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Optimum spacing of columns in a tubular frame for the design of tall buildings

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Abstract

For the design of tubular structures, various researches have been inducted in past but still, there is no regulation made for providing the column spacing in the tube frame. This paper presents the comparison of four different types of a tubular structural frame with different spacing of columns in their periphery. The main objective of the research is to find an optimum spacing of columns in a tube frame without compromising the structural response. The columns are assigned at 7.5ft, 10ft, 15ft, and 30ft respectively in four tubular structures with the building height of 600 ft. Here the flat plate system has been used and its effect on the cost of the structure is observed. A simple linear static analysis is carried out and seismic loading has been applied in each model and their base shear and drifts were optimized by changing the column cross-section to get minimum steel ratio. Based on their total cost consumption and drift control, the most optimum and economical framing system has been concluded and a tube frame with 10 ft column spacing is recommended as the most suitable option for a symmetrical high-rise structure. Furthermore, these tubes were also get compared with a conventional moment resisting frame system, and all the analyzed tube frames are found to be more economical than a moment-resisting frame.

Keywords: Tubular Structure, Moment resisting frame, optimal column spacing, cost comparison

INTRODUCTION

As the population of the world increases; the construction of tall buildings is in demand but from the design point of view, because of their extraordinary height, high-rise structure shows more sensitivity to wind and earthquake-induced lateral loads than low-rise buildings. That's why analyzing lateral loads is a difficult task. The estimation of those lateral loads plays an important role in the design of tall buildings. Lateral loads have dynamic behavior, earthquake loads increase according to the building weight, and wind loads increase according to the building height. With the advent of such a scientific era, several innovations have been reported in 20th century in the subject of civil and structural engineering. These innovations made it easier for engineers to design tall skyscrapers and thus maximum people can accommodate in the same land area. These structural innovations are Tubular frames, outrigger braced frames, diagrid, and Hexa-grids structural systems.

Dr. Fazlur Rahman khan was the 1st who gave the idea of converting civil engineering to vertical dimension by giving the concept of perforated tubes with closely spaced columns in the periphery. For his scientific contribution to civil engineering, he has been rewarded with several titles including the *Father of Structural Engineering* and *Einstein of civil engineering* (Weingardt, 2011). Tubular structures can be implemented as a single tube, tube in tube, or with several bundled tubes to strengthen the structures in lateral load resistance in the extreme events of earthquake and wind loadings. Many researchers have made a comprehensive comparison of different structural systems for high-rise buildings but still, there is not a lot available for the standard guidelines of column spacing in a tube, angles of diagrid, and locations for outriggers. Therefore, it is very necessary to put some effort into developing a general standard for such design practices.

In developing countries even, the trend of constructing high-rise structure is in practice and for this, structural designers are utilizing outriggers and tube structures frequently. It can be seen that a lot of advancement has been made in designing aspects of Tubular structure and its comparison with different framings have also been witnessed but not a significant research has been performed on the provision of optimal spacing of columns for a tube. This research has been made to assess the effect of different column spacing of periphery tube on the structural response of drift of a building. The main objective is to get an idea of providing column spacing for the tubular design of high-rise structures. The analysis comprised of different tube framings and their comparison with moment resisting frames simultaneously.

LITERATURE

A high-rise structure can be any structure having a height of more than 200 ft (Zaidi et al., 2020). Mahjoub et al. (2011) have provided two relation groups for tubular frame structures capable of considering shear lag in both web and flange of the base frame. In a research study, Kulkarni (2019) has implemented a tubular structure in a square and a rectangular bay plan frame and found a square frame structure more stiff and resilient to lateral loadings. Patil & Kavitha. (2016) has extended the same research of implementing tubular framings with different plans of square, rectangular, triangular, and hexagonal geometries and claimed hexagonal tube as the stiffest and resilient to lateral loadings. Lee et al. (2001) have proposed a simple mathematical approach based on a minimum potential energy method in conjunction with a variational approach for the analysis of framed structure with bundled tubes. Lu et al. (2016) have developed two models for fully braced and half braced tubular frames and he compared the results of modal analysis, static analysis, time history, and plastic energy dissipation of building across the height. Moon (2010) has prepared a methodology for determining preliminary sizes of the tube for tall buildings and he applied stiffness based methods for this purpose. He studied the influence of the diagonal angle of the braced tube and concluded with 40 to 50 degrees' inclination as the most optimum design.

