COMPARATIVE SEISMIC PERFORMANCE STUDY OF A RC BUILDING FRAME WITH AND WITHOUT OUTRIGGER SYSTEM USING ETABS

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Abstract Outriggers are regarded as a structural compo- nent which can effectively lessen the reactions generated by lateral loads in tall buildings. Depending on the connectivity between the core and the peripheral columns, the outrig- ger system can be divided into virtual outrigger system and conventional outrigger system (COS). The hybrid outrigger system (HOS) has one conventional outrigger and one vir- tual outrigger at two distinct floor levels. This study gives a comparison of optimal position and performance between COS and HOS based on formulated performance index criterion (PIC) for building heights of 140, 210, 280 and 350 m by considering variations in stiffness of the outrigger belt wall and beam, the stiffness of the building's core, the height of the structure and the length of the outrigger arm under static wind and equivalent static earthquake load. The outrigger behaviour assessed using PIC takes into account the combined response of displacement at top, absolute maximum inter storey drift ratio and acceleration response at the roof. Based on PIC, performance of both COS and HOS at their evaluated optimal position are compared, and is found that HOS are less effective than COS. Therefore, to enhance the performance of HOS to be in par with COS, an optimization study is performed by increasing the axial stiffness of column, stiffness of outrigger, and stiffness of slab while maintaining the increase in total concrete volume of the structure a minimum. From the findings, PIC values of HOS (PICHOS) for 40 to 100 storeys exhibits an increase of 10 to 1.1, 20.2 to 2.2 and 12.5 to 1.9% for variation in core thickness, length of outrigger arm, and outrigger thick- ness, respectively, compared to PIC values of COS (PICCOS). For PICHOS to be comparable with PICCOS, increase in the total concrete volume of HOS reduces from 1.4–16.5 to 0.6–2.5% as the model's height increases from 40 to 100 storeys, respectively, suggesting that the HOS with marginal increase in total concrete volume can perform effectively for taller structures.

Keywords Hybrid outrigger system, Conventional outrigger system, Performance

index criterion, parametric analysis, Comparative analysis, Optimization study

INTRODUCTION

The outrigger design principle is often used in the construction of tall buildings. The outrigger system has become increasingly relevant due to its capacity to enhance the building's behavior performance under seismic and wind stimulation. Extending from the load-resisting core to columns on the building's facade, outrigger walls are connected. Depending on the connectivity between the core and the peripheral columns, the outrigger system can be divided into virtual outriggers and conventional outriggers. Space restriction at the level of outrigger and challenges in architectural planning is a limitation in conventional outriggers due to its direct connection between the core wall and exterior columns. Virtual outriggers were created as an option to solve these challenges; they transfer moments indirectly through floor diaphragms. The vertical belt wall obtains the equivalent horizontal couple from the semi-rigid floor diaphragms and changes it into a vertical couple before transmitting it to the columns, and this movement lessens the core's bending moment . Conventional Outriggers (CO) which connects the core and outer columns directly with the outrigger arms, creates compression forces and tension forces in the leeward columns and windward columns, respectively to transfer forces bringing down the core moment. The conventional outrigger offers a superior reduction in lateral deformation compared to the virtual outrigger because conventional outriggers have the arms directly connected between the columns and the core. Virtual outriggers (VO) can be installed to solve space related issues created by conventional outrigger arms, allowing the floor to be occupied and increasing cost efficiency. A novel system called the hybrid outrigger system with one conventional and one virtual outrigger at two different floor levels is designed in this study, taking into account both the improved performance of conventional outriggers and the space effectiveness of virtual outriggers.

In order to lower the connection costs in complex connectivity between composite or steel outriggers and concrete core, a reinforced concrete outrigger and core are considered for the analysis in this study . According to the wind and seismic loading circumstances, different structural systems has different ideal placements . The position of the out- riggers is seen to be affected differently by the response and stiffness parameters which is taken into account. The optimum location of the outrigger varies depending on the response parameter considered to assess the behavioral characteristics of the structural system. While varying the stiffness parameters, the outrigger response has been accounted considering values of base shear reaction, moment at the base, displacement at top, inter storey drift ratio, acceleration response at the roof, column forces, time period and frequency . This study is based on a performance index criteria (PIC) which takes into account the combined response of displacement at top, inter storey drift ratio and acceleration response at the roof. The formulation of PIC is explained in Sect. (Procedure for analysis and evaluation of optimal position using Performance Index Criterion (PIC)). The Performance index criterion is used to assess structure's overall response than to analyze each dependent parameter separately .

