift and core moment depends on the relative flexural rigidities of the core, outriggers, columns and also location of the outriggers within the height of the core.

III. Building Configuration

In this paper an example of 50-storey building is discussed to understand behaviour of the outrigger structural system under lateral load. Modeling of the 50 storey building with Outrigger is carried out in ETABS [4]. Typical floor plan and elevation of three dimensional structures is shown in Fig. 3(a). Three dimensional structure is converted into a two dimensional structure based on its stiffness which is shown in Fig. 3(b). Following structural data are used for analysis and study of results [5]:

Height of story	: 3.5 m
Total height of building	: 175 m
Thickness of slab	: 0.125 m
Size of beam	: 0.4 m × 0.8 m
Wind load	: 1.5 kN/m^2
Three dimensional structure	
Thickness of shear wall	: 0.4 m
Size of column	: 0.5 m × 0.7 m
Outrigger Beam (two storey deep)	: 0.5 m × 7 m
Two dimensional structure	
Size of Core column	: 6.465 m × 6.465 m
Size of exterior column	: 2.05 m × 2.05 m
Outrigger Beam	: 2 m × 7 m

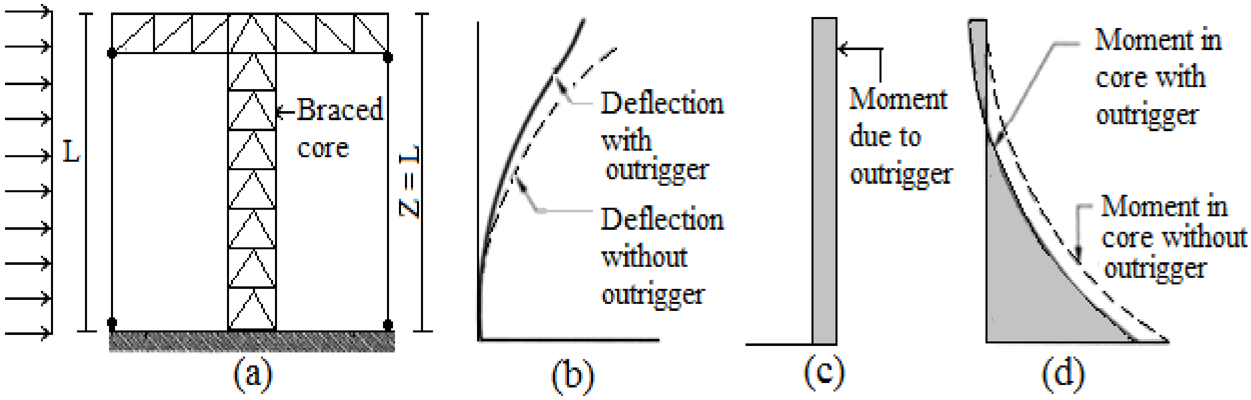


Fig. 2 (a) Cap truss subjected to uniform loading; (b) Deflection with and without outrigger; (c) Moment due to outrigger; (d) Core resultant moment diagram

