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Survey of Structural and Architectural Performance of Diagrid System for High Rise Steel Buildings

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Abstract: Building high constructions in civic crowded centers and specially preventing from destruction of farmlands and environment is to be considered as an essential need. In a low occupation level, the horizontal deployment of buildings can be decreased, while the deployment of vertical occupation level of buildings can be increased.Collaboration of building engineers and architects can be done to employ the structural resistant forms with architectural attractions. A set of diametrical diagonal elements that has high output in carriage of lateral loads which called as diagrid structure, is considered as a current structure for resistance against lateral loads of wind and earthquake in high buildings. In this research, 43-floor diagrid metallic building analysis is presented. A circular plan with 16m radius and a rectangularity plan with 25 to 35 dimensions is investigated. Comparison of analysis results is presented for changing the position of floors, base cutting force, length and sections of diagonal elements, attraction of lateral and gravitational force. It is shown that the circle plan is more suitable for designing tower, according to the loading level of wind and absolute geometrical symmetry and aesthetics predicament.

Key words: Sustainable storey · Sustainability · Energy resources · Super-tall buildings · Dynamic wind load

INTRODUCTION

With regard to the high demand of super-tall buildings; the whole aspects of the tall buildings should be considered as the first priority in order to achieve sustainability in the design process. It has been demonstrated that super-tall buildings could benefit from their great height to achieve sustainability [1]. The sustainabilityterm should be referred to the structure, architecture and energy efficiency. The architects, structural engineers, developers and urban planners should cooperate together to reach the goal of real sustainable tall buildings [2].

In fact, the architects and structural engineers can collaborate and use the structurally resistant forms, considering sustainable design issue along with carrying gravity, earthquake and wind loads [2].

This approach needs a great understanding of different structural systems to be applicable for super tall buildings, energy resources and their impact on the building and "engineering-aimed creativity''to come up with an attractive architecture which has a great sustainable storey behind [3]. The state-of-the-artof "diagrid" comes from diagonal grid which is appropriate for tall and super-tall buildings with complex form from both structural and architectural point of view [3]. The diagrid system is a development of tubular system which consists of diagonal members at the perimeter of the building. The difference between diagrid and conventional braced tube system is that vertical elements at the perimeter of the building system are almost eliminated in diagrid system (vertical mega columns could be placed at the corners to achieve more stability) and both gravity and lateral forces are resisted by diagonal members [4].

Despite of the other systems for super-tall buildings, the diagrid system has a great potential of attractiveness in addition to structural efficiency. A diagonal member of the system can cover more than 3 or 4 storeys. This condition without vertical columns makes an unobstructed view for the building. As the diagrid does not need a stiff core system in the tall buildings, the interior spacing can be done better. For the complex forms of tall and super-tall buildings, the diagrid system may be the best alternative in both structural and cost effectiveness aspects [4, 5].

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The diagonal members in diagrid structural systems can carry gravity loads as well as lateral forces because of their triangulated configuration. Diagrid structures are more effective in minimizing shear deformation, because they carry laterals hear by axial action of diagonal members. Diagrid structures generally do not need high shear rigidity cores because laterals hear can be carried by the diagonal members located on the periphery [6].

Meanwhile, length and section level of diagonal elements factors will be effective in attraction rate of lateral and gravitational loads and the behavior of tower structure can be investigated by changing these two factors. The role and effect of wind force in high buildings is a perceivable and determinant matter which is related to changes height and loading level of tower. Increase of height and loading level cause intensification of wind force. Obviously the kind of earth and weather of each region is effective on these factors. In a region with specified height, wind factor may be more intense and in other climate with the same height, earthquake factor may be more effective. In all the different periods of building the towers, the factor of geometrical form of a plan and the final volume of a tower were effective on the way of its behavior against lateral forces of earthquake and wind and were the great challenges for the designers. Therefore, investigating the behavior of circular and rectangularity towers against lateral and gravitational forces may be effective in the selection of optimum geometrical form for a tower [7].

