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INVESTIGATING THE EFFECT OF ARCHITECTURAL FORM ON THE STRUCTURAL RESPONSE OF LATERAL LOADS ON DIAGRID STRUCTURES IN TALL BUILDINGS

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Abstract

The inconsistencies between structure and architectural form of buildings are a usual cause of construction problems and added extra costs to construction projects, and designers are often interested in understanding the effects of the architectural form of a building on its structural responses. In this research, by means of the parametric modeling strategy, the interrelationships between the architectural form and the structural response of approximate 60 story tall buildings with diagonal grid (DiaGrid) structures are investigated. Various geometries and dimensions of the lower and top floor plans and the method of form generation which determine the ascending development of the building from base to top resulted in 49 architectural schematic forms. The Diagonal Grid (DiaGrid) members of identical steel tubular section as the structure of the tall buildings are later mapped on the generated architectural forms. Lateral loads, representing the equivalent static actions, are then applied to the structure and a static linear analysis is made. Eventually, results illuminate the structural behavior of initial models mostly depend on the base floor plan rather than other parameters and the architectural models in which the base floor plan has more side count approximately has better structural efficiency. This research can help architects in form generation phase in order that tall building experience better response to lateral loads and economically feasible structure are attained.

Keywords

Tall buildings; Parametric Modelling; Architectural Form Generation; Diagrid Structures; Structure Analysis.

1 Introduction

This research proposes a parametric based workflow that generates Schematic architectural form and structure of tall buildings and evaluates its structural efficiency. In this section a brief introduction to research basics will be present:

The word parametric means all design definitions such as dimension and topology of form and structure can be varied at any time in the design process. Also, computation design has provided researchers with the ability to generate complex models of form and structure where routine structural modeling methods are equipped to meet the complexity and speed requirements. Many changes can be applied to the complete model of a high rise in a glance and parameters which define architectural and structural part of the model are flexible to changes [1].

Tall buildings are great architectural phenomena and necessitate enormous resources with heavy costs due to their large scale. As they become more complicated, it is essential to find compatible configurations in structure. Furthermore, the architectural characteristics should be studied to approach efficient structure [2]. The cost of structure constitutes up to 30% of total construction cost of buildings. Therefore structural consideration should be addressed in the very early stages of design [3].

Moreover, the schematic design phase is the most important stage of design because 80% of resources required to build a structure are committed by decisions made during the conceptual design phase. so this early phase of design is the most crucial part of the entire process [4].

During the modern era, the development of tall building was the product of a great collaboration of architect and structural engineer. This trend disappears gradually and as a result, the structural efficiency of tall buildings has decreased [3]. In the context of current tall building design practice, structural concerns are generally are dealt with not until the architectural form is well established. This approach limits the structural process solely to solving the problem rather than integrating the structural solution into the architectural concept. While merely makes the eruption of a building possible, it will not result in economically sane solutions that “perform fully in the conceptual, formal, technical, financial and material sense,” particularly with reference to structure [5].

2 Proposed design workflow

The geometry and shape of a tall building have fundamental effects on its structural behavior. Many Architects are interested in complicated forms and they want to create fascinating buildings during the design phase, but structural considerations cause limitations for architects in tall buildings. When engineers design structures for these forms, they are faced with numerous problems and extreme costs are added to project construction budget if the design team does not attend enough to structural considerations. In addition to architectural aesthetics, plenty of technical consideration must be applied in the design of tall buildings. This paper focuses on structural considerations to figure out which architectural shapes have better structural responses to lateral loads. A workflow by parametric modeling (with Grasshopper- a parametric plug-in for Rhinoceros) in which architectural forms are generated intelligently will be followed. The structure is mapped on the generated forms and lateral loads are then applied. The static equivalent seismic load is applied to the structure representing the effect of the earthquake. With following steps, the structure is analyzed by Karamba (a parametric structure analysis add-on for Grasshopper). For the sake of comparison, the functional properties of the buildings, such as; total gross area, building substruction, total structural weight, the structural system used and etc. are remained unchanged. The final results are architectural forms subject to comparison based on their structure behavior to determine their structural efficiency.