Johnson (2015) has given the formula to find out an optimum spacing of columns in a storage house depending on the aisle width. Arvind & Santhi (2015) has made an extensive comparison of tubular, tube-in-tube, and bundled tube structures for high rise building frame considering p-delta effects. Khatri et al. (2019) have reviewed all the literature of a tube-in-tube structure with and without implementing cross bracings in structural framings and this cross bracing is simply referred to as an advancement of a simple tubular structure (Archana & Rashmi, 2016). Naik & Chandra (2017) has a comparison between tube-in-tube with conventional moment-resisting frame considering a 50 story structure, he compared the results of drift, displacement, stiffness, and period of both structures. Lunhaizhi et al. (2018) has performed wind tunnel test and field measurements of wind loading on a super tall structure and found a fine agreement between the two results. Yang et al. (2017) has introduced the concept of predesigned ellipsoidal dimples into circular tubes and evaluated the impact of different design input parameters on it.

METHODOLOGY

Although there are a lot of tubular design categories, which meet the structural design requirements of modern and hazard resistant construction. These tubular framings are simple tube, tube-in-tube, bundled tube, tubed mega frames, and many others, but here, a simple tube frame has been considered to evaluate the effect of varying column spacing in the structural response of a multi-story building.

A tall building structure of 60 stories with a typical story height of 10 ft has been considered here for this research with a square plan of 120 ft x 120 ft. the structure is assumed to be designed in a moderately seismic zone. Four tubular framings are developed with different column spacing at the outer periphery provided that they all have nine internal columns with symmetrical placement. These tubular framing systems are columns with 7.5 ft spacing (Tube 7.5), a column with 10 ft spacing (Tube 10), a column with 15 ft spacing (Tube 15), and column with 30 ft spacing (Tube 30). ACI-318-14, ASCE 7-16 & UBC-97 codes have been considered for analysis and design purposes. A live load of 50 psf and finishes of 36 psf were applied to each model. As Kayastha & Debbarma. (2019) has found the flat slab roof system satisfactory under seismic loading with the combination of the shear wall so for the research purpose a flat plate system of slabs is considered here with periphery beams and slabs are designed by using direct design method. ETABS is incorporated to model the building system. Soil profile Sc is selected for this research with a building importance factor of 1 and over strength factor for the RC frame has been taken as 5.5.

The tubular framing is developed in such a way that it is symmetrical in both axes. The employed framing plans are shown in figure 5 to figure 9. In addition to the discussed tube framings, a simple moment-resisting frame structure (MRF 30) is developed to get it compared with the most optimum tube framing system. The MRF has been developed with 30 ft spacing of column and braced with deep spandrel beams in the periphery. For the cost analysis, current rates from the construction industry of Pakistan has been considered and equivalent US dollar values are taken into consideration which is as follows,

1. I cubic feet concrete (cft) = 0.75 USD
2. 1 Ton of steel = 520 USD

Here, it is to be noted that for cost analysis, only the superstructure is considered and foundations are excluded in cost calculations

OPTIMIZATION OF CROSS SECTIONS

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ETABS software is used here for structural design as it is a user friendly and easily available. A simple static and linear structural analysis have been performed in addition to wind and seismic analyses. Four separate models of tubular frames have been analyzed and designed in a way that yields minimum steel reinforcement within the prescribed limit of drift and displacement by the building codes. So a minimum of 1% and a maximum of 2% of steel has been designed for the column. Initially, random cross-section sizes have been assigned to structural members and the most economical design has been achieved using trial and error technique. The curtailment in cross-sections have been made after every 10 story interval and the most optimum cross-sections found for each framing systems has been observed and tabulated in table 1.