A considerable amount of research on concrete outrigger systems, according to prior literature assessments, has only been done on conventional outriggers, facade riggers, virtual outriggers, outriggers with belt truss/wall, and out- riggers installed with dampers. The study of conventional and virtual outriggers in a single structure, which is phrased Hybrid Outrigger System (HOS) in this research work, is understudied in the previous literature. When comparing hybrid outrigger systems to Conventional Outrigger System (COS), conventional outrigger systems efficiency would be better; however, the behavioural performance of the HOS can be improved by altering the proportions of the structural components.

In this study, the stiffness of the outrigger belt wall and beam, the stiffness of the building's core, the structural height and the length of the outrigger arm are considered as the stiffness variables used to examine the behaviour of HOS and COS. The above-mentioned independent factors are represented by a dimensionless parameter β, taken as the relative stiffness ratio between core and outrigger. The optimal placements under static wind and equivalent static earthquake loads are calculated for a total of 12 β values, taking the PIC into account for both COS and HOS, and a comparison of optimal locations and performance based on PIC between HOS and COS is carried out. However, hybrid outriggers are less effective than conventional out- riggers with the same structural component dimensions due to their reduced rigidity at the virtual outrigger floor of HOS which has an indirect force transmission mechanism. Therefore, a study on the enhancement of the performance of HOS is carried out by increasing the bending stiffness of slabs, axial stiffness of columns, and bending stiffness of outriggers by certain folds for the formulated β values keeping the increase in total concrete volume of the structure a minimum.

Methodology

The independent parameters considered for this research are stiffness of core and outrigger, outrigger arm length and structural height. These factors are varied over a specific range and the analysis is done for those variations. The independent factors stated above are consolidated to form a dimensionless factor termed β considered as the ratio of relative stiffness of core to relative stiffness o

Locations Where Outriggers are placed for the Evaluation of Optimal Positions

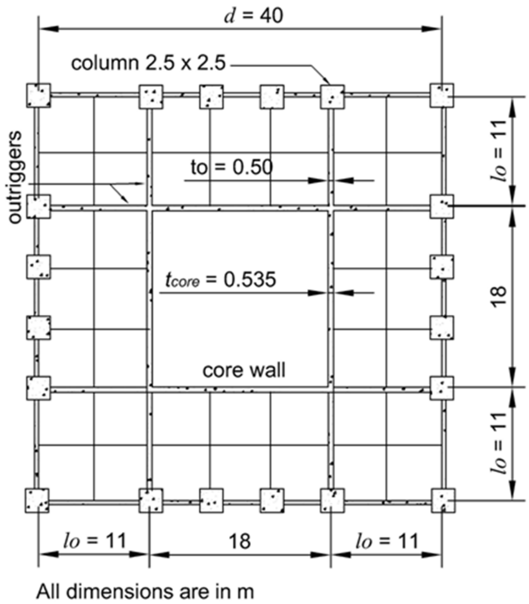
In order to provide for spacious foyer areas, the lowest level for the base outrigger is set for all models at the fifth story. The separation between the lower and higher outrigger is set for all models at H/3, where H is the height of the structure. Six placements of the hybrid outrigger are selected for models with 40 stories. The CO is below the VO in the first three sets, which are italicized.

The expressions to calculate the moment of inertia of core, conventional outrigger and virtual outrigger is explained in John and Kamath (2022) . As the hybrid outrigger has both conventional and virtual outrigger, the moment of inertia of VO and CO are calculated separately for the formulation of the β values. By altering the width of the building d, outrigger thickness to, and core thickness tcore across a defined range, 12 values for the parametric analysis are produced. For consistency, the breadth of the core wall b is kept at 18 m for the models studied, whereas t core is altered accordingly while maintaining a constant ratio of area of floor to area of core wall.

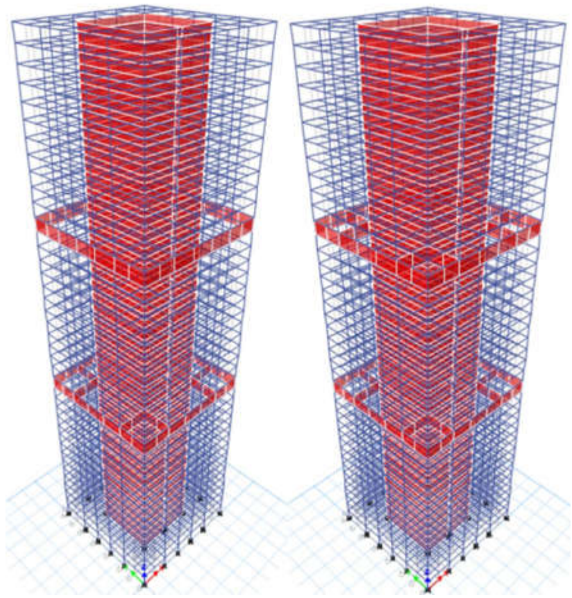
Modeling Details and Loading Conditions

The benchmark model has a core wall that is 18 m wide and no outriggers placed. Figure 1a shows the floor plan at CO level of βCO-40 = 332.97 and respective βVO-40 = 9.71. Figure 1b and c shows the 3-D view for HOS and COS model. The length of outrigger arm is represented by lo, and for 35 m wide models it is 8.5 m and is incremented from 8.5 to 16 m in 2.5 m increment varying the width of the model from 35 to 50 m in the models considered for this study.