3 Architectural form generation

It is important to make a framework by which various variations of forms can be generated. Geometrically primitive forms are focused on at the current phase of research, which later develop into more complex geometrical solutions. The Form generation process is based on the geometry of the base plan and top floor plan and the ascending scheme which connects the top floor plan to the base floor and determines the overall shape of the building. Various geometry and dimensions of the lower and top floor plans and the method of form generation which determine the ascending development of the building from base to top which defined in the parametric environment (Grasshopper) resulted in 49 architectural forms.

3.1 Geometry plans

With the intention of applicability to actual building designs, various functional factors are noticed in geometry plans, such as a vertical core with a constant prismatic shape within the building for vertical transportation within the building and building services. Studied tall buildings are about 60 stories and the core dimension is about 130 square meters on each floor from base to top. This core dimension was studied in standards and regulations according to approximate dimension for vertical transportation, efficient functional area for every floor level, mechanical equipment, ducts and emergency staircases. Another determinant factor is light penetration depth. In addition, the floor to floor height is 4 meters. Geometry plans include a top plan and base floor plan. Recommended dimension for the base floor plan is about 2025 square meters and 500 square meters for top plan. Therefore due to area proportion of base floor plan to top plan, (4:1), all architectural forms which focused in this paper are tapered and the other area proportion will be focused later. It is very important that all generated shapes have a same total gross area which is approximately 70000 square meters. These parameters were designated by authors' overview.

As shown in figure (1), simple polygons from triangle to hexagon and 24-sided polygon with the mentioned dimensions for the core, top floor plan, and base plan were generated. Moreover with considering that all of these 7 polygons for top and base, 49 architectural models were made as shown in figure 2. The ascending methods for form generation are straight section morph explained in next section.