Table 1. Optimized cross-section sizes for each framing system (in inches)

Column cross-sections		Tube 7.5	Tube 10	Tube 15	Tube 30	MRF 30
1st to 10th story	External column Internal column	38 x 38 92 x 92	42 x 42 92 x 92	52 x 52 92 x 92	72 x 72 92 x 92	76 x 76 99 x 99
11th to 20th story	External column Internal column	34 x 34 80 x 80	40 x 40 80 x 80	48 x 48 80 x 80	66 x 66 80 x 80	66 x 66 92 x 92
21st to 30th story	External column Internal column	32 x 32 72 x 72	38 x 38 72 x 72	39 x 39 72 x72	58 x 58 72 x 72	61 x 61 82 x 82
31st to 40th story	External column Internal column	29 x 29 58 x 58	33 x 33 58 x 58	36 x 36 58 x 58	50 x 50 58 x 58	53 x 53 72 x 72
41st to 50th story	External column Internal column	24 x 24 47 x 47	27 x 27 47 x 47	31 x 31 47 x 47	38 x 38 47 x 47	43 x 43 58 x 58
51st to 60th story	External column Internal column	20 x 20 30 x 30	22 x 24 at corners 22 x 22 ext 30 x 30 int	24 x 24 30 x 30	30 x 30 30 x 30	32 x 32 40 x 40
Beams	Periphery beam Internal beam	8 x 18 Nil	10 x 24 Nil	14 x 40 Nil	10 x 84 Nil	18 x 56 18 x 56
Slab		10	10	10	10	7

The design for wind pressure is also taken into consideration with a wind speed of 90 mph and wind exposure of category C. The results of wind loading are found satisfactory under the prescribed limits of ASCE code. Furthermore, the seismic loadings are found to be more critical than wind pressure thus the optimization has been made for seismic loadings and the results are displayed here accordingly i.e. results of wind loadings are excluded as it was not that critical. Figure 1 shows the drift analysis of all the systems employed in analysis with the above tabulated optimized cross-section. The limiting values from building code ACI has also been marked to check whether it is under control in a system employed or not. Since all the systems are optimized with the possible least cross-section with a minimum steel percentage, it can be observed that almost all the systems show satisfactory performance in drift analysis. Figure 2 shows the results of the base shear analysis for all employed systems and it is observed that MRF 30 provides maximum base shear of 7983 KN while Tube 7.5 yields with a minimum of 5670 KN among all framing types.