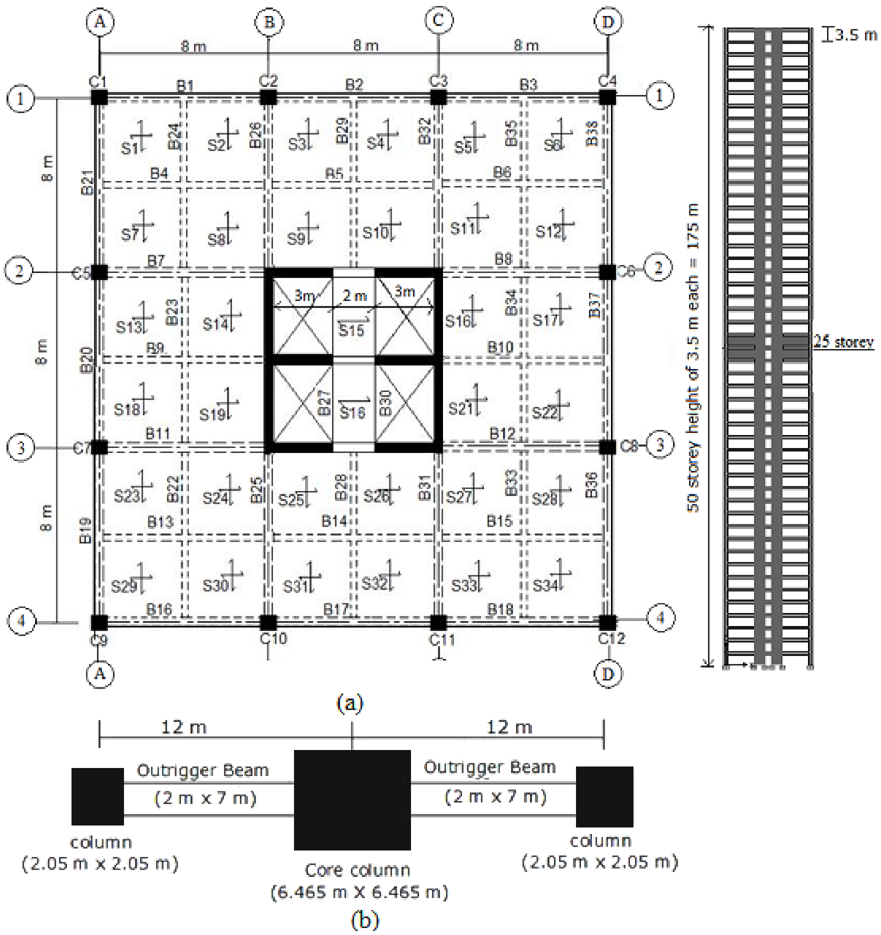


Fig. 3 (a) Typical plan and elevation of three dimensional structure; (b) Two dimensional structure converted from the three dimensional structure

IV. ANALYSIS METHODOLOGY

Following four different methods are adopted for analysis of the outrigger structural system under uniform lateral load of 36 kN/m (i.e. Wind pressure 1.5 kN/m^2 × width of building 24 m).

1. Approximate manual analysis (Manual)
2. Approximate two dimensional structure (2D)
3. Two dimensional structure (Exact-2D)
4. Three dimensional structure (3D)

For the purpose of inducing only axial forces in the columns, moment release is provided at both the end of column.

1) Approximate manual Analysis (Manual)

Approximate manual analysis of structure under lateral uniform wind pressure is carried out by converting three dimensional building into equivalent two dimensional building. Structural member considered for approximate manual analysis are core, columns and outrigger beam. Slab and beam are not considered for manual analysis. Two dimensional structural model for manual analysis is shown in Fig. 4(a). Horizontal top displacement and bending moment in core are calculated based on theory of bending by following equations [1]:

$$M = \frac{wX^2}{2} - M1 \quad , \quad \Delta = \frac{wH^4}{8EI} - \frac{M1(H^2 - X^2)}{2EI}$$

Where,

$$M1 = \frac{w}{6EI}\left[\frac{H^3 - X^3}{S1 + S(H - X)}\right], S = \frac{1}{EI} + \frac{2}{d^2 (EA)_c} \quad ,$$

$$S_1 = \frac{d}{12\,(EI)_o}$$

EI = Flexural rigidity of the core
H = Total height of the structure
w = Intensity of uniform horizontal loading
X =Height of the outriggers from the top of the structure
M1 = Moments created at the level of the outriggers
(EA)c= Axial rigidity of the column
(EI)o = Effective flexural rigidity of the outrigger and
D = Distance between the exterior columns.