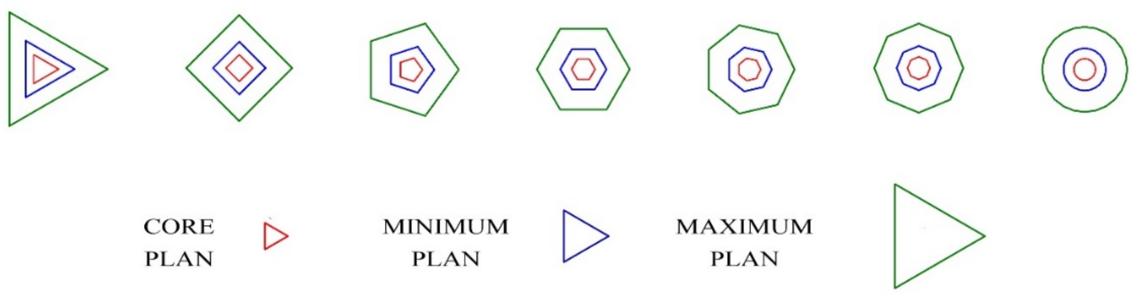

Figure1. The 7 polygons which used for form generation

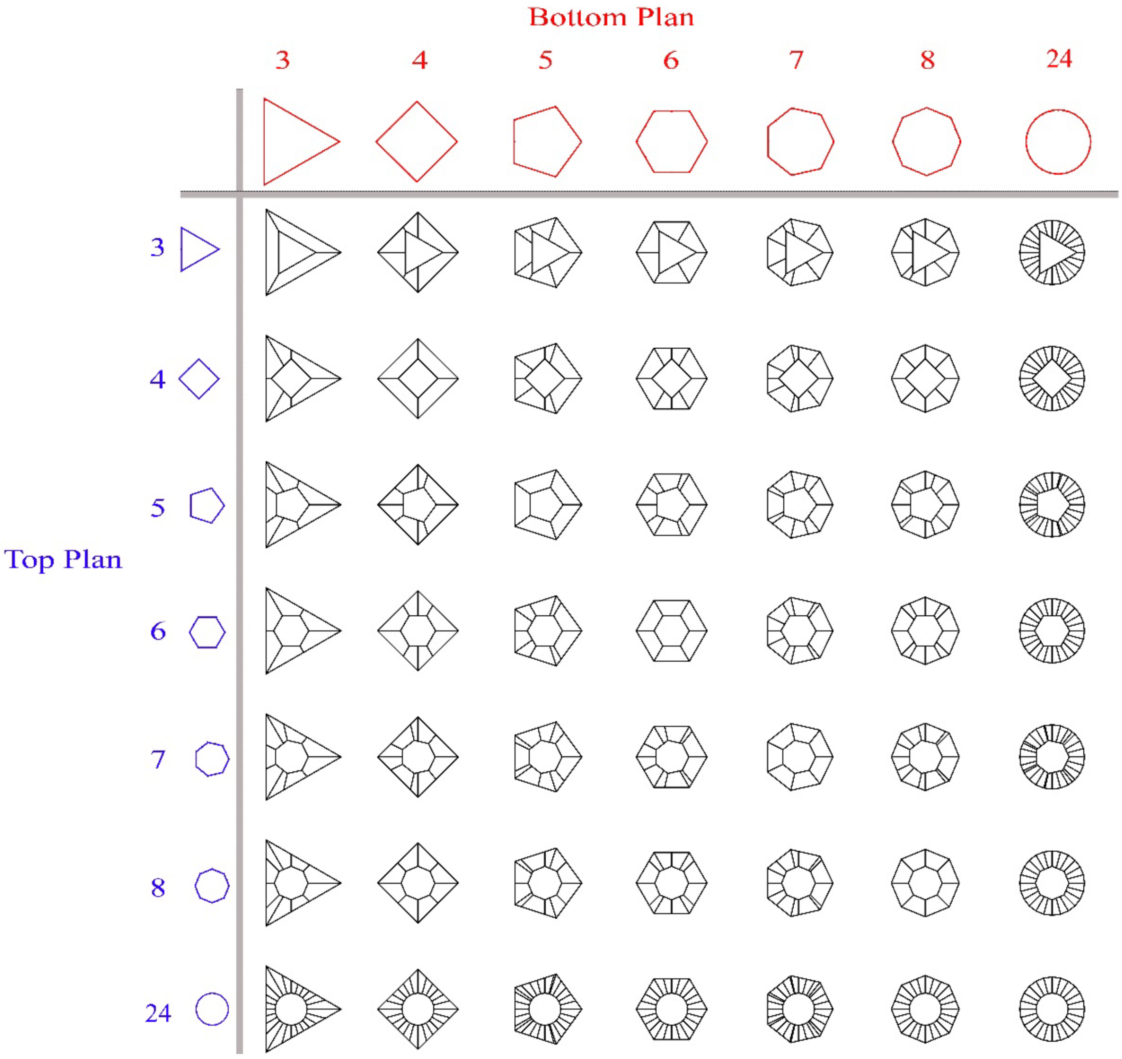

Figure2. The top and base floor plan in form generation phase.

3.2 Ascending scheme

According to previous research 4 vertical transformations from base to top for tall buildings are introduced: Straight Section Morph, Curvilinear, Twist, and Setback [6]. Three of which are under study within this research and the first method (Morph) was used in this paper.

Straight section Morph: in this method for every corner of the polygonal geometries of the top and base floor a corresponding point assigned in the other which are connected directly with straight lines. A maximum second-order surface (most cases a planar surface), sheets the space in-between the resulting straight lines. The union of all these generated surfaces that have a common line with their adjacent ones creates the envelope in which define the form of the building and its structure.

Twisted form: In the twist method the generated forms from the straight section morph method are twisted proportionally from base to top around the vertical axis connecting the centroids of the top and base floor.

Curvilinear form: In this method, the corner points of the base and top floor are no more connected with straight lines but by a curve with a nonlinear form that can be generated with different mathematical functions and resulting in concave or convex forms.

The initial height for all models is assumed to be 300 meters, but in order to maintain identical functional properties, corrections are made to the total height of every sample which is described in the following.

3.3 Height correction algorithm

As mentioned earlier all models should have the same total gross area, therefore after form generation, a correcting algorithm was used for the regeneration of forms. The heights of the models which exceed the total gross area (70000 square meters) were reduced and vice versa. Finally, 49 architectural forms generated as figure 3.