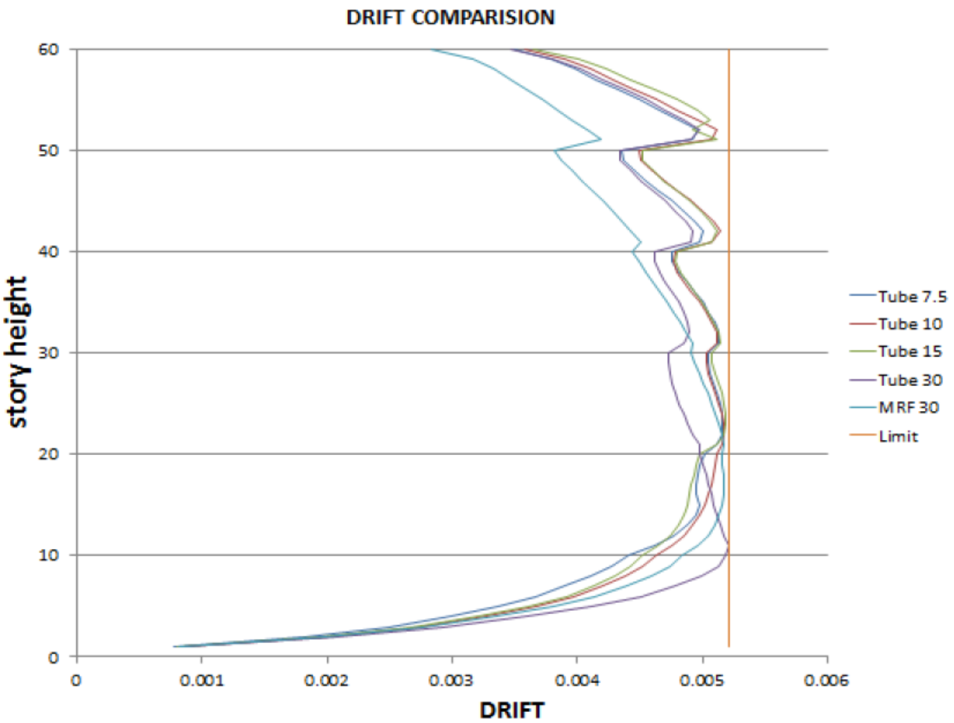

Figure 1. Drift comparison of all analyzed system with optimized cross-sections

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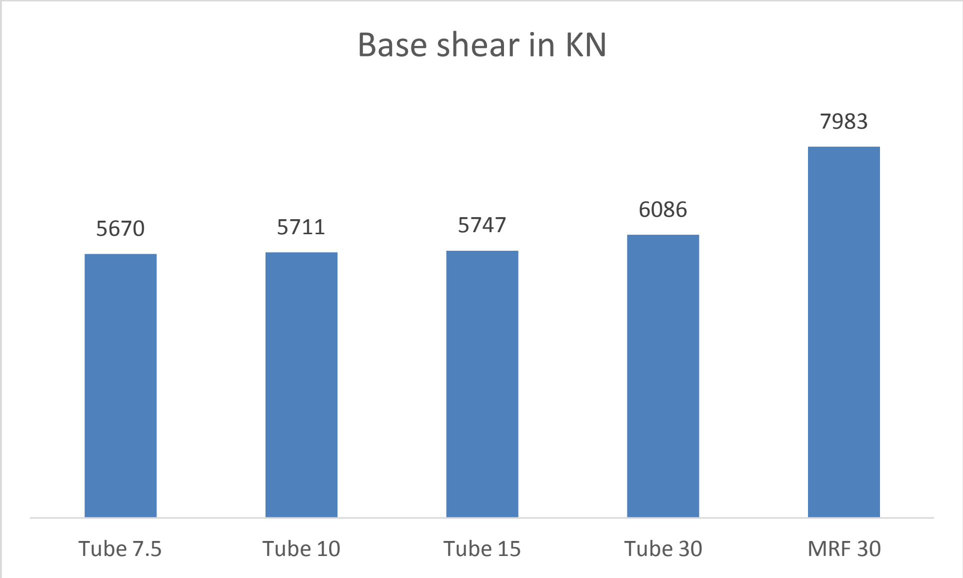

Figure 2. Comparison of base shear for all analyzed framing systems

COST ANALYSIS

The cost of each system has been calculated separately for concrete and steel using previously cost rates of Pakistan. Almost 50% of the cost is associated with the design of a flat plate slab system which makes it costlier. Table 2 shows the calculated cost for each structural member with concrete and steel. Figure 3 shows the comparison of all four types of tubes in their cost estimation and Tube 10 found to be most economical among them.

Table 2. Detailed cost estimation of every element in analyzed systems (in million USD)

Elements	Tube 7.5	Tube 10	Tube 15	Tube 30	MRF 30
Concrete in column	0.306701	0.303047	0.2709	0.273127	0.293776
Steel in column	0.893248	0.760386	0.792629	0.707651	1.07156
Column ties	0.036108	0.030762	0.031485	0.024333	0.022701
Concrete in beam	0.016856	0.03612	0.08428	0.150199	0.37926
Steel in beam	0.023207	0.055565	0.118871	0.240336	0.46956
Shear rings beam	0.009596	0.008428	0.046661	0.079338	0.078441
Concrete in slab	0.5418	0.5418	0.5418	0.5418	0.37926
Steel in slab	0.903	0.903	0.903	0.903	0.55986
Total cost	2.70298	2.639168	2.78726	2.9197	3.2508

Table 3 shows the relative difference in total cost in percentage among all tubular framing systems, where the maximum cost has been taken as 100 percent.

