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Effects of different geometric patterns on free form gridshell structures

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ABSTRACT

Gridshells are commonly known as structures with the shape and rigidity of a double curvature shell consisting of a grid, not a continuous surface. In recent decades, these structures have attracted significant attention. The impact of various geometric patterns on free form gridshell structures is investigated here to demonstrate the necessity of collaboration between structural and architectural characteristics in enhancing structure efficiency. To that goal, a framework is proposed where three shells are first designed, and then six geometric patterns are formed on them. The main factors for evaluation of gridshells are decreasing the steel weight as an economic index and decreasing the displacement as a structural index, also, finite element method is used for structurally analyzing the gridshells, and the generated gridshells are compared to each other based on the mentioned indices. For the optimization process, an approach is suggested to find the most optimum gridshell, then numerical results show the efficiency of the proposed alternative approach.

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1. INTRODUCTION

It can be said a building cannot be designed without an understanding of structure. According to their shape, purpose, and material of construction, structures can be categorized in a variety of ways. Architecture and engineering will always have a place in shell constructions. More than any other structural system, shells have the capacity to produce striking forms and offer creative freedom [1], [2]. With the passage of time due to the reaching lightweight structures, gridshells attracted the attention of engineers and architects [2]. Gridshells are one of the most widely used structures for lightweight large-span roofs without the need for intermediate supports and can be made of any kind of material such as wood, aluminum, steel, or even cardboard tubes [3], [4]. Although the use of these structures is more desirable as the material usage is reduced and the internal space is increased [5], it is sometimes a notable challenge to design and form efficiently such structures on a given surface [3], [6]–[10]. In fact, the problems of designing and optimizing gridshell structures have been very attractive in recent decades [3], [6], [11], [12]. The widely known techniques for designing or form finding of gridshells are force density technique [6], [13], inversion procedure [7], [14], and dynamic relaxation [15], [16]. Several different geometric patterns including triangular, quadrangular, and hexagonal. have been applied for designing gridshells among which the most commonly used ones in real-world projects are the triangular and quadrangular patterns [6], [7], [16]–[20]. In fact, the triangular geometry pattern is of intrinsic stability and easier constructing process, and the quadrangular structures are shown to be more efficient against some forces such as wind, strain energy, and earthquake [6], [7], [21]. Moreover, some researchers have used Voronoi tessellations to improve the aesthetic and strength of the gridshells simultaneously. In fact, the grids obtained by Voronoi approach contain different faces with variable density which has made this kind of grids interesting for researchers and architects [22]. We consider the triangular, quadrangular, and Voronoi patterns in this work. For optimization of gridshells, several approaches including the gradient-based techniques such as compass method [7], evolutionary approaches such as genetic algorithms [3], [16], [23], or some other techniques such as sphere packing approach [6] have been studied in the literature.

By the march of time different approaches to face challenges of collaborating design and optimization between gridshells have studied by researchers. Compass method, a novel method for creating elastic gridshells on an imposed shape with boundary constraints, was proposed. It consists of a few genetic algorithms and certain geometric techniques [7]. Feng and Ge [24] proposed a multi-objective morphology optimization technique for free-form cable-braced gridshells. They have considered three categories of indices; mechanical indices such as maximum displacement and strain energy, geometry indices such as mean-square deviation of the steel tube lengths, and economic indices such as cost of the structure. Goodarzi *et al.* [17] introduced two indexes to measure the regularity of a gridshell structure, and then compared the PSO and GA techniques to improve the regularity of gridshells. A two-phase design technique was proposed in [16] which in the first phase used dynamic relaxation for finding the funicular form of the gridshell and in the second phase determined the optimal nodal positions through a generic algorithm with minimizing the material and improving the structural performance as objectives. Wang *et al.* [25] proposed a framework for generating gridshell structures by working on free form surfaces and concentrating on the triangular gridshells. They demonstrated the efficiency of the proposed framework [3] considered some load cases such as wind load and used a multi-objective genetic algorithm for establishing a design tool for synthesis of optimal gridshell structures. It is noted that among the mechanical indices, minimizing the maximum displacement and among the economic indices, minimizing the structure's weight are two important objectives in optimization of gridshells and have been considered [6], [7], [18], [24]–[26]. Therefore, these two objectives, i.e., minimizing the displacement and structure's weight, are considered in this work. Moreover, as minimizing each item may have a negative impact on the other one, we proposed a multi-objective optimization approach in this work.

