Categorization of Buildings Based on the Relative Effect of Lateral & Vertical Forces with Change in Height

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Abstract In this research an attempt has been made in order to determine the efficiency of different types of structural systems at different heights up to 30 stories (300 feet). The investigation has been carried out on three types of lateral load resisting systems i.e. moment resisting frame, building frame system and outrigger braced frame system for seismic zone 2B as per UBC 1997 considering dead, live, seismic, wind load and their combinations. It was found that up to a 5 story building (50 feet) moment resisting frame was found more cost efficient as moment resisting frame was found stiff enough to resist lateral load and addition of shear wall was not required for further increase in stiffness. From 6 story building up to 20 story building (200 feet) building frame system was found more cost efficient and from 21 story building and beyond outrigger braced frame system was found more cost efficient. Accordingly, from one to five story buildings were categorized as low rise, from six to nineteen story buildings as medium rise and from twenty stories onwards as high rise buildings.

Keywords: low-rise buildings, high-rise buildings, cost comparison

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1. Introduction

In this modern world of scientific and engineering development, civilization is often characterized by mass population and to accommodate this population density, construction industry all around the globe is moving towards the trend of high rise residential structures. For contemporary societies worldwide, high-rise structures are becoming common thing and inevitable part of new living style. Whether high-rise buildings function as commercial, residential or educational use of these forms of vertical architecture is becoming more and more popular [1]. In a common way, every city has some structures which are classified as high rise primarily with reference to their height [1]. With view point of construction engineering, no standards have been set for classification of buildings as high rise or low rise structures. Every country is classifying their own parameters of structural engineering to identify the building type. [2] has studied different structural systems for the construction of high rise sky scrapers.

[3] studied and proposed different scenarios for applying different frame systems to high rise buildings. These frame systems include Rigid frames, Braced frames, Outriggers and different frames of tubular structures. Some latest development in structural buildings are termed as super tall and mega tall structures where major components are combined for structural framing to fulfill

the modern design requirements [4] where some core outriggers with mega columns are also studied. Zaidi *et. al.* 2018 has conducted a study using a new concept of reduced depth outriggers for constructing multistory high rise structures in a moderately active seismic zones [5].

The National Fire Protection Association (NFPA), in United States, defines the high-rise buildings as a structure having higher than 75 feet [6] while Emporis standards define high-rise buildings as a structure between 35 to 100 meters tall [7]. [8] describes the high-rise buildings as any structure between 75 and 491 feet while a skyscraper is a structure taller than 492 feet.

2. Analysis for High-Rise Building Classification

Literature review shows there is no universal standard to classify a building as a low-rise or high-rise structure, but every country and region can assign their own definitions with respect to some architectural or structural parameters. Here, this research is really meant for developing or under developed regions of Pakistan, India, Nepal etc. In these countries there are only few mega cities existed and most of the region constitutes a rural network of life, and any structure higher than 100 feet is considered as a high-rise structure in a common public mindset. However, it is needed to make a category of building structures on the assessment and evaluation of

some structural engineering parameters. In addition, cost of a construction project is a major part of construction cycle in such countries so cost is taken as a prime interested area for this evaluation.

Here, all this research is made for concrete structures as it is the most common construction material in developing countries especially in Pakistan, and also it constitutes to the minimum cost of construction compared to steel and wooden work as concrete is easy to prepare and easily available across the country.

2.1. Research Input Parameters

In this present study, comparison of different lateral load resisting systems are made in terms of their load resisting capacity and cost efficiency. These structural systems are:

1. Moment Resisting Frame System
2. Building Frame/ Dual Frame System
3. Outriggers Braced Frame System

The main target of this research is to determine the height level where lateral forces become effective and a proper design become necessary for lateral loads. For the sake of simplicity, a square plan has been considered with 90'x90' (four bays of 15' and one bay of 30' on each direction as shown in Figure 1) size with a typical story height of 10' as per the common practice in Pakistan. Concrete compressive strength is taken as 4 ksi and yield strength of reinforcing bars are kept 60 ksi. Analysis is purely made for moderately active seismic zone i.e. zone 2B while wind exposure is taken as C. Software of ETABS and SAFE are used to carry out the analysis.