In the current research, a 43-floor diagrid metallic building analysis presents. A circular plan with 16m radius and a rectangularity plan with 25 to 35 dimensions investigates. ETABS software 9.7.4 employees for modeling and analysis of its structural members. All the structural members analyze and designs based on regulation factors AISC_ASD89 and Iran cementite regulation. In addition, dynamic force of wind analyzes. Comparison of analysis results presents for changing the position of the floors, base shear force, length and sections of diagonal elements and attraction of lateral and gravitational force.

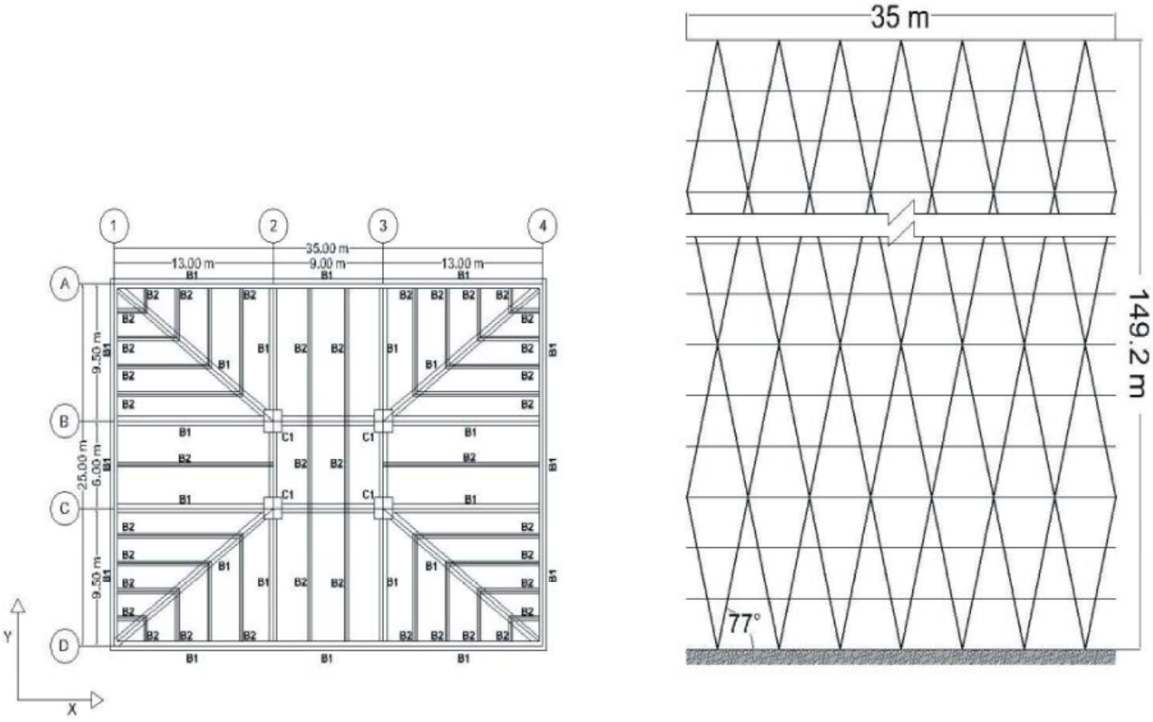
Analysis 43-Storey Building

Building Configuration: Rectangularity building has 43-storey with 25m × 35m dimensions. The typical plan and elevation are shown in Fig. (1). 43-storey circular high building has a plan with 16m radius. Height of floors in both high buildings is 3.5m; the plans and facades are shown in Fig. (2).