The main aim in this work is to investigate the effect of collaboration between structural and architectural features in improving the gridshells' efficiency in non-regular surfaces. To this end, a framework is proposed in which three shells are designed to cover a given span of approximate 25 meters, and then various geometric patterns are formed on each designed shell. Afterward, the obtained patterns on each shell are analyzed and compared in order to determine the best grids aiming at decreasing the displacement and the steel weight. Finally, all the generated gridshells are compared together to determine the best ones.

The rest of this work is organized as follows. Section 2 provides the framework which consists of two phases and explains each phase in details. Moreover, it proposes an alternative approach for optimization. The experimental results are given in section 3. Finally, section 4 provides the concluding remarks.

2. METHOD

As stated in preceding section, according to aesthetic quality, constructability, and economic advantages, the most widely used geometric patterns on the free form surfaces are triangular and quadrangular [6], [19], [25]. In addition to these two patterns, another interesting pattern is the one obtained from Voronoi approach [20]. Therefore, the focus of this work is on triangular, quadrangular, and an example of geometric pattern obtained from Voronoi approach which is called Voronoi pattern. The main aim of this work is studying the effect of different geometric patterns on the designed shells for which a 2-phase framework is presented. The framework is described in detail next.

2.1. Overview of the framework

The proposed framework consists of two phases and is based on Rhino from which several plug-ins are used. In the first phase, the initial gridshells are generated and analyzed. In the second phase, the best gridshells are determined taking into account the minimization of steel weight and displacement simultaneously. For generating gridshells, parametric structural and architectural models are generated using appropriate computer programs such as Rhino/Grasshopper in the first phase, we first design several freeform shells parametrically. Then, some of them selected as candidates to cover a given large space by structurally analyzing the designed shells in the first stage. It is attempted to select freeform shells with a variety of architectural aspects in terms of plan boundary, which is a line or border that separates one region from adjacent or nearby areas, and height. Afterwards, various geometric patterns from triangular, quadrangular and Voronoi classes are generated on each shell. We note that there is no limitation on the number of selected shells, however it is important that the selected shells are structurally stable in terms of displacement and weight per unit of area. Moreover, it is noted that by varying the density of faces in each pattern many similar geometrically patterns with different structural characteristics are obtained. This way, a potentially infinite number of grids can be generated on only a few numbers of designed shells in the initial stage. In the second phase, the generated gridshells are first analyzed by using the finite element method and Karamba plug-in which can analyze any parametrically generated structure in Grasshopper plug-in in Rinho [27]. Then, taking into account the minimization of steel weight and displacement, the generated gridshells are sorted and the best ones are determined. Afterwards, we adopt a novel algorithm to improve structural efficiency, in which the algorithm is implemented in Rhino using the Python programming language, allowing it to interact with other parts of the framework. In the next sections, each phase of the framework is described in more details.

2.2. Phase I: production and initial analysis of gridshells

In this phase, to cover a given large space, three shells are designed in grasshopper 3D by defining four fixed supports and covering a specific area to reach structural efficiency in non-regular surfaces, and economic advantages. It is vivid that one can design any number of shells in this stage; however, we are satisfied with these three shells as an example of freeform shells and how they can be grided parametrically. It is noted that more than two thousand grids are generated on these three shells. For ease, the shells are called as Type I, Type II, and Type III, as depicted in Figures 1 to 3, respectively. Then, three different triangular (called triangle A, B, and C) which they are different in u and v divisions described in Figure 4 and two different quadrangular (called quad and diamond) patterns are formed on each shell through the Lunchbox plug-in. Moreover, a Voronoi pattern is formed on the shells. This way, 18 models are generated in general. To have a better understanding, we considered a large space with area of 717 m^2, there models are generated and depicted in Figures 1 to 3. In order to investigate and study a wide range of producible gridshells under the desired patterns, we vary the density by using the *u* and *v* divisions which is a uniform meshing and refers to UV mapping. This mapping is used in computer graphics for describing the transformation of a texture map when it is applied onto a 3-dimensional object [28]. Indeed, *u* and *v* refer to the number of faces in each unit of area as shown in Figure 4.