Table 3. The relative difference in cost in percentage with maximum value

Tube 7.5	Tube 10	Tube 15	Tube 30
93.1%	90.3%	95.5%	100%

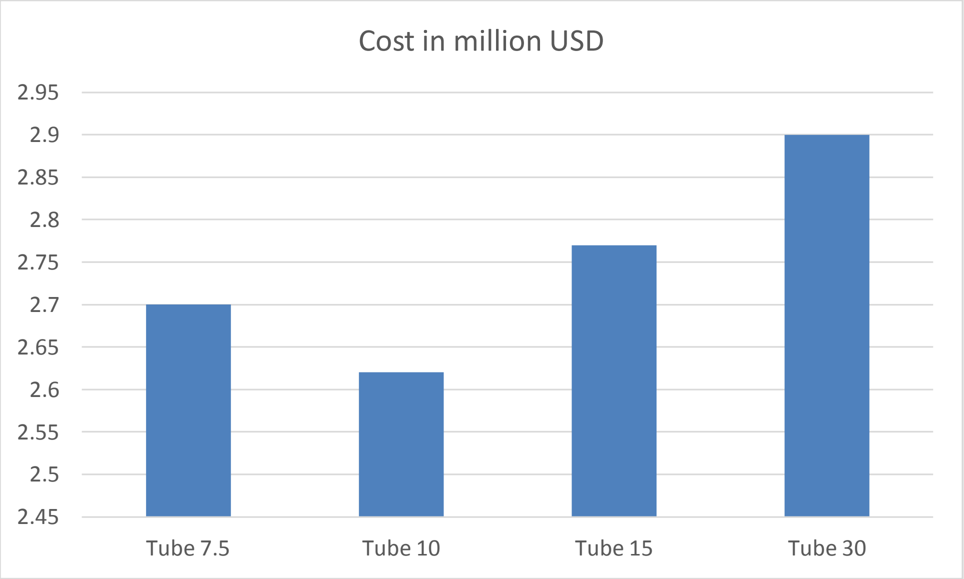

Figure 3. Cost comparison of all tubular framing systems

COMPARISON OF TUBE WITH MRF 30

The most economical tube system is found be Tube 10 from previous cost analysis while the most expensive one is Tube 30. Here both of these systems were compared with the cost of the MRF 30 system. Figure 4 shows a comprehensive comparison of cost for Tube 10, Tube 30, and MRF 30 system. Here it is observed that Tube 10 is 20% economical and Tube 30 is 10% economical than MRF 30.

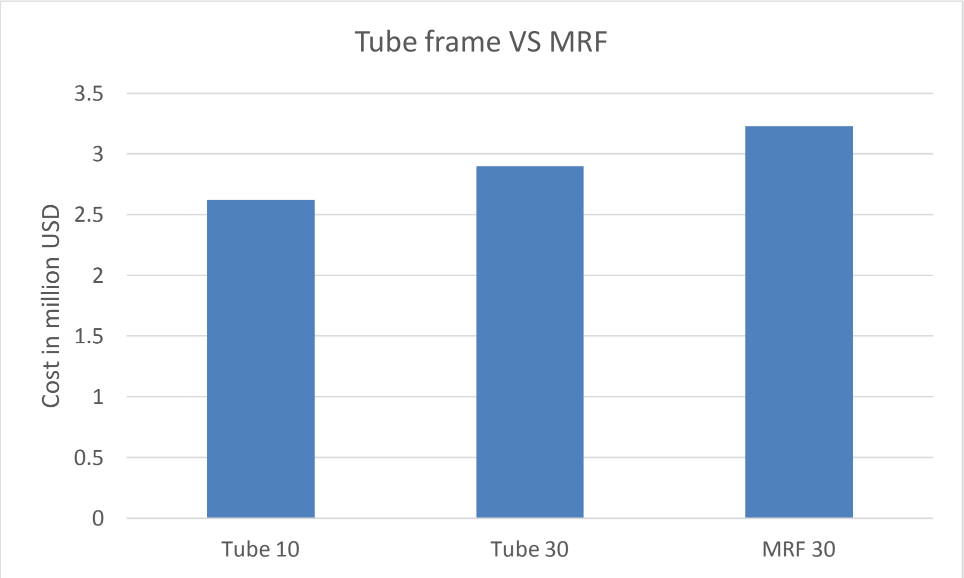

Figure 4. Cost comparison of Tube 10, Tube 30 and MRF 30

CONCLUSIONS

It can be concluded that the height of a structure plays a vital role in lateral sway and thus it results in the close spacing of columns in the tube periphery. The comparative analysis shows Tube 10 as the most economical system among all and it is 10% economical among all tubular frames while it is 20 % economical than the MRF system. Also, it is observed that the implementation of flat plate slabs contributes 50% of the total cost hence for high rise structure such types of slab framings are not suggestable to get the structure economical. The more the spacing of columns minimum will be the base shear but it costs more as the design is to be carried out with thick sections. So, for a 60 story building structure, a tubular structure with 10 ft column spacing is suggested as the most economical frame.