In the diagrid buildings, trusses are located binary over ambient of building. Diagonal angles are considered identical in all height of building. Diagonal columns are placed along with rectangularity tower ambient with 5m distances and in a circular tower ambient with 12m distance. Internal frame of diagrid structure is designed only for gravitational loads. Dead and live loads of the design over floor slab are approximately 3.04 kN/m and 1.96 kN/m. Dynamic load of wind is standed on base wind speed about 27.77 m/s and was calculated according to annex number 6_3 sixth subject of Iran building national regulation (Gust Effect Factor,cg). The design load of earthquake is calculated based on regional factor of 0.3, local coefficient of 1.73, alternation time of 2.13, response spectrum scale factor of 0.4646 and third kind soil. Modeling and analyzing the diagrid structure is accomplished by ETABS software 9.7.4. For dynamic and linear static analysis, beams and diagonal columns are modeled with beam components and columns with columns components and trusses are modeled by truss components. The qualification of rigid pier's supports is taken into the account. Secondary effects like thermal transformations are not investigated in analysis. In addition, it is postulated that there is a little transformation in internal and external temperature.

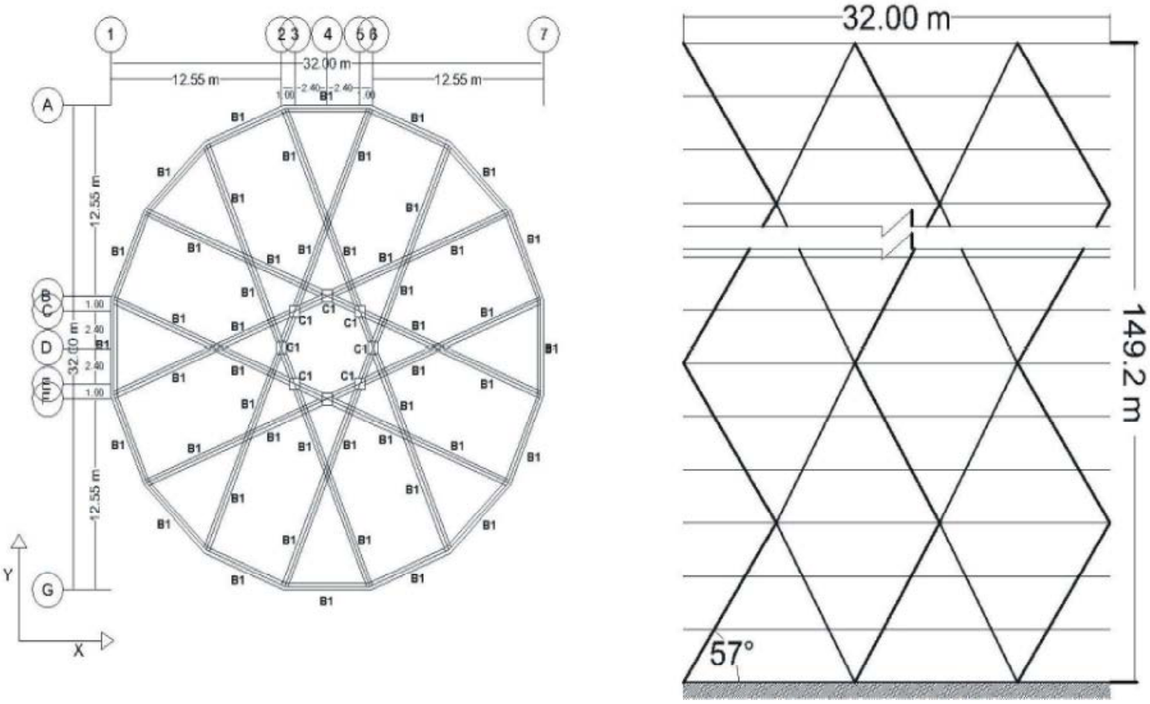
Analysis Result of 43-Storey Circularity and Rectangularity High Buildings and Their Comparison.