We emphasize that any number of shells and on each one any number of patterns including the ones not considered here like pentagonal or hexagonal grids can be considered to design and produce the initial gridshells in our proposed framework. However, we consider the three shells given in Figures 1 to 3 to avoid the prolongation of the paper. Moreover, it is reminded that the triangular and quadrangular patterns are the most widely used ones in the literature and the Voronoi is a different pattern but interesting one, and this is why we consider on these patterns in this work. Next, the formation of Voronoi pattern and the procedure of initial analysis is explained.

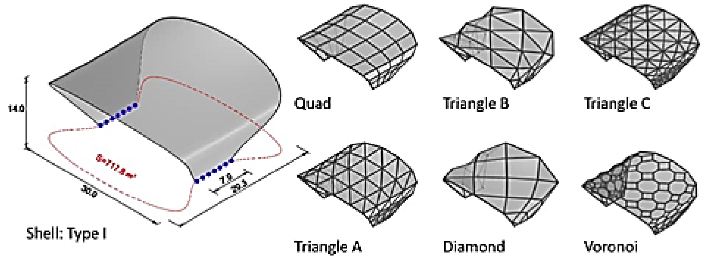


Figure 1. The shell Type I and associated geometric patterns

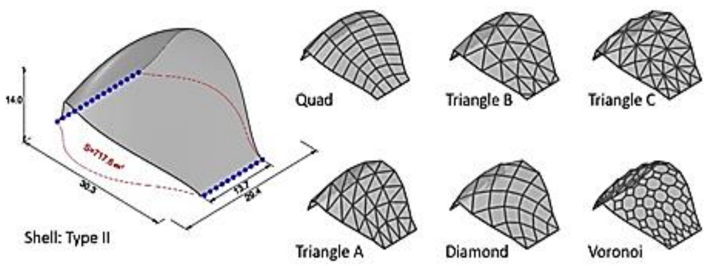


Figure 2. The shell Type II and associated geometric patterns

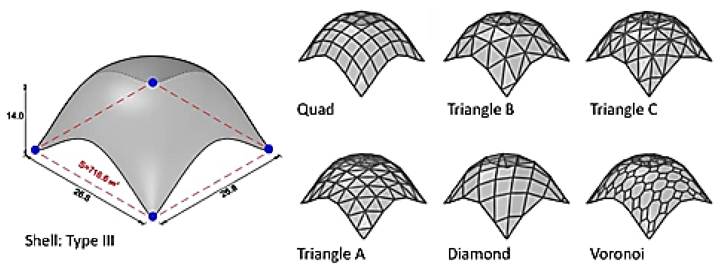


Figure 3. The shell Type III and associated geometric patterns

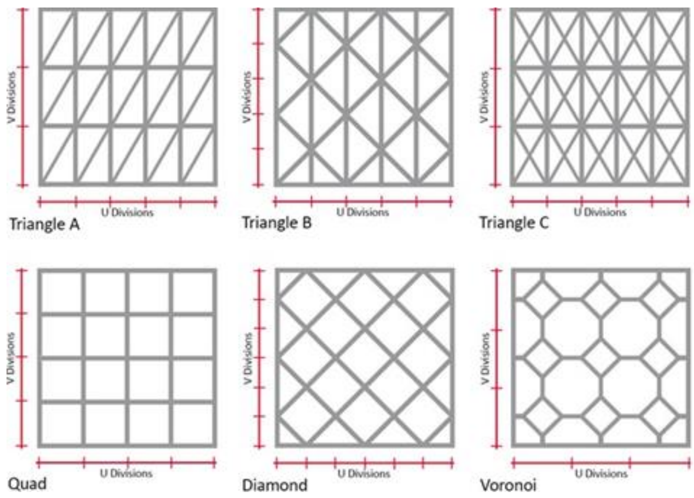


Figure 4. A sample of u and v divisions for each pattern

2.2.1. Initial analysis of the gridshells

After forming all the gridshells, now is the time to analyze the grids. Taking into account the criteria of weight and wind and applying the Karamba plug-in, the initial analysis of the generated gridshells is made. In fact, in this analysis, the amount of steel used for each gridshell and the maximum allowable displacement of the joints are calculated. It is noted that the wind force is applied horizontally and the dead load is considered as the weight of structural steel elements. The structural dead load includes the weight of steel diagrid. Wind load rules are taken from Issue 6 of the Iran National Building Regulations standards, as this building is considered to be designed in Tehran, Iran. As a result, wind applied as a horizontal load in the models; the prevalent wind in Tehran is west, and the wind speed is considered to be 100 km/h. The maximum permitted lateral displacement for the top floor must thereafter be limited to (height/500), according to Code of Standard Practice for Steel Buildings and Bridges [29]. As a result, the models were able to deflect 9 cm horizontally on each side. The gridshell is modelled to have hinges at all intersection nodes and composed of uniform size members. The support conditions are considered as fixed.

2.3. Phase II: determination of best gridshells

In order to reach the best and the most optimum gridshell, structural optimization methods are applied. In an inverse process known as structural optimization, parameters are implicitly or indirectly optimized to determine the shape/geometry of a structure in order to minimize or maximize an objective function or fitness criterion [1]. In this phase, by considering displacement and steel weight per unit of area as objectives, i.e., the decrease in the values in all designed gridshells are sorted for determination of the best ones. A novel simple approach is proposed in this work to optimize outcomes. It is noted that although both objectives of the decrease