Live load on floors are taken as 50 psf, partition load as 20 psf, finishes with 36 psf and an additional miscellaneous load of 10 psf is applied on slab system. Software modeling is done in such a way that started from single story building and two systems were employed separately and their results were compared. Similarly, each system is incorporated on software and number of stories are added in each trial. Starting from single story to 25 story, 25 different models are made and different structural systems are then utilized on each model to get their results compared for lateral stiffness and cost efficiency.

Figure 1. Building plan for study

2.2. Analytical Discussion for Cost

From preliminary design, all the structural components and slabs design were optimized for lateral stiffness and deflection control limits using ACI standards [9]. The results are as follow:

Minimum thickness for slabs were found to be 4", 7" and 8" for panel sizes of 15'x15', 30'x15' and 30'x30' with steel area of 1 in. sq. The minimum cross section for beam is found to be 10"x30" with 2.44 in. sq. steel area.

For column cross section minimum dimensions varied according to the number of floors added to the plan. Keeping reinforcement ratio to 1% the following cross sections for columns were calculated

- For single story building the minimum cross section for column was found to be 8"x8"
- For a 5 story building the minimum cross section for column was found to be 16"x16"
- For 10 story building the minimum cross section was found to be 24"x24"
- For 15 story building minimum cross section for column = 28"x28"
- For 20 story building minimum cross section for column = 32"x32"
- For 25 story building minimum cross section for column = 38"x38"

Quantities of concrete and steel are calculated from software and unit cost taken as 80000 per ton for steel and 8000 per cubic meter of concrete.

2.2.1. Single Story Building

For a single story building, there is no need to employee outriggers so moment resisting frame (MRF) and Building frame system (BFS) are used to compare their results. Comparison of inter-story drifts are shown in Figure 12 to 14. here only quantities of concrete and steel are shown in Figure 2 and 3 respectively. Figure 4 shows overall cost comparison of two structural systems.

The quantities of BFS is found a little more than that of MRF hence MRF is found to be more economical for a single story building as shown in Figure 4. Table 1 shows the cross section details for the two systems.

Figure 2. Quantities of concrete for single story building in m³

Figure 3. Quantities of steel for single story building in Ton

Figure 5. Quantities of concrete for 5 story building in m³

Figure 4. Cost comparison of BFS and MRF for single story building in PKR

Figure 6. Quantities of steel for 5 story building in Ton

Table 1. Structural member sizes for single story building

Structural system	Structural Members		
	Beam size	Column size	Shear Wall
MRF	8"x21"	16"x16"	---
BFS	8"x18"	14"x14"	8"

2.2.2. Five Story Building

After analyzing a single story building, several trials were made for comparing the two employed system till MRF becomes costlier than BFS. Therefore, in a five story building frame BFS becomes cheaper than MRF and their results are shown in Figure 5 to 7.

It is evident now that quantities of both concrete and steel are more in MRF that's why it yields to a more expensive construction project for five story building as shown in Figure 7. However, it is observed that difference in cost is not much for these two systems. Table 2 describe the optimized cross sections of structural component for five story structure.

Table 2. Structural member sizes for five story building

Structural system	Structural Members		
	Beam size	Column size	Shear Wall
MRF	10"x30"	20"x20"	---
BFS	8"x24"	18"x18"	8"

Figure 7. Cost comparison of BFS and MRF for five story building in PKR

2.2.3. Ten Story Building

Same two structural frames are further analyzed until the difference in cost is evident. The results for ten

story building are summarized below. (Here only cost comparison is shown since the same two structural frames are analyzed so quantities of concrete and steel are not shown here).

Figure 8. Cost comparison of BFS and MRF for ten story building in million PKR

Figure 9. Cost comparison of MRF, BFS and OBFS for 15 story building in million PKR

Table 3. Structural member sizes for ten story building

Structural system	Structural Members		
	Beam size	Column size	Shear Wall
MRF	10"x30"	30"x30" (1 to 5 story) 24"x24" (6 to 9 story) 20"x20" (10 th story)	---
BFS	8"x27"	24"x24" (1 to 4 story) 20"x20" (5 to 10 story)	12"

2.2.4. Fifteen Story Building

For 15 story building an outrigger braced frame (OBFS) is induced now in addition with MRF and BFS. Cross sections were optimized with respect to lateral stiffness and results are shown here. In OBFS, two outriggers were used at 6th and 12th floor. The quantities of concrete and

steel were estimated from software and their cost comparison is shown in Figure 9. Cross section details for each system in 15 story building is shown in appendix A. It is found that BFS is 39% economical than MRF and 30% economical than OBFS.