Drift of the Storeys and Their Comparison: According to Fig. (3) and (4), the drift rate of the storeys under wind dynamic load is in direction X of tower with circular plan in the period of 0 to 0.0011. However for a tower with rectangularity planis in the period of 0 to 0.0006. In the first view by attention of lower drift of the storeys in the tower with rectangularity plan in direction of X, it can be dedused that the behavior of rectangularity tower against wind is better than circular one. Nevertheless by investigating of the drift rate of the storey under the wind load in the direction of Y, it is recognized that its rate in 0.00013 is more than the circularity tower. This discrepancy in the drift of rectangularity plan storeys is because of inequality of loading area of tower in X and Y directions. By comparing diagrams of both towers in two directions, we can see that the behavior of circularity tower against wind is better and displaced with an especial regulate. Complete symmetry of circularity plan and equality of loading area in all directions caused identical drift storey in both X and Y directions.



(a) (b)

Fig. 1: Typical (a) Rectangular Floor Plan[7] and (b) Elevation of 43-storey Buildings



(a) (b)

Fig. 2: Typical (a) Circular Floor Plan and (b) Elevation of 43-storey Buildings

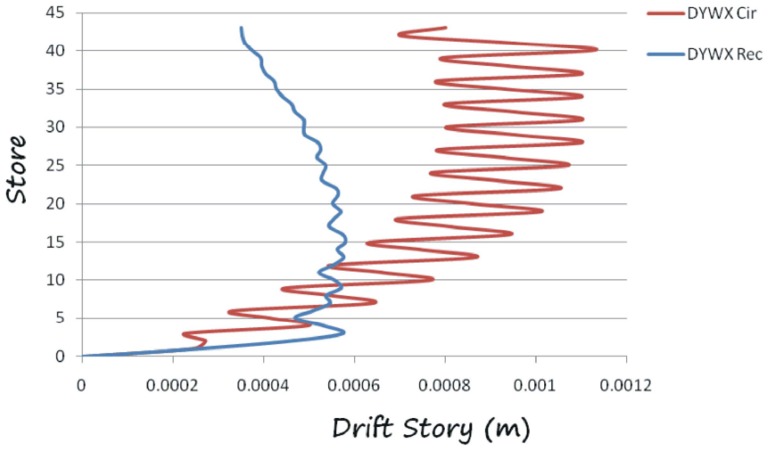


Fig. 3: Comparison: storey drift of 43storey diagrid structural system rectangular & circular plan

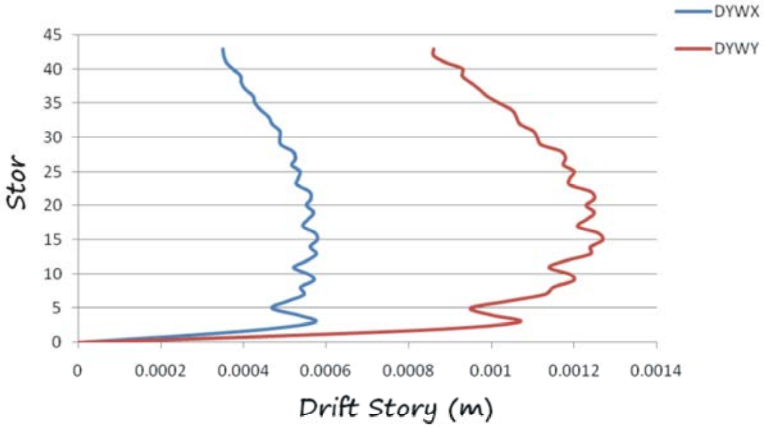


Fig. 4: Comparison: storey drift of 43-storey diagrid structural system rectangular plan