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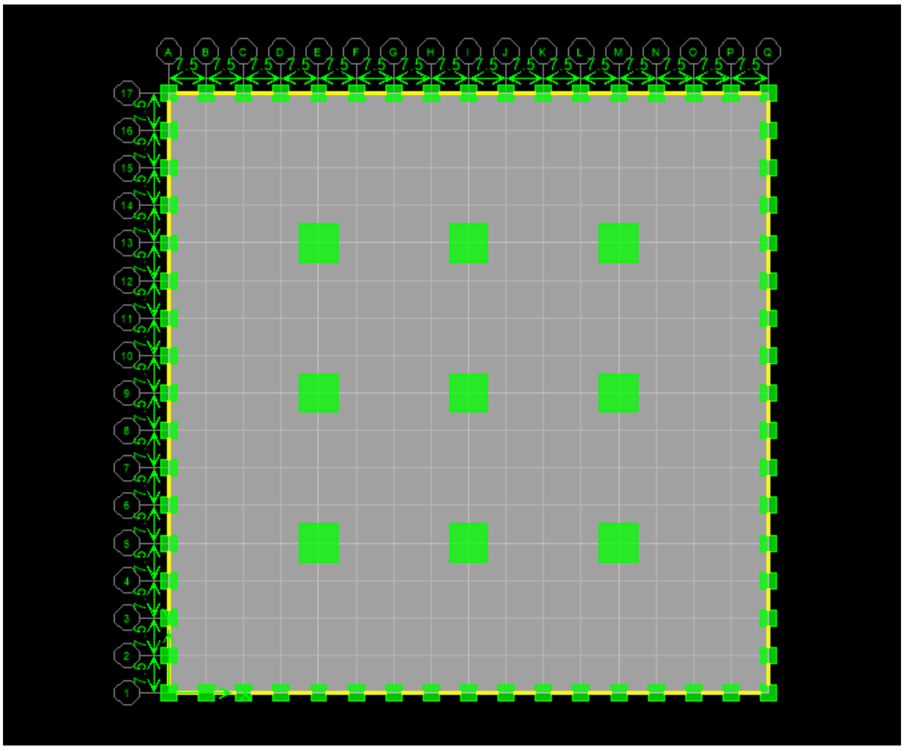