in displacement and in steel weight should be considered simultaneously, as decreasing in steel weight is an economic factor, it is more important than the other. To elaborate more on objectives, although admissible displacement is a constraint at one point (9 cm), all float numbers smaller than this value are known as a range, the least of which is the best. In fact, one can make sure that the formed gridshells are in a permitted range of displacement, and then find the most optimum ones according to the steel weight index. Although it seems a good approach, it is more appropriate to consider the two objectives together and simultaneously.

2.3.1. The proposed approach

As the aim is minimizing simultaneously the displacement, denoted by d, and steel weight, denoted by *w*, in the designed gridshell structures. Also, the cost function is considered as $f(d, w) = \alpha d + \beta w$ in which α and β are the corresponding coefficients to the displacement and steel weight, respectively. This algorithm is called weighted sum method.

To obtain the most optimum outputs, one of the most important stages is to normalize d and w values and determine some values for these coefficients. To this end, generating thousands gridshell patterns, we examined different combinations of coefficients to determine the best ones. To obviate the effect of the values' sizes, or to have a fair comparison not affected by the large values of weights, we firstly divided all the displacement' values (weight' values) by the associated maximum displacement (weight). Then, we tested three strategies; $\alpha_1 = d_{\min}/d_{\max}$, $\alpha_2 = d_{av}/d_{\max}$ and $\alpha_3 = d_{\min}/d_{av}$, where $d_{\min}$, $d_{\max}$ and d_{av} are respectively the minimum, maximum and average displacements among all the generated gridshells. In fact, once the displacement of all the generated gridshells is calculated, these parameters can be simply determined. Similarly, we considered $\beta_1 = w_{\max}/w_{\min}$, $\beta_2 = w_{\max}/w_{av}$ and $\beta_3 = w_{av}/w_{\min}$ as the corresponding values for the coefficients of steel weight. It is easy to see that all the αs are between zero and one, and all the βs are greater than one. In fact, it is noted that steel weight is an economic index while displacement is a mechanical index which points out to the importance of steel weight compared to displacement. This is why the coefficients of steel weight are calculated in some way that they are surely greater than the coefficients of displacement. Afterwards, we tested the results.

$$\alpha_{av} = \frac{\alpha_1 + \alpha_2 + \alpha_3}{3} \text{ and } \beta_{av} = \frac{\beta_1 + \beta_2 + \beta_3}{3} \tag{1}$$

It can be observed that the calculated α_{av}s for different types of generated patterns on the same area are different, and accordingly we considered the final coefficients in our proposed algorithm as (2).

$$\alpha = \frac{\alpha_{av,t1} + \alpha_{av,t2} + \alpha_{av,t3} + \alpha_{av,all}}{4} \text{ and } \beta = \frac{\beta_{av,t1} + \beta_{av,t2} + \beta_{av,t3} + \beta_{av,all}}{4} \tag{2}$$