Along both x and y axis, the models are symmetrical and are analyzed in a finite element software, ETABS. The individual storey height is assumed to be 3.5 m and the compressive strength of concrete is taken as 60 MPa. The loads are defined as per IS codes. The models are subjected to static wind and earthquake loads (EQ). Slab thickness at outrigger level is taken as 250 mm to carry the higher loads of outriggers and other floors has a typical slab thickness of 180 mm.



(a) Floor plan at outrigger



(b) 3-D view of HOS (c) 3-D view of COS

The slabs are given a super dead load of 1.5 kN/m2, a live load of 3.5 kN/m2, and a live load of 1.5 kN/m2 on the roof. The IS codes are utilized to calculate the wind speed, pressure coefficients, and seismic zone factor on the assumption that the structure is located in Mumbai. The seismic zone and wind speed are 0.16—III and 44 m/s, respectively. Shell-thin modeling is used to design the out- riggers and core wall as wall sections. Frame elements are used to represent beams and columns and shell-thin elements are defined for slabs. Semi-rigid diaphragms are defined to the slabs linking the outrigger walls in order to simulate real in-plane stiffness characteristics and the transmission of force through beams and slabs attached to the VO walls. Static wind and equivalent static earthquake analysis are performed on all models in accordance with IS standards.

Analysis Results

Performance Comparison between Hybrid Outrigger System and Conventional Outrigger System

To analyze the efficiency of hybrid outrigger system over conventional outrigger system, the percentage reduction in the values of ISDAMR, DSPROOF and ACLRROOF are com- pared for both systems placed at the same floor level keeping the bench mark model as the model with core wall alone. For instance, Table 3 shows a comparison of percentage reduction in the dependent parameters for β values formulated for increase in outrigger thickness under wind loads for 40 storey models under various outrigger positions as in Table 2. The benchmark model considered is model with core wall alone and the response of the HOS and COS is compared to the benchmark model response so as to calculate the percent- age reduction values. The values marked in bold shows the maximum reduction in the responses for both COS and HOS, and is visible that the COS offers a better performance when compared to HOS models.

Similar performance pattern is noticed for other heights as well. Comparing all the building heights, the optimal position evaluated for conventional out rigger system is nearly obtained at 1/3rd and 2/3rd position of the building height and is close to the optimal locations obtained for COS from the previous research studies. It is also noticed that the performance of COS is slightly better than the HOS because of the increased stiff- ness of conventional outrigger arms.

Figure 3 gives a comparison between conventional and hybrid outrigger system in terms of ISDAMR and DSPROOF at their optimal position under wind and earthquake loads for 40, 60, 80 and 100 storey models. On comparing the results of HOS to COS from 40 to 100 storeys, the percentage increase in the values of ISDAMR, DSPROOF and ACLRROOF for HOS are within 12.5–1% for tcore and to variations, but a percentage increase of 22–1% is observed for lo variations. This is because of the increased relative stiffness of core to outrigger and reduced aspect ratio. But, incorporating hybrid outrigger system can make the structure more economical as the virtual outrigger can eliminate the problem of space obstruction due to outrigger arms, thus utilizing that floor for occupants. Once the responses from the above dependent parameters are obtained for all the building heights, the optimal position for both hybrid and conventional outrigger system based on PIC is evaluated.

The mode shapes of the models with COS and HOS have been studied. The natural period of fundamental torsional mode of vibration is not exceeding 0.9 times the smaller of the natural periods of the fundamental translational modes of vibration in each of the orthogonal directions in any of the cases. The Fig. 4 gives sample representation of the first three mode shapes of COS and HOS for βco – 40 = 175.25 having position at 2–40-sq. Similarly, for other models, vibration in mode 3 is not exceeding 0.9 times smaller of natural periods in orthogonal directions (mode 1 and 2).