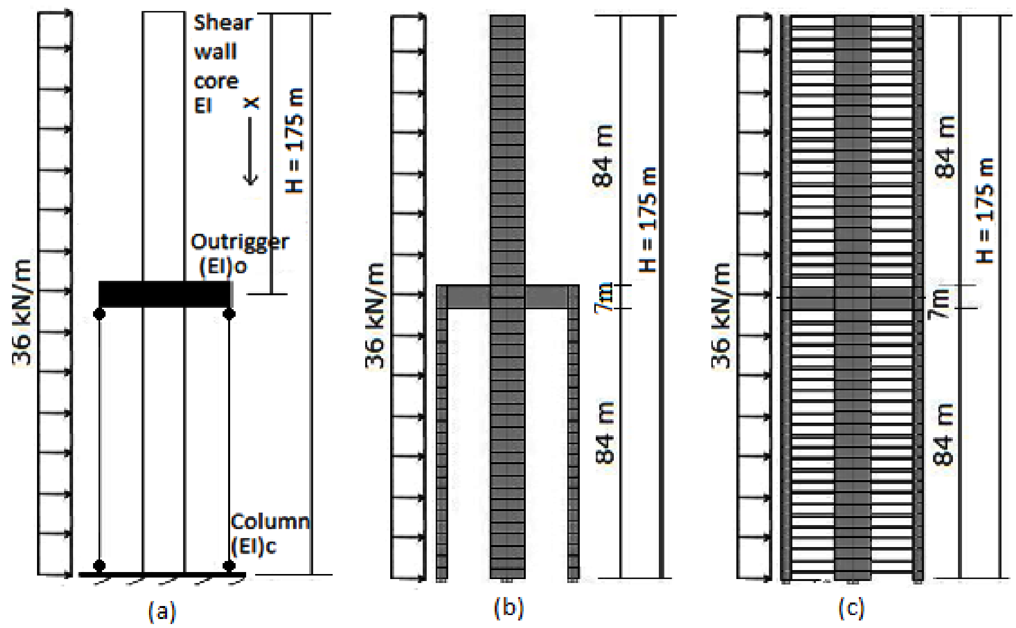


Fig. 4 (a) manual analysis; two dimensional Approximate (b) Approximate structure; (c) Exact two dimensional structures

2) Approximate two dimensional structure (2D)

In this analysis, structure considered in manual calculation is modeled in ETABS. Approximate two dimensional structural model is shown in Fig. 4(b). Here only core, outrigger and columns are considered. Horizontal top displacement and bending moment in core are considered for the comparison purpose.

3) Two dimensional structure (Exact-2D)

Two dimensional structure is derived from the three dimensional structure based on its equivalent stiffness. Modeling and analysis of this structure is carried out using ETABS. In this analysis core, outrigger, full height column and beams at all levels are considered. Exact two dimensional structural model is shown in Fig. 4(c).

4) Three dimensional structure (3D):

Typical floor plan of building is shown in Fig. 3. Three dimensional model of the building under uniform lateral load is developed using ETABS. Shear wall core in center, outrigger beams, peripheral columns are modeled with the dimensions mentioned in section II.

V. Optimum Location of One Outrigger System

Different arrangements of one outrigger are considered to obtain optimum location of outrigger under uniform lateral load. Following models are analysed for optimum locations of one outrigger system as shown in Fig. 5:

1. Outrigger at the top level of the structure height
2. Outrigger at 2/3 level of structure height
3. Outrigger at the middle of structure height
4. Outrigger at 1/3 level of structure height

Three dimensional models of above structures are analysed using ETABS for comparison of storey displacements, core bending moment and lateral drift.

VI. Analysis Results and Discussion

Comparison of analysis results in terms of top storey displacement and core bending moment by above four analysis methods is shown in Table 1. Variation of storey displacement and core bending moment along the height of structure for mid-level outrigger with all the four analysis method are shown in Fig. 6.

Analysis results by all the four methods show minor variation in top storey displacement and core bending moment. This validates equivalent two dimensional modelling of outrigger structural system. Two dimensional model can be used for preliminary analysis while three dimensional model can be used for exact analysis.