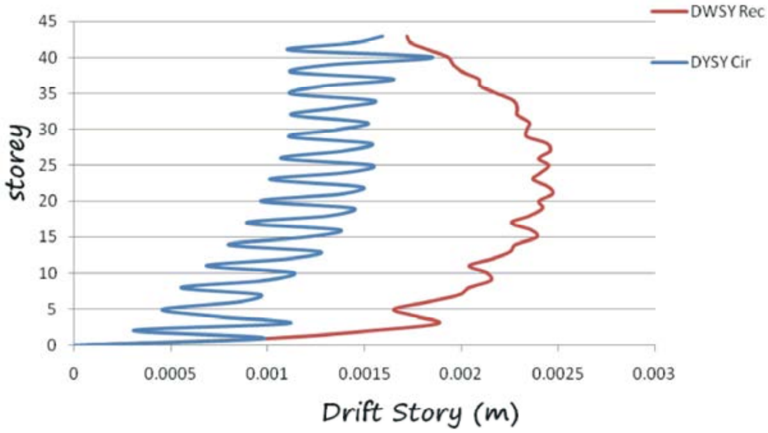


Fig. 5: Comparison: storey drift of 43-storey diagrid structural system rectangular &circularplan

According to Fig. (5), the drift rate of the storeys under the dynamic load in Y direction of the tower with circularity plan is in range of 0 to 0.0018. However, in a tower with rectangularity plan is in range of 0 to 0.0025. This factor implies that the behavior of circularity plan is better than rectangularity plan. In diagram of tower with circularity plan, it can be observed that from the first floor to the 23th floor, the drift of the storeys increases under a linear slope. This drift remains constant from the 23th to the 4th floor under a little output and moves in the floors in reciprocating way. In the diagram of tower with the rectangularity plan, three outputs can be observed. From the first floor to the 15th floor, with an incremental linear slope, the drift of the storeys goes up from 0 to 0.0023, whilein the mean output from the 15th to the 30 th floor changes between 0.0023 to 0.0025. Then, in the terminal output it can be seen a decremental trend in drift of floors from the 30th to the 43th floor that goes down from 0.0023 to 0.0016. The cause of ascensional increase in the drift of the storeys from the first to the 25th floor is considered the distance from foundation level. On the other hand, from the 25th floor, this tower structure does not allow more displacement and preserves the balance of building. That causes decrease of the storey drift and eventually control it up to the permissible limit.With the comprehensive investigatingof all the diagrams, it is distinguished that the most storey drift occurs in the 23th floor and in 77m height which it could be because of the effect of high modes. This point has to be considered as a critical point and employ essential schemes for decreasing the maximum drift in this part.

Base Shear Force & Maximum Drift Storey: According to Table 1, the base shear of static earthquake loads in circularity tower is equal in both X and Y directions and in this way, it is equal in both directions for dynamic earthquake load and dynamic wind load. This case indicates the selection of symmetric, balanced and completely identical geometry, which is in a circularity form. As a result, it is very effective and applicable in structural design.

According to Table 1, the base shear of static earthquake loads in rectangularity tower is equal in both X and Y directions and in this way it is equal in both directions for dynamic earthquake load, however the dynamic wind load is not equal in rectangularity form; the loading area is not equal in both X and Y directions. As a result, the base shear of one direction is more than the other. This case is difficult in designing structure and predicting schemes because of differences in the base shear in both directions. In each direction, design and performance is different by considering high floors of tower. Theeffect of wind force on tower is very important in high rises buildings. Considering the shear forces for both towers form Table 1, it can be clearly observed that the effect of earthquake force is more than the wind force up to 150m height in Amol (a city in the north part of Iran) region. This force is preferred as a prevailing force for designing structure. This matter may change based on the weather and regional factors and in other places in identical height, wind factor is more intense. Obviously, the main point is that by increasing of height, the wind factor intensifies. In addition, it is forecasted that in higher heights, the base shear of wind will be more than earthquake and this question is a kind of case study.