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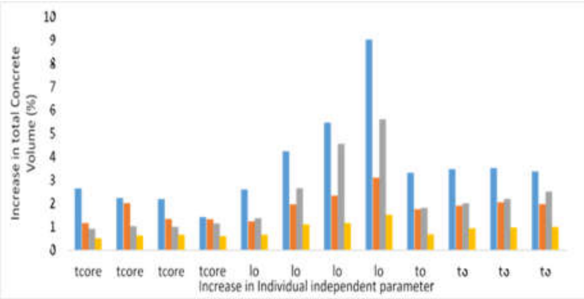

Fig:-Percentage increase in total concrete volume of the structure when only the column and outrigger stiffness is increased under wind loads

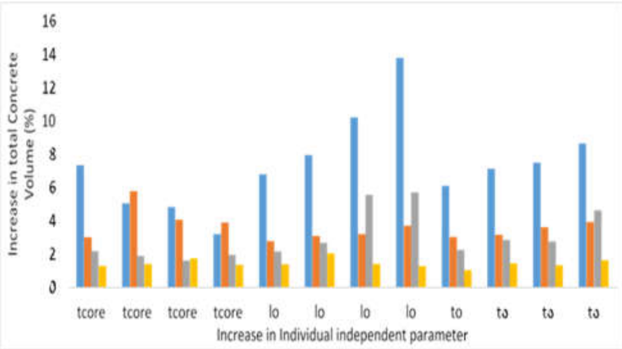

Fig:-Percentage increase in total concrete volume of the structure when only the outrigger and slab stiffness are increased under wind loads

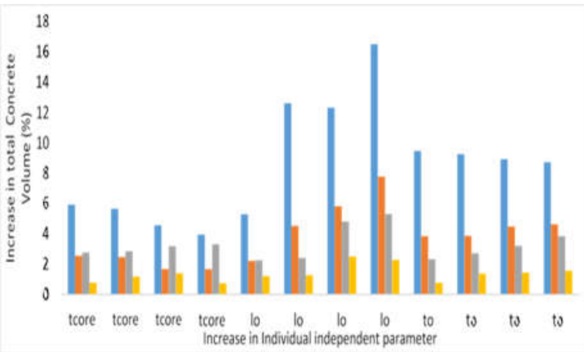

Fig:- Percentage increase in total concrete volume of the structure when only the column and outrigger stiffness is increased under EQ loads

Conclusion

Hybrid outrigger system adopts collectively behavioral efficacy of conventional outrigger system and space efficiency of virtual outrigger system. COS shows an improved resistance to lateral deformations compared to HOS. This study quantifies and compares the efficiency of both COS and HOS using a performance based analysis, and also portrays how the performance of HOS can be enhanced to be comparable to COS using an optimization study. The optimization study performs various trials for each β variation to improve HOS' performance by raising the stiffness parameters, while keeping the increase in total concrete volume of the structure to a minimum. The results of the analysis lead to the subsequent conclusions.

- In the 60, 80, and 100 storey models for the EQ loads, the COS system's optimum position is higher than the HOS, while in the 40 storey models, the HOS optimum position is higher than the COS system. In the case of wind loads, HOS has a higher optimal placement than COS for all four building heights.
- A higher PIC wind and PICEQ value is found in the models with HOS compared to the COS system in their optimum position proving the improved resistance capacity of COS to lateral loads. PIC

values of HOS for 40 to 100 storeys exhibits an increase of 10 to 1.1, 20.2 to 2.2 and 12.5 to 1.9% for variation in core thickness, length of outrigger arm, and outrigger thickness, respectively, compared to PIC values of COS.

- Increase in total concrete volume under wind and EQ loads are greater for models with enhanced outrigger and slab stiffness than for models with increased column and out- rigger stiffness. The increase in total concrete volume for PICHOS to be at par with PICCOS under wind loads varied from 1.4 to 9, 1.15 to 3.1, 0.98 to 5.6% and 0.9 to 1.51% in 40, 60, 80 and 100 storeys, respectively in models where column and outrigger stiffness alone is increased, and from 3.2 to 13.8%, 2.7 to 3.9%, 1.6 to 5.7% and 1 to 2% in 40, 60, 80 and 100 storeys, respectively in models where slab and outrigger stiffness alone is increased. The increase in total concrete volume for the same under EQ loads varied from 3.9 to 16%, 1.6 to 3.8%, 2.2 to 5.2%, and 0.7 to 2.5% in 40, 60, 80 and 100 storeys, respectively for models where column and outrigger stiffness alone is increased.
- For PICHOS to be comparable with PICCOS, increase in the total concrete volume of HOS reduces from 1.4–16.5% to 0.6–2.5% as the model's height increases from 40 to 100 storeys, respectively, suggesting that the HOS with marginal increase in total concrete volume can perform effectively for taller structures.

The study is limited to uniform material proper- ties, cross-section and sizes for the structural elements throughout the height of the building. Study pertaining to the reduction in cross-section of the vertical elements at higher levels has to be performed to analyze the practical implementation of HOS in taller structures. Further, connection detailing of outrigger to the core and columns has to be addressed for proper implementation of HOS in taller structures.