TABLE I
COMPARISON OF VARIOUS ANALYSIS METHODS

	Manual	2D	Exact-2D	3D
Top storey displacement (mm)	208.23	216.36	242.12	225.82
Variation (%)	-	3.76	14.00	7.79
Bending Moment in core (kN.m)	284056	287135	294405	287539
Variation (%)	-	1.07	3.52	1.21

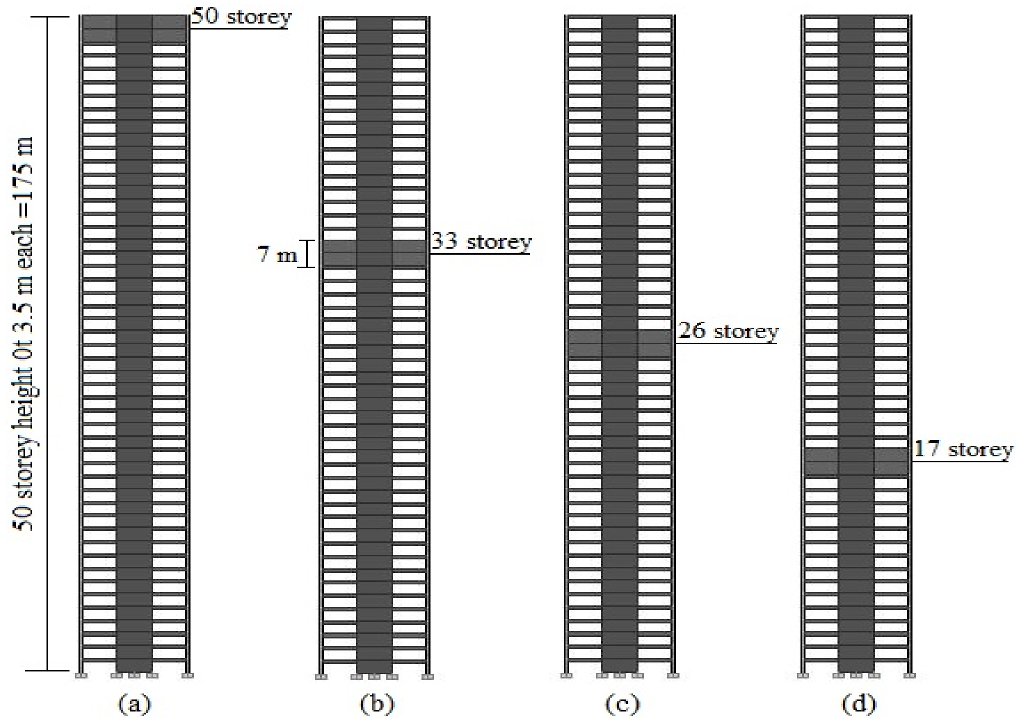
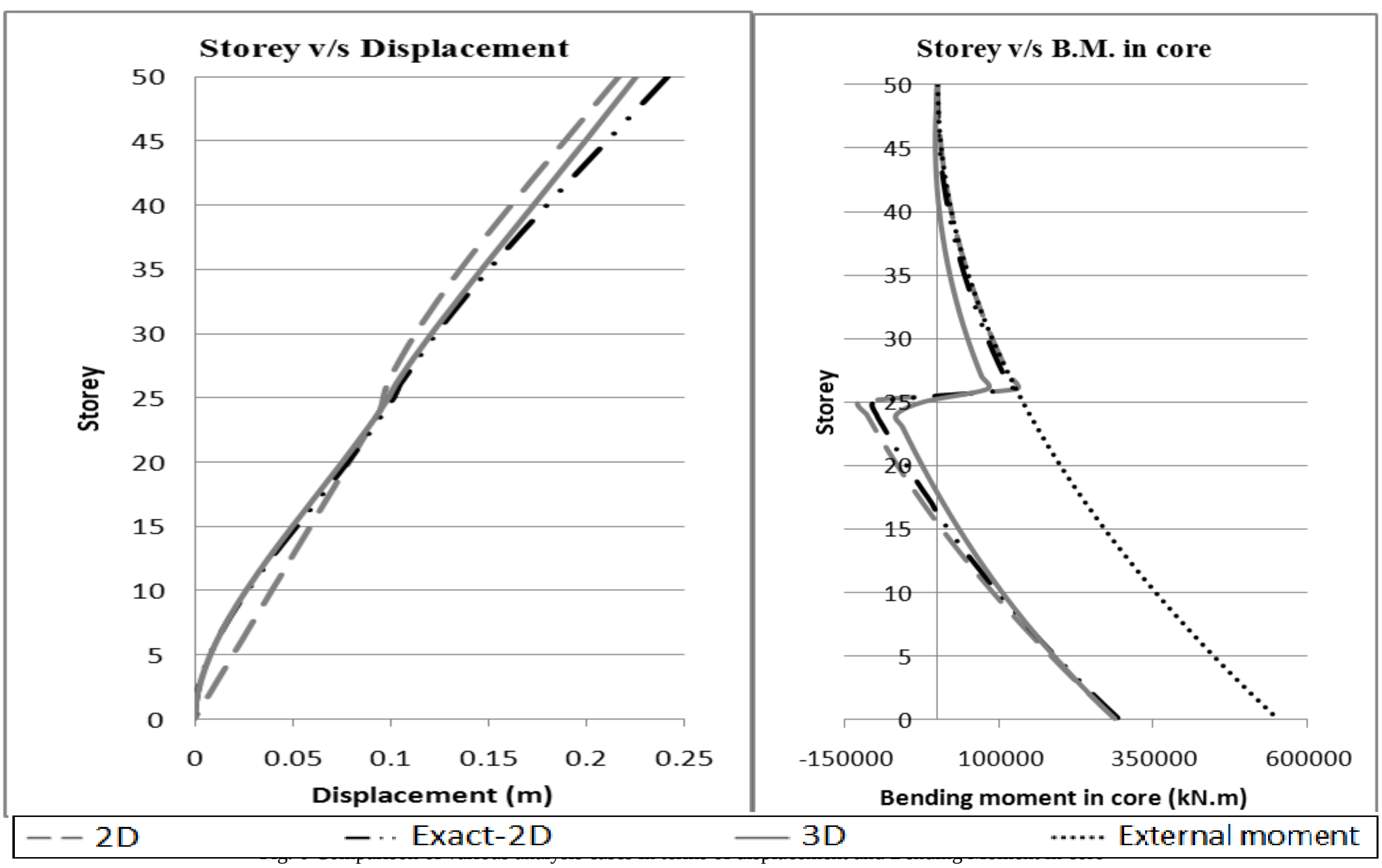