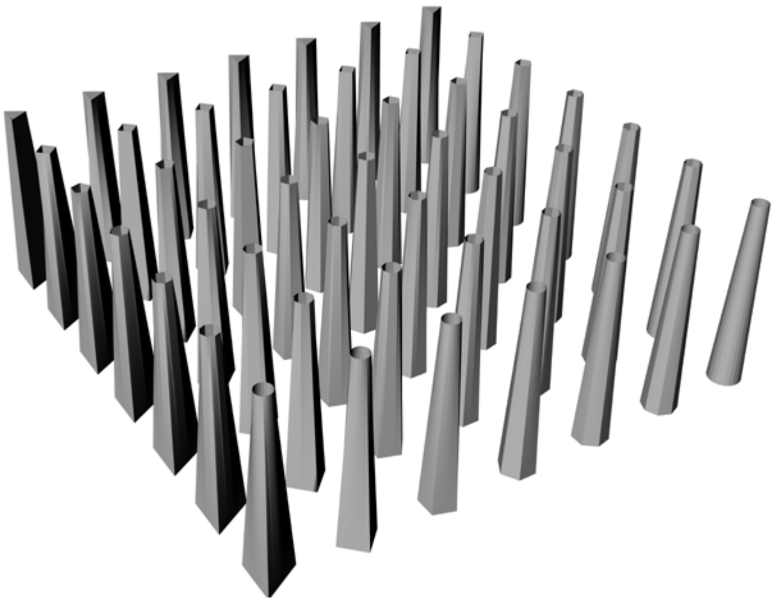

Figure 3. Generated Architectural models after height correction algorithm

4 Structure mapping

As specified, DiaGrid structure system will be used as the main structural system for all samples. the optimum angle of DiaGrid members depends on the height-to-with aspect ratio of building and for taller buildings steeper angle is optimum and vice versa [2]. "The optimal uniform angle ranges from 60 to 70 degree with the height-to-with aspect ratios ranging from about 4 to 10"[7].

The result of architectural form generation process is the peripheral surface of the building. Further on, a structure should be added on to it. A structure of Diagonal Grid (DiaGrid) members is mapped on it with variations over the height and width of every module. The height of DiaGrid modules defined by the count of floors it covers which is assumed 2 floors height. The width of DiaGrid modules is defined by the number of the nodes assigned to the borders of the floor plan at each story level. These parameters are specified in structure generating phase, and for the purpose of comparison are considered fixed for different shapes. Also, the rigidity of structure should be similar in all architectural model so they could be comparable, so the node counts of DiaGrid should be in a specific range. Since the DiaGrid nodes should be placed on the corner of architectural forms, it is dependent on the number of vertices of the base and top floor plans (in each form the plan in which has more vertices).

So a range in which the count of vertices should be divisible should be assumed. Therefore a range of 22 to 30 was considered, so the number of vertices for of all forms could be divisible in at least one number in this range. The count nodes of DiaGrid are listed below in table 1.

Table1. The diagrid count nodes of architectural forms

Model No.	Diagrid nodes	Model No.	Diagrid nodes	Model No.	Diagrid nodes	Model No.	Diagrid nodes	Model No.	Diagrid nodes
1	24	11	24	21	28	31	22	41	24
2	24	12	30	22	24	32	24	42	24
3	28	13	24	23	24	33	28	43	24
4	24	14	24	24	30	34	28	44	24
5	27	15	28	25	24	35	30	45	28
6	30	16	24	26	24	36	30	46	24
7	24	17	25	27	24	37	24	47	30
8	24	18	30	28	24	38	24	48	24
9	24	19	22	29	27	39	24	49	24
10	24	20	24	30	30	40	28		

Furthermore, vertical structural members with no effect on the lateral response of the building are added just to avoid huge unsupported floor slabs. The mapping of the structure is performed with identical tubular members while keeping the total weight of the structure of the building constant.

5 Structural loading

Lateral loads, representing the equivalent static actions, are applied to the structure and a static linear analysis is made. The simplified approximate loads are studied in the initial phase of the research. Statically Equivalent Avenue for determining lateral loads is applied in the following manner. The equivalent loads are distributed on the floor slabs. In this research, a statically equivalent load of seismic was focused and all models which pass through architectural and structural phases were analyzed with same loads.

5.1 calculating Seismic response base shear coefficient

The base shear force was computed by presented equation (1) and (2), which is then distributed on floor slabs based on equation (3).

$$C = \frac{A \times B \times I}{R_u} \tag{1}$$

Where: C is the seismic response coefficient, A is the base considered acceleration, B the reflection factor of the structural behavior of the building, I the importance of building and R_u the response factor of the building. Based on the Iranian National design code for earthquake loads [8] the value of seismic response coefficient for all samples is considered equal to 0.055.

