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Linear Dynamic Analysis of Different Structural Systems for Medium Rise Buildings (A Case Study)

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Abstract**:** *A comparative study is carried out to examine the behavior of different structural systems under seismic loads in structurally irregular medium rise building. The structural systems analyzed in the case study include Intermediate Moment Resisting Frame (IMRF), Dual RCC Wall-Frame and RCC Braced Frame Structures including Cross Braced, Single Diagonally Braced, V Braced and Inverted V Braced Frame Structure. The structures are modelled and analyzed in "ETABS" Software using 2D modeling. Response spectrum analysis has been carried out to study the performance of structures under the action of dynamic loads. Design considerations were made according to "UBC-97" and Building Code of Pakistan (BCP-2007). The effectiveness of Wall-Frame structure has been analyzed by varying the location of shear walls while RCC Braced structure is analyzed by altering the type of bracing system in different cases. The parameters considered for analyzing the structural response of structural systems subjected to seismic loads are lateral drift, base shear force and structural time period. It has been concluded that for high intensity seismic zones dual RCC wall-frame structures are most suited to control lateral drift in medium to high rise structures. For low seismic zones a frame structure or a braced-frame structure gives better structural performance under dynamic loads.*

Keywords: *Braced Structures, Concrete Bracing, Shear Walls, Dual Wall-Frame Structures, Intermediate Moment Resisting Frame Structures, Medium Rise Buildings, Case Study.*

1. Introduction

In low rise buildings, seismic loading does not produce significant lateral displacement therefore, moment resisting frames are sufficient to resist both gravity and lateral loading. In medium to high rise buildings, acceleration due to lateral loads significantly increase with height of structure. Therefore, RCC Shear walls or RCC bracing are additionally designed and incorporated to cater for lateral loads [1].

The earthquake that stuck Pakistan on Oct 8th, 2005 with recorded magnitude of 7.9 on Richter scale also initiated the need to optimize the design of lateral force resisting structures located in medium to high risk seismic zones [2]. Shear walls are generally used in Medium rise buildings in Pakistan to control lateral drift. In a dual structural system; comprising frame and lateral force resisting system, torsional forces are generated when Center of mass and Center of rigidity for a building vary by more than 20%. The center of rigidity depends on the location of shear wall and bracing in the building. Therefore, placement of shear wall and bracing elements has significant effects on behavior of a structure subjected to earthquake loading.

To determine the effectiveness of structural systems, an existing 19-story building (excluding three basement floors) located in Blue Area, Islamabad has been studied with different proposed shear wall locations and proposed bracing types coupled with intermediate moment resisting frame structure. The building is originally designed with RCC shear walls and RCC bracings.

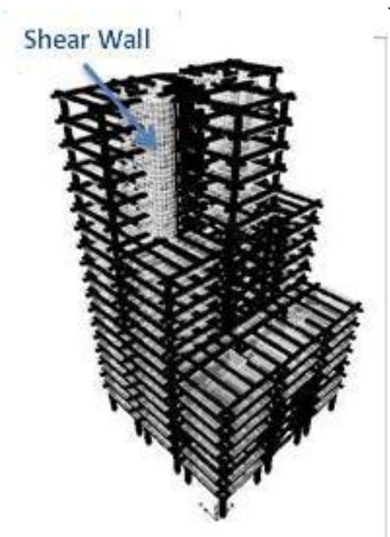
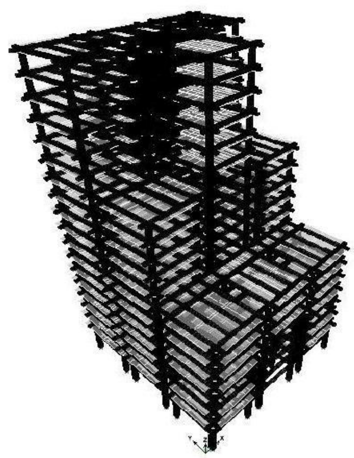
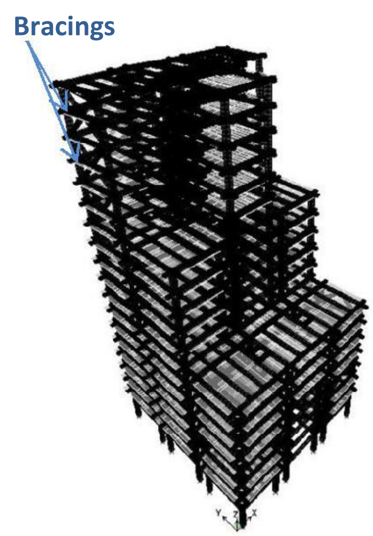
2. Case Study