Load Distribution in 43 Storeys High Raises Buildings and Their Comparison

Load Distribution in Circularity High Rises Building: According to Table 2, in a tower with circle plan, the attraction rate of gravitational load in the external diagrid structure is about 37.65% and the attraction rate of lateral forces is about 94.58%. On the contrary, the internal columns with attracting 62.35% of gravitational force and 5.42% lateral force, supportthe tower resistance. This load attraction is in terms of equal number of supports for the diagrid and the columns, which in this special case, 8 supports for the columns and 8 supports for the diagrids are modeled. Gotten statistics indicate that according to the predictions, the diagrid structure is very successful in attracting the lateral load and even could attract about 1/3 gravitational load of the tower and increase the tower resistance. This process implies high output of the structure and these diagonal elements in the design of tower.

Load Distribution in Rectangularity High Rises Building: According to Fig. (6), in a tower with rectangular form plan, the attraction rate of gravitational load in external diagrid structure is about 66.26% and the attraction rate of lateral forces is about 72.70%. Furthermore, the internal columns with attracting 33.74% gravitational force and 27.30% lateral force, support the tower resistance. This load attraction is gotten in a situation whereas4 and 24 supports are modeled for the columns and the diagrids, respectively.

It cab been observed that the attraction of gravitational load increased and its rate is twice of power in central columns of tower, considering the increase of the number of diagrid supports and using more diagonal elements in tower ambient.

This factor implies capability of the diagrid structure in carriage of high gravitational loads. With regard to this matter, the elimination of the central columns can be predicted byincreasing of the ambient supports and the length of diagrids. This is a great priority for architects in the design of architectural spaces and flexible plans.

Table 1: Lateral load due to earthquake and wind on 43-storey diagrid system rectangular &circular plan

Story Shear (KN.M)		
Load Case	Rectangular	Circular
EX	21973.7	17855.64
EY	21973.7	17958.19
WIND X	10187.83	13450.73
WIND Y	14262.96	13503.74
SY	21977.69	18912.37

Table 2: Load distribution in 43 storey diagrid system circular plan

Loading	Total load on diagrid system (kN)	Loading on perimeter diagonals (kN)	Loading on internal columns (kN)
Gravity loading	300702.8	113207.3	187495.5
Lateral loading	18912.37	17886.2	1026.17

Table 3: Load distribution in 43 storey diagrid system rectangular plan

Loading	Total load on diagridsystem(kN)	Loading on perimeter diagonals (kN)	Loading on internal columns (kN)
Gravity loading	362728.3	240334.8	122393.5
Lateral loading	24639.81	17912.01	6727.8

Table 4: Unit length and trusses sections

Circular Tower					
Story	Element Type	Material	Total Weight	Floor Area (m^2)	Unit Weight (KN)
STORY42	Column	STEEL	76.356	751.167	0.1017
STORY42	Beam	STEEL	466.875	751.167	0.6215
STORY42	Brace	STEEL	3516.685	751.167	4.6816
STORY42	Floor	CONC	2651.914	751.167	3.5304

Table 5: Unit length and trusses sections

Rectangular Tower					
Story	Element Type	Material	Total Weight	Floor Area (m^2)	Unit Weight (KN)
STORY42	Column	STEEL	312.548	838.4	0.3728
STORY42	Beam	STEEL	1393.822	838.4	1.6625
STORY42	Brace	STEEL	939.736	838.4	1.1209
STORY42	Floor	CONC	2959.882	838.4	3.5304