2.2.5. Twenty Story Building

For 20 story building two outrigger models were developed, one in which outrigger is applied at 14th floor and second one where two outriggers are employed at 7th and 14th floor. These two models were analyzed and compared with MRF and BFS. Their cost comparison is shown in Figure 10.

Here it is observed that using 2 outriggers at 7th and 14th floor is the most economical output while MRF is costliest in result.

Figure 10. Cost comparison of MRF, BFS and OBFS for 20 story building in million PKR

Figure 11. Cost comparison of MRF, BFS and OBFS for 25 story building in million PKR

2.2.6. Twenty-Five Story Building

For 25 story building, again 2 different models for outriggers were developed. A single outrigger at 17th

floor model and two outriggers at 7th and 17th floor. The comparison was made among all four structural systems and comparison results is shown in Figure 11. It is observed that outriggers system is the most economical for 25 story building and both the models of outriggers gives approximately same cost with a minor difference.

2.3. Analytical Discussion-Story Drift

The comparison for inter-story drifts for all studied models are also generated and compared graphically. For some understanding purpose drift comparison of 10, 15 and 20 story buildings are shown here. For a 5 story building drift was so small that it was of not much importance and for 25 story the same trend was observed as it is in 15 and 20 story plot.

Figure 12. Drift comparison for 10 story building

Drifts for both models are found to be in allowable limits as described by [9]. Similarly, the drift comparison for 15 and 20 story structure is also plotted shown in Figure 13 and 14 respectively.

Figure 13. Drift comparison for 15 story building

Figure 14. Drift comparison for 20 story building

3. Conclusions

Based on over all research it is concluded that,

Buildings up to 4 (40 feet) stories are categorized as low-rise structures as MRF is most economical till 4 stories

Buildings ranges from 5 (50 feet) stories to 19 (190 feet) stories are classified as medium rise or medium tall buildings as MRF becomes uneconomical and BFS is found to be most economical. Also OBFS is found to be costly for these range of building stories.

Building with 20 (200 feet) or more stories are classified as high-rise structures as MRF and BFS becomes costly and outriggers braced frames found to be most economical.

4. Suggestions for Further Research

- In this research, the depth of outriggers is taken equals the floor height, so it is advisable to carry out further research by reducing the depth of outriggers as done by [5]

Research must be made for base shear and torsion induced with lateral loadings and their remedies

Research can be made with different soil types and seismic zones

Effects of varying concrete compressive strength can be analyzed further

Tubular system can also be compared with these 3 studied system

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APPENDIX-A: Cross Section Details

Table A1. Cross section details of structural members for 15 story building

Structural system	structural member			
	Beam size	Column size	Shear wall	outriggers
MRF	12”X 36”	30” x30”	----	----
BFS	10”X30”	28” X 28” (STORY 1-4) 24” X24” (STORY 5-15)	16”	----
OBFS	8” X 24”	20”x20” (story1-4) 24”x24” (story5-15)	8”	12” X 10’

Table A2. Cross section details of structural members for 20 story building

Structural system	structural member			
	Beam size	Column size	Shear wall	outriggers
MRF	12”X 36”	36” x36”	----	----
BFS	12” X36”	28” x 28” (1-10) 30”x30”(11-20)	24” (STORY 1-12) 20” (STORY 13-20)	----
OBFS	12” X 30”	20” x20” (1-10) 24” x24”(11-20)	16” (STORY 15-20) 20” (STORY 8-14) 24”(STORY 1-7)	12” X 10’

Table A3. Cross section details of structural members for 25 story building

Structural system	structural member			
	Beam size	Column size	Shear wall	Outriggers
MRF	12”X 36”	44” x44” (1-10) 40” x40”(11-25)	----	----
BFS	12” X36”	32”x32” (1-10) 36” x36”(11-25)	24” (STORY 1-13) 16”(STORY 14-25)	----
OBFS	12” X 30”	28”x28” (1-10) 30”x30”(11-25)	24” (STORY 1-13) 16”(STORY 14-25)	12” X 10’

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