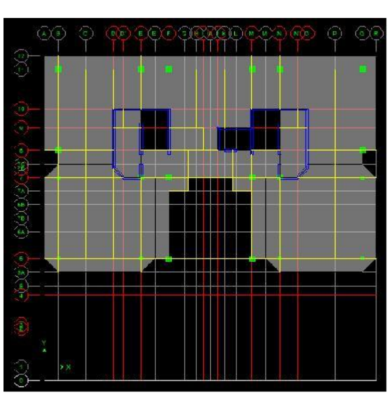
State Life Tower building is a 19-story (excluding basements) medium rise building situated in Blue Area, Islamabad. It is originally designed as a dual structural system consisting of intermediate moment resisting frame reinforced with shear walls and concrete bracings. Building lies in seismic zone 2B (PGA range is 0.16g to 0.24g) with occupancy category of III i.e. Special occupancy structures [3]. Total building height from the ground level is 66m. Analysis is carried out on aforementioned structural systems. The best possible case for each system is selected and then compared with other systems to reach conclusion.

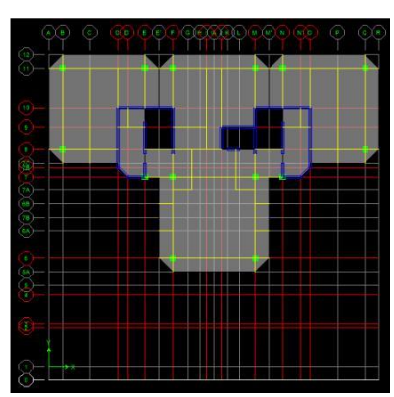
2.1. Structural Systems

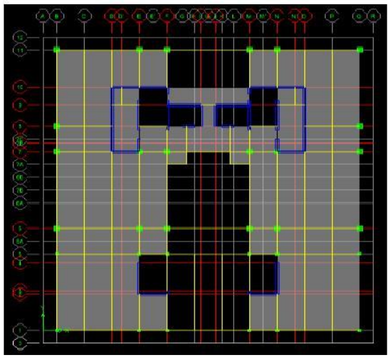
A brief description of different structural systems that are analyzed and compared in the case study are presented in Table 1. The layout plan of different floors of State Life Tower, Islamabad, is shown in "Fig. 1."

TABLE I: Comparison of Structural Systems used in Case Study

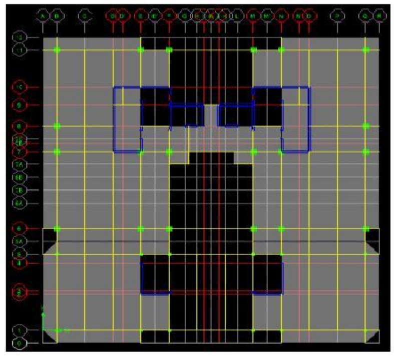
Type of Structure	Dual Wall-Frame Structure	Intermediate Moment Resisting Frame Structure	Concrete Bracing Structure
Behavior Under Lateral Loading	This structural system consists of RCC frames interacting with RCC shear walls. Beams and columns primarily take vertical loads while shear wall is designed to resist lateral loads as well as vertical loads to some extent.	The frame system consists of columns and beams that are interconnected with restrained moment connections. With a moment connection a column is attached to a beam with no release at the joint when structurally analyzed. Loads are resisted in moment-frame systems by flexure in the beams and columns that induce shears and moments into beams, columns and the moment-connected joints.	This structural system is designed primarily to resist lateral loads like wind and earthquake forces. Members in a braced frame are designed to work in tension and compression, similar to a truss. A braced frame resists lateral loads by the actions of its diagonal members. Buildings are braced by inserting diagonal structural members into the rectangular open areas of a structural frame.
Representative ETABS Model			