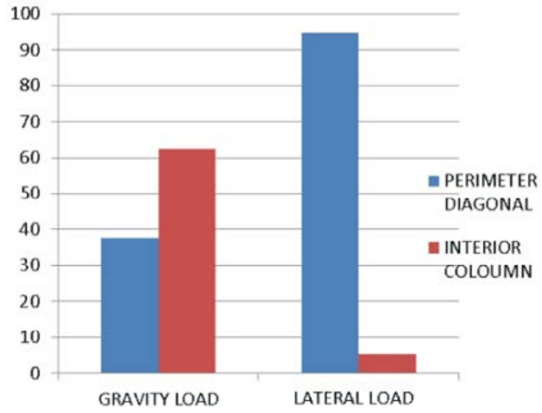


Fig. 6: Load distribution in exterior and interior frame

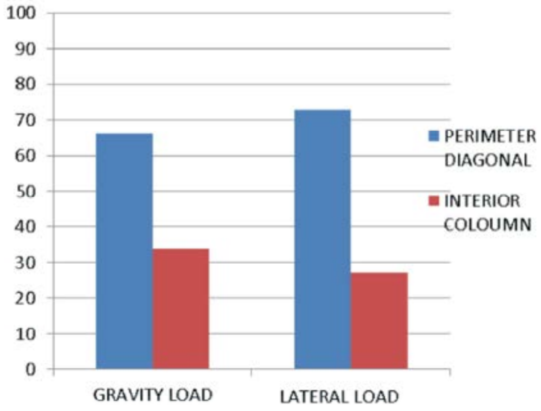


Fig. 7: Load distribution in exterior and interior frame

Unit Length and Trusses Sections: The tower with circle plan has 8 central columns with unit weight of 0.1017 kN/m and the total length of 1204.1m. Neverthelessthe tower with rectangular plan has 4 central columns with unit weight of 0.3728 kN/m and the total length of 596.8m. With regard to this problem, the number of columns has to be considered and the cause of bearing more gravitational load, which is about twice, can be related to the doubleness of the columns and supports number. Of course we can relate difference in attracting lateral force to greatness of tower's columns section with rectangular plan and also to plan geometry.

The tower with circle plan has the diagrid structure with unit weight of 4.6816 kN/m and the total length 2736.203m. However,the tower with rectangular plan has the diagrid structure with unit weight of 1.1209 kN/m and the total length 7253.243m. The first case mentioned in the problem of difference in the attracting gravitational force is that the number of the diagrid supports in circular tower is 8, nonethelessthe number in the rectangularity tower is 24. That is in the rate of 1 to 3. As a result, the rectangularity tower bears more and about twice of the gravitational load than circular tower. In the circle tower, althoughthe diagrid elements have a lesser length about 1/3 of the rectangularity diagrid structure, however, they bear more weight about four times than the lateral load. This factor is very important for creating more empty spaces and making spaces without obstacle in a surrounding environment and tower facade to enter more natural light and weather from qualitative and quantitative view in to the internal spaces.

CONCLUSION

The diagonal elements in circularity and rectangularity diagrid structure have very high output in transmitting of the lateral loads and confirms of previous researches in this matter. From one side it can be observed that it has a great role in the transmitting of the gravitational loads and can transmit about one third of the gravitational loads. Nevertheless, using the columns in transmitting of the gravitational loads is more economical.

In the design of the diagonal elements, less length and little nodes can be applied that transmit greater forces.Agreater cross section area and eventually more weight of diagonal elements can be used to have more architectural priorites. More length and many nodes can be utilized to transmit the little forces and less cross section area and as a result, less weight can have more economical benefits.

Effect of wind force on a tower is very important in high rises buildings. With analyzing the results of the table of shear forces for both towers, it can clearly observed that the effect of earthquake force is more than wind up to 150 meters height in Amol region and is prioritized as a prevailing force for the structure design. This subject may change based on weather and regional factors and in other places in the same height, wind factor may be more intense. It should be mentioned that wind factor intensifiesby increase of the height and it is predicated that in higher heights, the sheer force of wind will be more than earthquake.This issue can be investigated for the future research.

As the final conclusion for the tower design, it has to be mentioned that some elements that takemore priorities have to be considered, such as: a) the circle plan,b) the cylindrical volume based on decreasing of the factor of wind loading area in X and Y direction, c) geometrical complete symmetry that have a proper behavior against the base shear forces and drift storeys, d)thecapability of optimum use of spaces in the plan and e) architectural aesthetics predicament and its more attractionin facade.

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