Figure 5: Plan of Tube 7.5

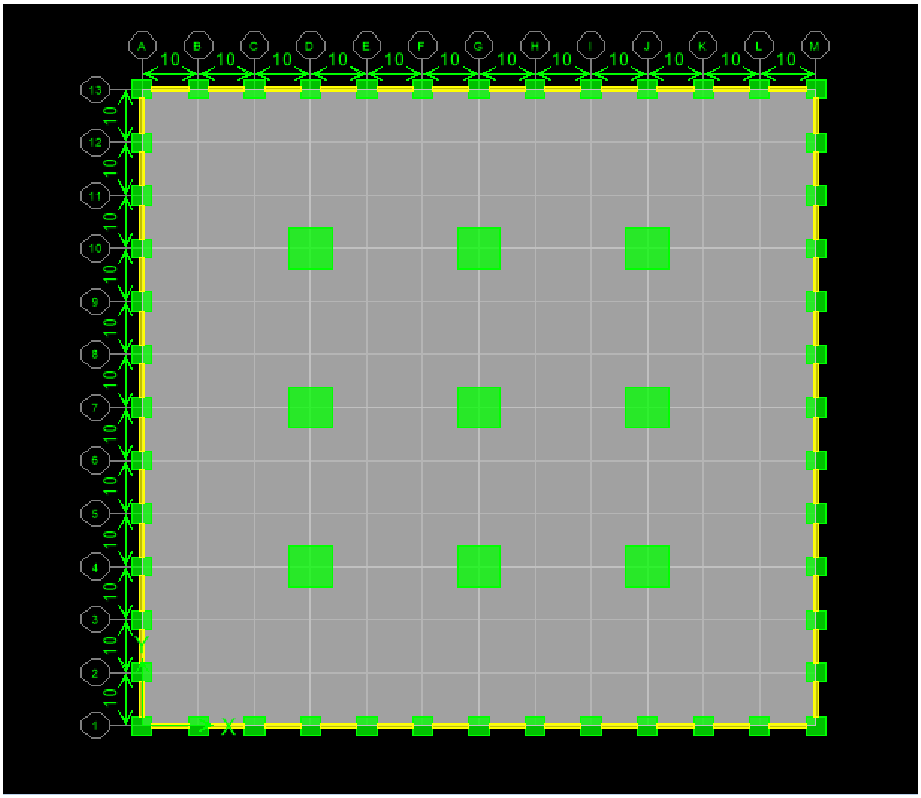

Figure 6: Plan of Tube 10

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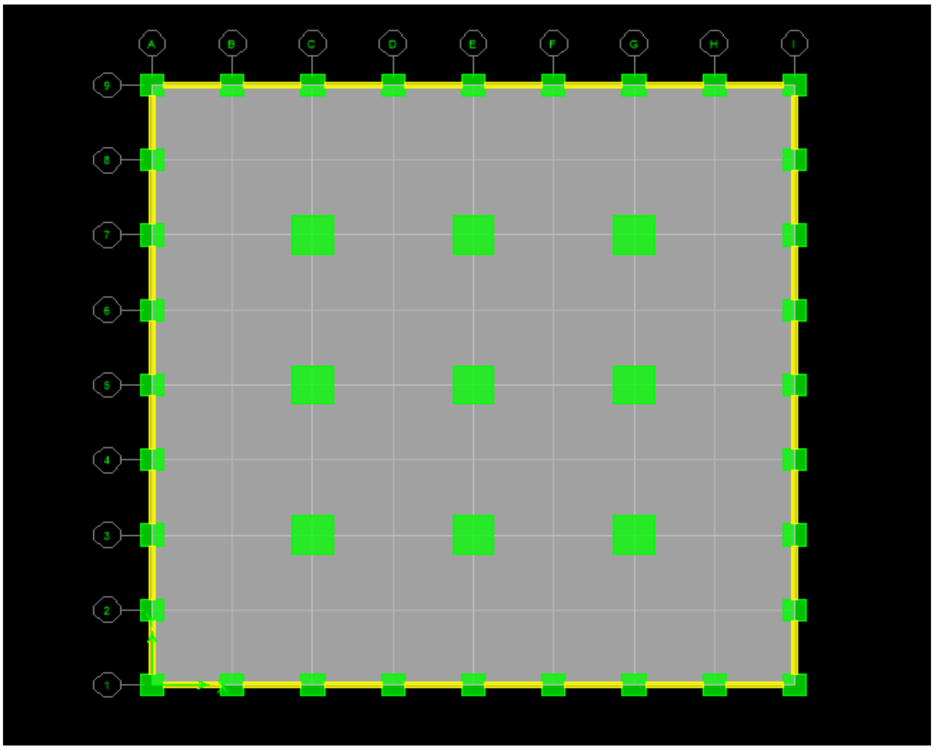