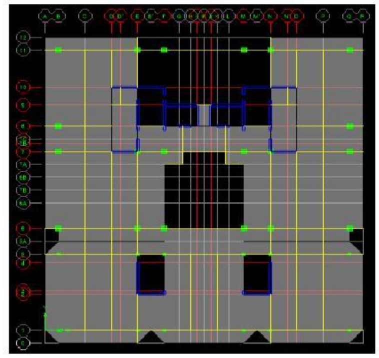




Ground Floor Plan



2nd Floor Plan



6th Floor Plan

9th Floor Plan

14th Floor Plan

Fig 1: Plan View of different floors of Original State Life Building in Islamabad

2.2. Modelling in ETABS

The structure is analyzed using response spectrum analysis method in ETABS with following assumptions;

- Beam-column joints were modeled as rigid joints. Frame was detailed as an intermediate resisting frame (IMRF), as IMRFs are usually detailed in seismic Zone 2B [4].
- The system was assumed to be linearly elastic and floors and beams were assumed to be rigid, which will overestimate the stiffness of building. Considering the general trend of acceleration of the response spectrum; the fundamental time period of structure will decrease which in turn will result in larger earthquake induced forces. Hence, the assumption of floor and beam rigidity can be thought as a safe engineering assumption.
- All supports were assumed to be fixed supports.
- Only structural elements with significant stiffness; beams, columns, shear wall, concrete bracings were modeled and non-structural elements were ignored.
- Ramps in basements were modeled as slab structures to account the rigidity and stairs were not modeled.
- For mass source 100 % D.L and 25% L.L is used. The mass is lumped at each story level.
- P– effects are considered when the ratio of secondary to primary moment is > 0.10 and our calculations show that P-Delta effects are not required in any structural scenario analyzed in the case study [4].

2.3. Structural Irregularities

The building under consideration is fairly irregular in various dimensions. It has vertical geometric irregularity between story levels 8 and 9. Stiffness irregularity exists between story levels 1 and 2 [4]. Torsional irregularity is dependent on plan layout which is variable in each structural scenario. Hence, torsional check is performed for each scenario separately. Summary of various structural irregularities present or absent in the building is shown in Table 2.

TABLE II: Summary of Structural Irregularities

Horizontal Irregularity	Check Performed	Vertical Irregularity	Check Performed
Torsional Irregularity	To be checked for each case	Stiffness Irregularity	Yes
Re-entrant Corners	Nil	Weight Irregularity	Nil
Diaphragm Discontinuity	Nil	Vertical Geometric	Yes
Non Parallel structural irregularity	Nil	In Plane Discontinuity	Nil
Out of plane irregularity	Nil	Strength Irregularity	Not checked

2.4. Analysis Procedure

According to Section 5.29.8.4 of BCP 2007, Dynamic Analysis is preferred because, it is an irregular structure and lies in Seismic Zone 2B with Occupancy Category of III [4]. Response spectrum analysis with Ritz vectors has been performed on all cases [5, 6]. The spectrum cases in ETABS are defined according to UBC 97.

3. Results and Discussions

3.1. Case 1: Shear Wall-Frame Structure

The State Life building is designed as a dual system consisting of intermediate moment resisting frame coupled with shear walls. The layout and location of shear walls is shown in “Fig. 1”. Two sets of shear walls run up to 6th floor with location so adjusted as to reduce torsional stresses. Beyond 6th floor, the plan area reduces significantly and lower shear walls are terminated. Analysis is carried out without altering the position and configuration of the building. The allowable maximum lateral drift/displacement value is calculated using H/500 expression, where “H” is the height of building from ground surface. The building has no torsional irregularity [7, 8].