Fig. 5 Structure models with outrigger at (a) top-level; (b) 2/3-level; (c) mid-level and (d) 1/3-level



Analysis of three dimensional structures with different locations of outrigger is carried out using ETABS. Variation of storey displacement and core bending moment along the height of the structure for all four models with one outrigger are shown in Fig. 7 and Fig. 8 respectively. Variation of storey drift along the height of the structure for all four models with one outrigger is shown in Fig. 9.

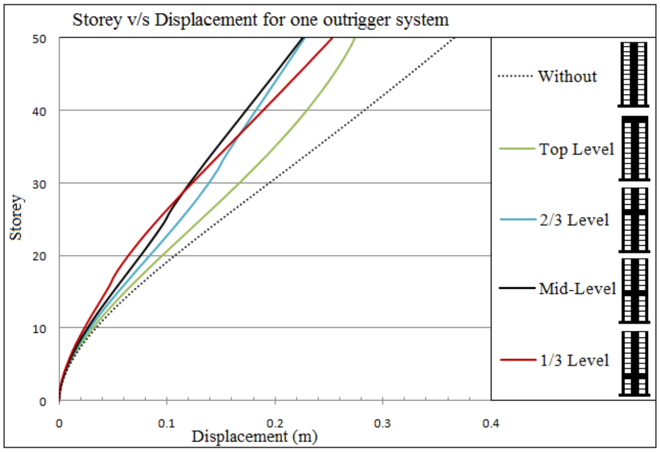


Fig. 7 Variation of storey displacement along the height of the structure

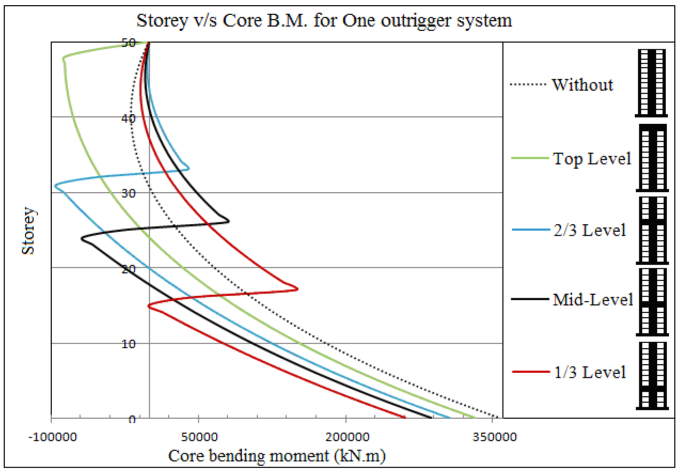


Fig. 8 Variation of core bending moment along the height of the structure

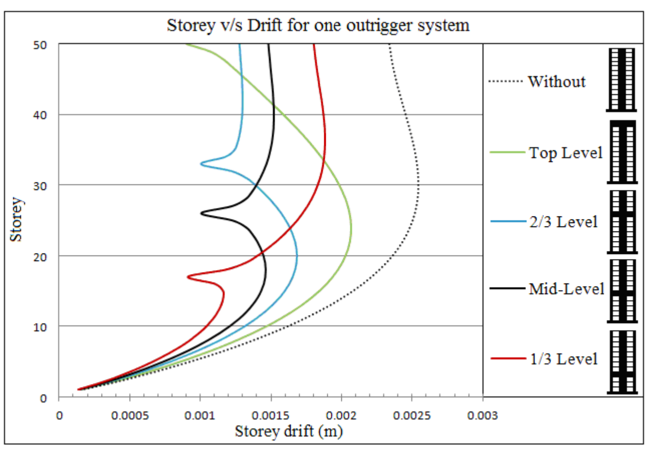


Fig. 9 Variation of storey drift along the height of the structure

Results show that one outrigger provided at mid-height of building reduces the top storey displacement by 38.26% and reduces core bending moment by 19.40% compared to building without outrigger. The reduction in maximum story drift is by 40.34% when one outrigger is provided at mid height.

VII. Conclusions

Outrigger is very effective in increasing stiffness of structure, reducing both the horizontal top deflection and overturning moments in core.

In this paper approximate manual analysis of structure under lateral uniform wind pressure is carried out by converting three dimensional building into equivalent two dimensional building to understand the behaviour of the outrigger structural system and to get optimum location of outrigger in structural system is studied to minimize the lateral load responses.

Variation in results of approximate manual analysis, two dimensional analyses and exact three dimensional analysis are within 3 to 14% for top storey displacement and 1 to 4% for core bending moment at base. Small variation in approximate manual analysis, two dimensional analyses and exact three dimensional analysis validates analysis methods. Equivalent two dimensional analysis is useful for approximate estimate of the deflections and forces for use in a preliminary design of practical three dimensional structures.

It is observed that one outrigger provided near to middle height of structure is most effective in resisting lateral loads.

VIII. References

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