Figure 7: Plan of Tube 15

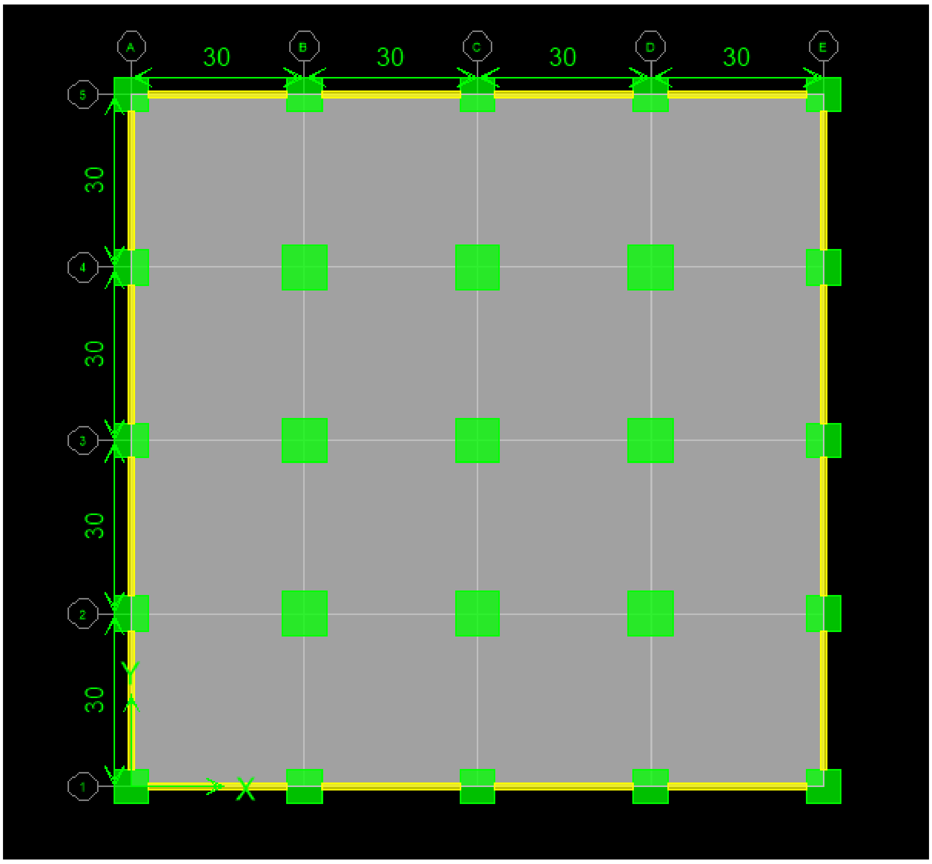

Figure 8: Plan of Tube 30

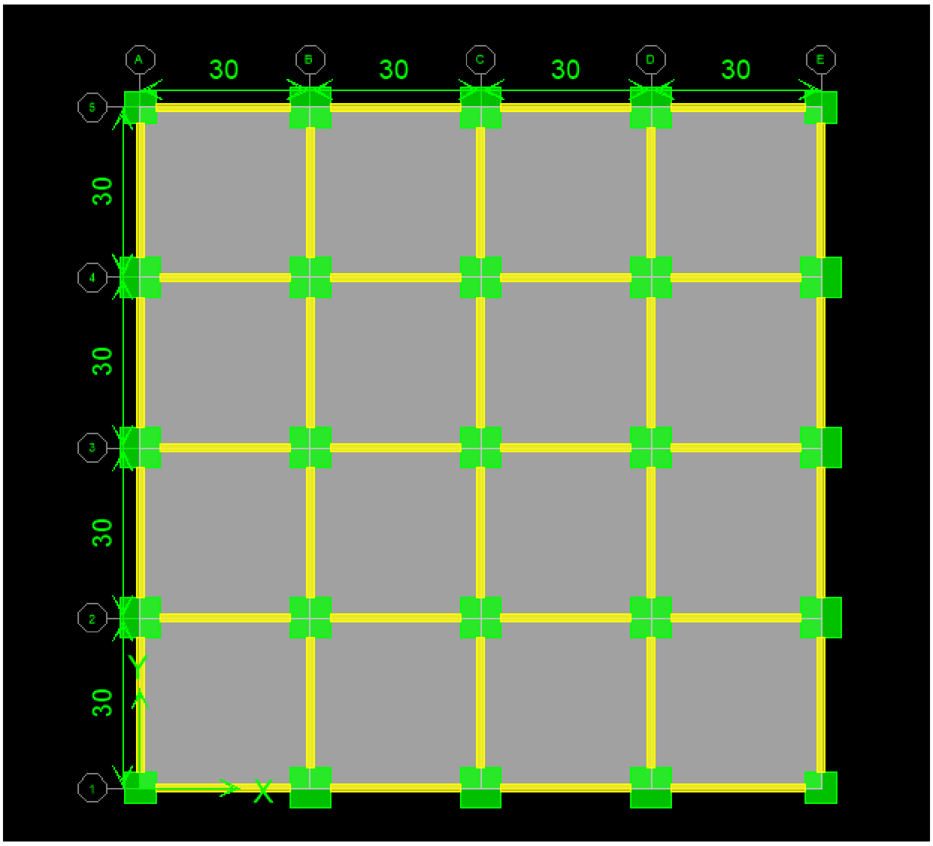

Figure 9: Plan of MRF 30

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