Further analysis is carried out by altering the location of shear wall in the building to understand the structural behavior subjected to peak ground acceleration of up to 0.24g. Two sub-cases are analyzed with respect to shear wall location. In shear wall proposed layout 01 (SW-PL-01), shear wall is placed at the center of the building where it acts as a core wall. Shear wall proposed layout 02 (SW-PL-02) is formulated by moving shear wall towards the periphery of the building. Torsional irregularity is present in both proposed layouts. Analysis results are shown in Table 3.

TABLE III: Analysis results for wall-frame dual structure

Parameters	Original Structure	SW-PL-01	SW-PL-02	Allowable Value
Max. base shear (kN)	9487	8767	7317	---
Time period 1st mode (sec)	1.12	1.22	1.26	---
Max. lateral displacement (mm)	38.6	43.2	43.4	131

Lateral displacement as a function of story level for wall-frame cases is plotted in “Fig. 2(a)”. The structural response is non-linear and slope of lateral displacement curve increases after Floor 9. The lateral drift curve for SW-PL-01 and SW-PL-02 is almost identical up to 8th floor, where afterwards there is a break between 8th and 9th floor for SW-PL-01. One possible reason for this behavior is the vertical geometric irregularity that exists between floors # 8 and 9. The maximum lateral displacement at top floor is 43.4mm. It can be seen from analysis results that the time period of building in 1st mode for proposed layouts has small variation compared to original case that dictates a more ductile response of building under seismic loading. The base shear force for proposed layout 2 is 2170kN less than the original case. However, the maximum lateral displacement has increased by almost 5mm with respect to original structure but is well below the allowable limits prescribed in building codes i.e. 131mm. Proposed layout 02 has the minimum base shear force and highest time period with well controlled lateral drift values among the considered Wall-Frame dual cases. Hence, this layout is selected for further comparison with other structural systems.

3.2. Case 2: Intermediate Moment Resisting Frame (IMRF)

The performance of frame structure for medium rise structures under lateral loads is also important aspect of this study. The shear wall is removed from the structure to analyze the intermediate moment resisting frame in ETABS. The parameters considered are same i.e. the effectiveness of frame structure in controlling lateral displacements and structural response to seismic loads. For this layout of the building additional torsional stresses are also produced in the structure. Analysis results are shown in Table 4.

TABLE IV: Analysis results for frame structure

Parameters	Maximum Value	Allowable Value
Base shear (kN)	4412	---
Time period 1st mode (sec)	2.7	---
Max. lateral displacement (mm)	102	131

The base shear forces have reduced to about 50% by removing shear wall compared to wall-frame original case results. The stiffness of frame structure is quite less as indicated by time period in 1st mode i.e. 2.7sec. This accounts for ductile behavior of structure under the action of dynamic loading. However, the lateral displacement in this case is very high i.e. 102mm which is a clear indicative of effectiveness of shear wall in controlling lateral drift of structure.