It is noted that *t1, t2, t3* and *all* in (2) refer respectively to the patterns of Type I, Type II, Type III and all the patterns together. It is observed that $\alpha_{av,all}$ is different from the sum or average of $\alpha_{av,t1}$, $\alpha_{av,t2}$ and $\alpha_{av,t3}$, and this is why it is considered in (2). We note that these coefficients are considered based on thousands of generated numerical results. Finally, it can be observed that the gridshell with lower cost value is the better gridshell. Also, the pseudocode of the proposed approach is described in Figure 5. Now, let see the proposed algorithm to find the best designed gridshell structure.

```
1  displacement = x
2  displacement = [int(i) for i in displacement]
3  dis_avg = sum(displacement)/len(displacement)
4  dis_min = min(displacement)
5  dis_max = max(displacement)
6  alpha1 = dis_min/dis_max
7  alpha2 = dis_avg/dis_max
8  alpha3 = dis_min/dis_avg
9  alpha_avg = sum([alpha1,alpha2,alpha3])/3
10 # line 1 to line 10 should be repeated for each shell.
11 #alpha = sum [alpha_avg1 + alpha_avg2 + alpha_avg3 + alpha_avg_all]/4
12
13 steel_weight = y
14 steel_weight = [int(i) for i in steel_weight]
15 sw_avg = sum(steel_weight)/len(steel_weight)
16 sw_min = min(steel_weight)
17 sw_max = max(steel_weight)
18 beta1 = sw_min/sw_max
19 beta2 = sw_avg/sw_max
20 beta3 = sw_min/sw_avg
21 beta_avg = sum([beta1,beta2,beta3])/3
22 # line 13 to line 21 should be repeated for each shell.
23 #beta = sum [beta_avg1 + beta_avg2 + beta_avg3 + beta_avg_all]/4
24
25 d = []
26 [d.append(int(i/dis_max)) for i in displacement]
27 w = []
28 [w.append(int(i/sw_max)) for i in steel_weight]
29
30 def f(d,w) :
31      f1 = alpha*d
32      f2 = beta*w
33      f3=f1+f2
34      return f3
```

Figure 5. Pseudocode of the proposed approach

Step 1. Generate all the producible gridshells in Karamba plug-in and save the parameters of steel weight, displacement, *u* division, *v* division, pattern, and type of each grid shell.
Step 2. Calculate α and β as given in (2).
Step 3. Divide the displacement and steel weight of each gridshell by the associated maximum ones, i.e., d_{max} and w_{max}, respectively, in order to find the associated *d* and *w* with each gridshell.
Step 4. For each generated gridshell, calculate $f(d,w) = \alpha d + \beta w$.
Step 5. Sort the gridshells ascending in accordance with the calculated values in Step 4. The first gridshell is the best one.

3. RESULTS AND DISCUSSION

Here, several numerical results are provided to illustrate how the proposed framework can be used to determine the best gridshells taking into account minimization of the displacement and the steel weight. To generate the numerical results, a large space with area of 717 m^2 is considered and three shells with height of 30 meter are designed. On each shell, six different geometric patterns including three triangular (Triangle A, B, C), two quadrangular (quad and diamond), and a Voronoi pattern are implemented. By using the *u* and *v* divisions and varying the density of the faces, 2,098 different gridshells are designed to cover the desired space. It is noted that the designed shells cover a wide range of steel weight from less than 30 kg to more than 1,700 kg. As the steel weight is the economic index which plays an important role, we consider an upper limit of 250 kg on steel weight which results in remaining 1,517 designed gridshells. As it is explained earlier, any number of shells can be designed to cover the given space, however we considered three designed shells to avoid prolongation of the paper. Also, about the geometric patterns, one can generate many other patterns and consider them in the framework, however as the most widely used patterns are triangular and quadrangular, we work with these patterns along with the pattern generated by Voronoi technique which is a different one.

The best patterns for each shell are first determined by analyzing all the generated patterns on that shell. Second, all three shells' geometric patterns are examined and compared with one another. To ascertain which gridshells will best cover the given large space.