5.2 Earthquake equivalent base shear

In this section, the total earthquake equivalent shear force is calculated according to equation (2) [8].

$$V = C \times W \tag{2}$$

The total weight of all models are approximately similar because all of them has same “total gross area” and the heavier part of buildings are the weight of floor slabs. The total approximate weight which concludes the floor slabs weight and the external structure assumed 44370Ton, therefore the total earthquake equivalent shear load due to equation (2) calculated 24403.5 KN.

5.3 The distribution of resulted earthquake shear force on floors

in the final step of the structure loading, the distribution of resulted earthquake shear force must apply to the structures following equation (4) which suggest that each floor slab gain load base on its weight and the height from the base level. [8]

$$F_i = \frac{w_i \times h_i^k}{\sum_{j=1}^{n} w_i \times h_j^k} \times V \tag{3}$$

“F_i”: the earthquake force of the ith floor “w_i”: the weight of the ith floor, “h_i”: the height of the ith floor, “V”: the total earthquake shear forces which calculated according to equation (3).

The structural model of the tall building categorized into 3 parts: The DiaGrid, the floor slabs, and the core. The core just bears the dead load and it has nonrigid connections to floor slabs. It does not contribute to lateral loads bearing capacity of the building. The DiaGrid structure is modeled as complex of beams with pinned joints and all nodes located in floor slabs level. Two steel tube sections were assigned for members of DiaGrid: a tubular section with 80 cm diameter and 2 cm thickness and another section with 60 cm diameter and 1.5 cm thickness.

6 Analysis results and comparison

In this section, structure analysis is performed by Karamba (a parametric structure analysis add-on for Grasshopper) and structural responses of 49 architectural forms are compared according to parameters such as overall Drift, the total mass of the structure, Total structure member count, and the Maximum Utilization ratio of elements in each model.

6.1 Drift and Total Mass

It is observed that forms that are located on secondary diagonals of architectural forms matrix (7 by 7 forms matrix) have similar structural behavior. For example, in the 6th diagonal line (figure 4-a), all forms have low drift and the forms that have the lowest drift are located on the 11th matrix Diagonal. The first form and the last form of second part of diagonals (8th-13th diagonal) have similar behaviors with respect to structural stiffness, e.g. 35th forms and 47th forms; the first one is defined by a 24-sided polygon in base floor plan and a 7-sided polygon in top plan and the other vice versa. The Total mass Diagram (figure 4-b), as Drift diagram, state that with more sides constituting the geometry, there would be higher total mass and therefore, heavier forms have fewer drifts. Forms presented in this paper, fluctuations of base floor plans are higher than top plans due to the tapering effect of them.

6.2 Simple forms

In this category, top and base floor plans are constituted of same polygons including numbers1, 9, 17, 25, 33, 41 and 49 in figure 4. Due to miscellaneous geometric features, these forms need to be divided into two different categories: Forms with even and odd sides. The difference in side numbers which directly affects their stiffness toward lateral loads is shown in Figure 5. Forms with 3, 4 and 5 sides are loaded within a single vector- green vector (the vector crossing the center and one of the sides – as all the polygons are symmetrical, then there is no difference for the crossed side to be selected). This vector addresses the centers and so as the floor plans perform as structural diaphragms, automatically distribute the load to corners (red vectors). In 4 sided polygon, this vector crosses the axis of two sides, however, it crosses one side in the 3-sided polygon. Moreover, this vector crosses two sides of a 6-sided polygon which is aligned with other 4 sides. Consequently, the stiffness of these forms is different with each other and for an appropriate evaluation, this classification is obligatory. According to figure 4, there is approximately less drift for those with a higher number of sides.