3.3. Case 3: RCC Braced Frame Structure

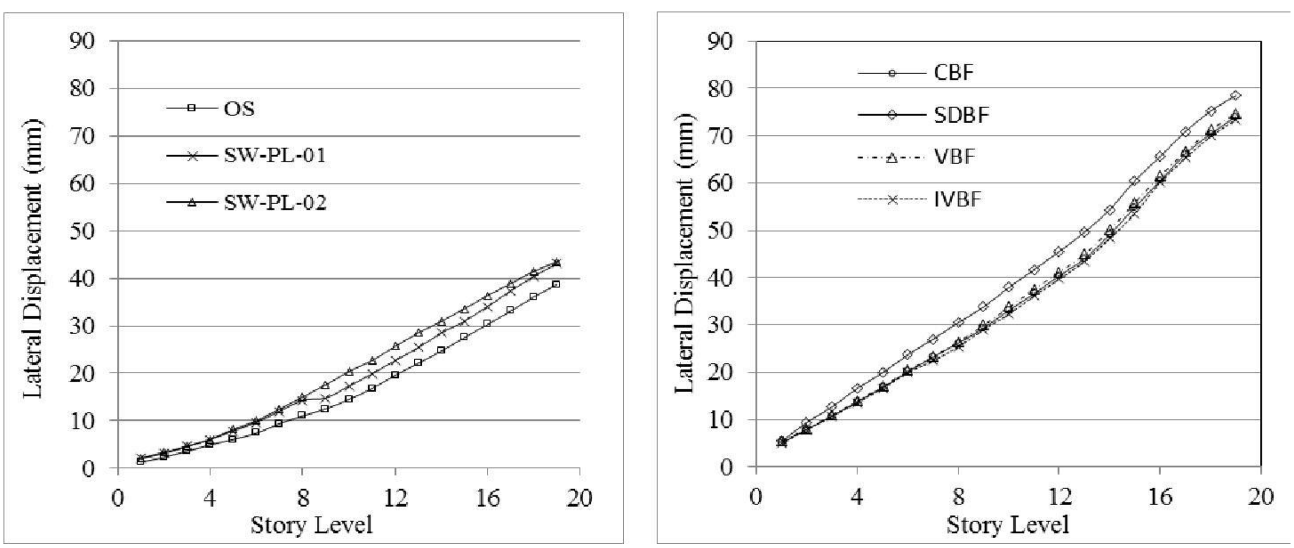
In this case, different types of RCC bracings are separately incorporated into IMRF model of the building. Each different type i.e. Cross bracing, Single Diagonal bracing, V bracing, Inverted V bracing gives a distinct structural response [9]. Based on analysis results (Table 5) the best scenario among these bracing systems is selected for comparison with selected structural systems. However, in this study the effects of location of bracings in the structure are not studied.

TABLE V: Analysis Results for Braced Frame Structure

Parameters	Cross Bracing	Single Diagonal Bracing	V Bracing	Inverted V Bracing	Allowable Value
Max. base shear (kN)	8091	7285	7775	7970	---
Time period 1st mode (sec)	1.67	1.84	1.73	1.69	---
Max. lateral displacement (mm)	74	78.5	74.6	73.4	131

Lateral displacement profile for Braced-Frame structures is shown in "Fig. 2(b)". The response of lateral displacement is quite linear up to 14th floor and increases non-linearly afterwards (also refer "Fig. 1" where floor area changes at 14th floor). It is evident from analysis results that the base shear forces of braced frame are quite comparable with that of shear-frame results. Cross bracing system produces maximum base shear force and single diagonal bracing the least. The structural time period for single diagonal bracing is higher i.e. 1.84sec whereas the results of other three bracing types are quite comparable. This time period is higher compared to wall-frame structure imparting more ductility in the structure. The stiffness of braced frame structure is higher than the IMRF but quite less than the shear-frame structure producing higher values of lateral displacement.

The lateral displacement values vary from 73.4mm for Inverted V Bracing to 78.5mm for single diagonal bracing. Single Diagonal Braced Frame (SDBF) is the best possible scenario as the base shear forces are minimum and time period is highest compared to other bracing types.



a. Case 1 b. Case 3

Fig. 2: Lateral displacement profile for Shear Wall and Braced Frame structures

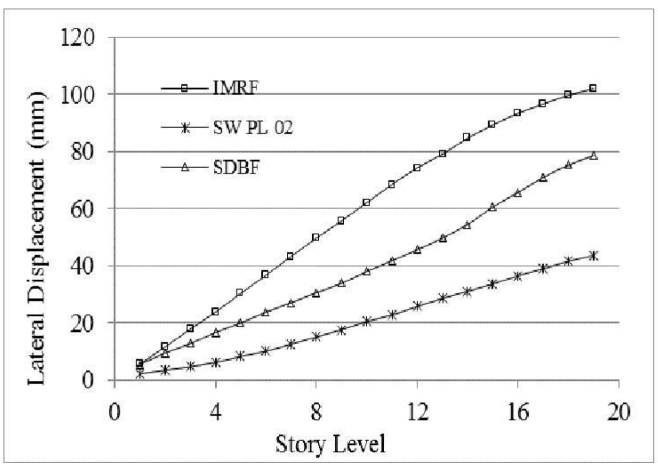
4. Comparison Between Different Structural Systems

The selected cases from different structural systems are compared based on analysis results to evaluate the most optimum and suitable structure keeping in view the parameters i.e. base shear force, time period and lateral displacement of the building subjected to an earthquake load corresponding to a PGA of 0.24g. The analysis results of selected cases are shown in Table 6 and plotted in "Fig. 3".

TABLE VI: Comparison of Selected Cases

Parameters	SW-PL-02	IMRF	SDBF	Allowable Value
Max. base shear (kN)	7317	4412	7285	---
Time period 1st mode (sec)	1.26	2.7	1.84	---
Max. lateral displacement (mm)	43.4	102	78.5	131

Graph shows that lateral displacement in SW PL 02 is almost linear throughout the height of the building. However, there is a break in the linear curve of SDBF and IMRF where the trend becomes non-linear at story level 14 due to structural irregularity between levels 13 and 14. Base shear forces generated in IMRF are quite less i.e. 65% of dual systems. Results indicate that lateral drift for IMRF and SDBF has increased by 135% and 80% respectively compared to dual shear wall system. Dual systems incorporating shear walls coupled with frame are stiffer as compared to braced frames and rigid moment resisting frames based on results of time period of structure. Effectiveness of dual system in controlling lateral drift is quite obvious compared to frame structure. "Fig. 2" also shows a good representation for lateral drift control of wall-frame structure compared to braced-frame structure. Though the increased time period of structure gives better structural response under dynamic loading but it alone cannot serve as a design criterion [10]. For high rise structures where lateral drift is the governing criteria for design, dual wall-frame systems are recommended be used [11]. The lateral displacement values for braced frame and IMRF are less than the allowable limit from building codes but for structures lying in occupancy category III, a lateral displacement value of 78.5mm or 102mm cannot be tolerated. Keeping in view the structural parameters and lateral drift control shear wall dual system is most suited for medium rise structures.



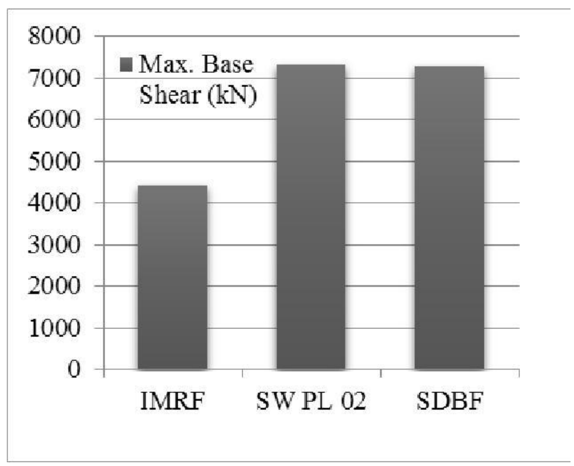


Fig. 3: Comparison of Lateral displacement and maximum Base Shear force for selected cases

5. Conclusion

The selected case i.e. SW-PL-02 is now compared with the results of actual structure. The base shear in selected case is 29.6% less whereas the time period of structure in 1st mode and lateral displacement has increased up to 12.5% compared to original structure (Table 7). The increase in lateral displacement is small and can be compromised. The reduced base shear forces will result in reduced cross sections of concrete members and steel reinforcement. This will affect the overall economy of structure. The concrete braced and IMRF structure can be used for medium to high rise structures in areas with low seismic intensity but dual systems are recommended for high intensity seismic zones to control lateral drifts.

TABLE VII: Comparison with Original Building

Parameters	Original Building	SW-PL-02	% age Difference
Max. base shear (kN)	9487	7317	29.6% decrease
Time period 1st mode (sec)	1.12	1.26	12.5% increase
Max. lateral displacement (mm)	38.6	43.4	12.4% increase

6. Acknowledgment

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