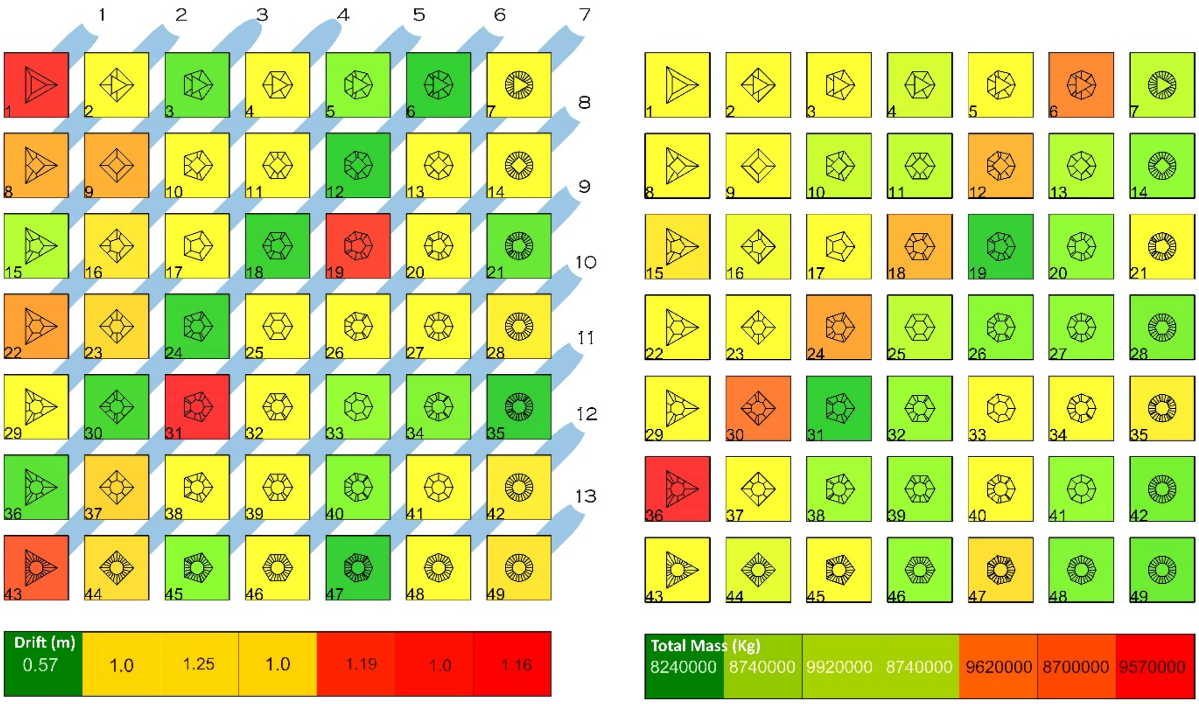

Figure 4. (a)Overall Drift and (b) the total mass of the structure

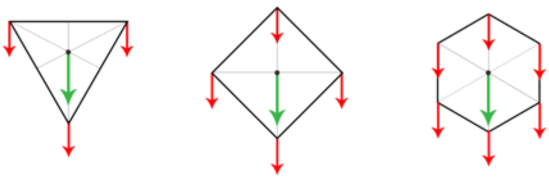

Figure 5. The effect of geometry on the load bearing resistance on same loading vector

As shown in table 2, for those forms with an odd number of sides, from 7 to 3 sided polygons, there is 42% drift reduction and 2% reduction in total mass. Additionally, for those forms with an even number of sides, from 8 to 4 sided polygons, there is 8.5% drift reduction and 3.5% reduction in total mass.

Table 2.Drift and the total mass of forms in which the top and base floor plan are same

odd-sided polygon	Drift	total mass	even-sided polygon	Drift	total mass
3	1.213033	9372100	4	1.098634	8868400
5	0.943904	8856000	6	1.019957	8626500
7	0.701374	9207700	8	1.004548	8556500

6.3 The total amount of the structure members

In the diagram of figure 6, the relative values (the amount of each parameter over its mean in all cases) of Drift, Total Mass the total amount of Diagrid members are shown for each form. Generally speaking, there is much Total Mass and fewer drifts for geometries with a higher number of sides due to higher structural stiffness. As mentioned in section 4 (Structure mapping), total diagrid nodes are defined by a number of polygons' corners in plan and this may restrict the overall structure configuration and because of differences in diagrid nodes (based on table 1), there are differences in structural stiffness. As shown in the diagram of figure 6, this difference in total amount of the structure members, obviously had effects on the total weight as well as structural drifts.

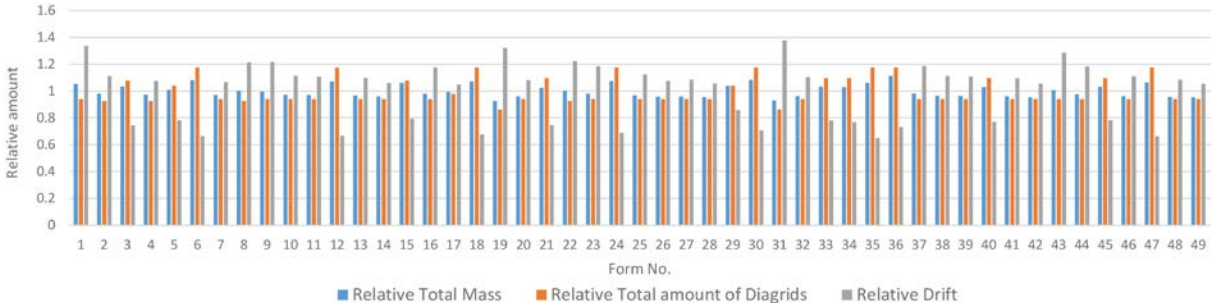

Figure 6. Relative Drift, relative Total Mass and relative Total count of Diagrids members

6.4 Maximum Utilization Ratio

As seen in figure 7, 49 architectural forms are categorized into 7 groups of the matrix rows, which represent the variations in the base floor plan. The left side (7-a) shows lower values of maximum utilization ratio (resulting force in the structural member divided by its load bearing capacity) in all structure members of a model for each group. In right side (7-b), the result of utilization ratio multiplied by the total weight of each category is shown with a specific color. This parameter also illustrates the structural behavior. There is a general trend line for each category in this dialog. This time, the 7 by 7 forms matrix is categorized with columns. Each ellipse demonstrates one category. The number below each ellipse shows the polygon, constituted them. As mentioned in simple forms section, for an appropriate evaluation, forms need to be classified into two different groups. For polygons with even sides and odd sides, blue and red colors are specified respectively. Based on this theory, forms constituted of same polygons showed similar structural behaviors. With changes in side numbers of floor plans, from odd to even, there seem to find a fluctuation which stabilizes this statement. In respect of the dialog, with an increase in side numbers of base floor plans, the result of utilization ratio multiplied by total mass, decreased which shows a better structural behavior.

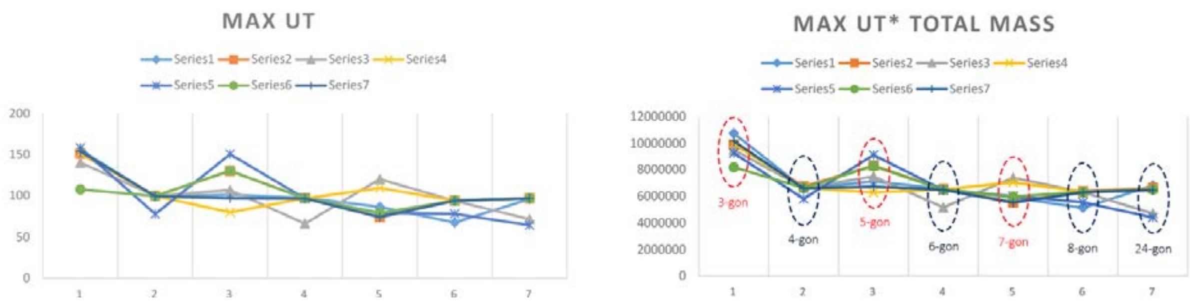

Figure 7. (a) Max Utilization and (b) the multiplication Max Utilization by Total Mass

7 Conclusion

The structural efficiency of architectural forms is investigated by means of design parameters in this paper. Based on many parameters as top and base floor plan and an ascending method for vertical transformation, and according to supposed planning specification (total gross area, top and base floor plan area, number of floor plans), architectural forms were generated. Due to supposed areas of the base floor and top plans, generated forms became tapered. A diagonal grid (DiaGrid) of steel tubular sections mapped on it and the equivalent statically seismic load applied on. A comparison between the generated forms base on factors which represent the structural efficiency as overall Drift, the total mass of the structure, Total amount of structure members, and Maximum Utilization of elements in each model. The effect of the base floor plan resulted as the most important factor in the structural efficiency of these architectural forms. Also, it was figured out that the structural behavior of architectural forms depends on its base floor plan polygon side numbers. Therefore, architectural forms should categorize into two groups: even-side polygons and odd-side polygons. In both categories when the polygons side numbers of base floor plan increased, the structural efficiency generally improved.

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