3.1. The best pattern on each shell

The main aim here is to find out which pattern is the best one for each designed shell. Taking into account minimization of the displacement and the steel weight simultaneously. Analysis of three types of shells is described further.

3.1.1. Analysis on shell Type I

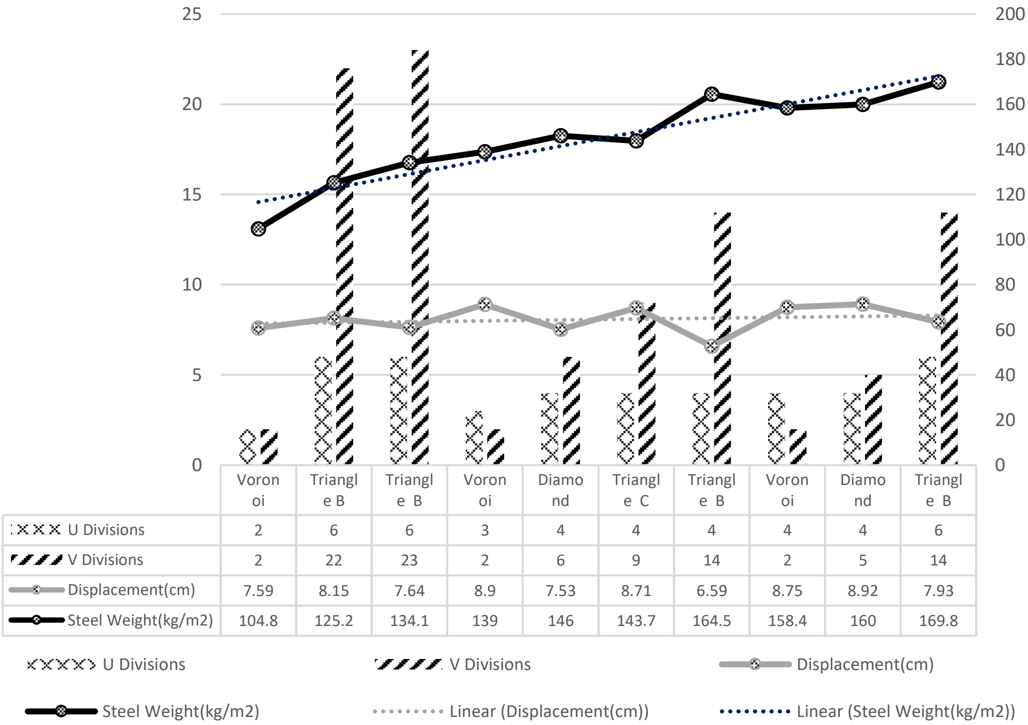
Considering shell Type I and implementing the six desired geometric patterns on it, 430 gridshells are generated in total by varying the density of faces among which only 38 gridshells are less than 250 kg. It is noted that all the 430 generated gridshells are feasible to be constructed in reality, however we consider only the 38 gridshells with the weights being less than 250 kg. According to our proposed approach, α=0.6161 and β=3.7840 are calculated. We note that these values are the same for all the types of the generated shells. Then, the cost of each gridshell is computed and the best ten ones are introduced in Figure 6. As it is seen in this figure, the gridshells with only minimum value of displacement or only minimum value of steel weight are not the best ones. For instance, the displacement in the seventh best gridshell is less than the displacements in all the other ten best ones, or the steel weight in the sixth best one is greater than steel weight in the fifth best one as shown in Figure 6. In fact, it is a multi-objective determination process. Figure 6 shows that Triangle B and Voronoi are the most frequent patterns among the best ten ones. Moreover, it is seen that there is no meaningful relation between the variables *u* and *v* with displacement and steel weight in the gridshells.

3.1.2. Analysis on shell Type II

By implementing the six desired geometric patterns on shell Type II, 826 different gridshells are generated in total by varying the values of u and v divisions among which only 654 gridshells are less than 250 kg. The same coefficients α=0.6161 and β=3.7840 are used here as well. The best ten generated grids on this shell are introduced in Figure 7. The figure shows that quad is the only pattern appeared among these ten best ones on shell Type II. And again, it is seen that there is no meaningful relation between the variables u and v with displacement and steel weight in the gridshells.

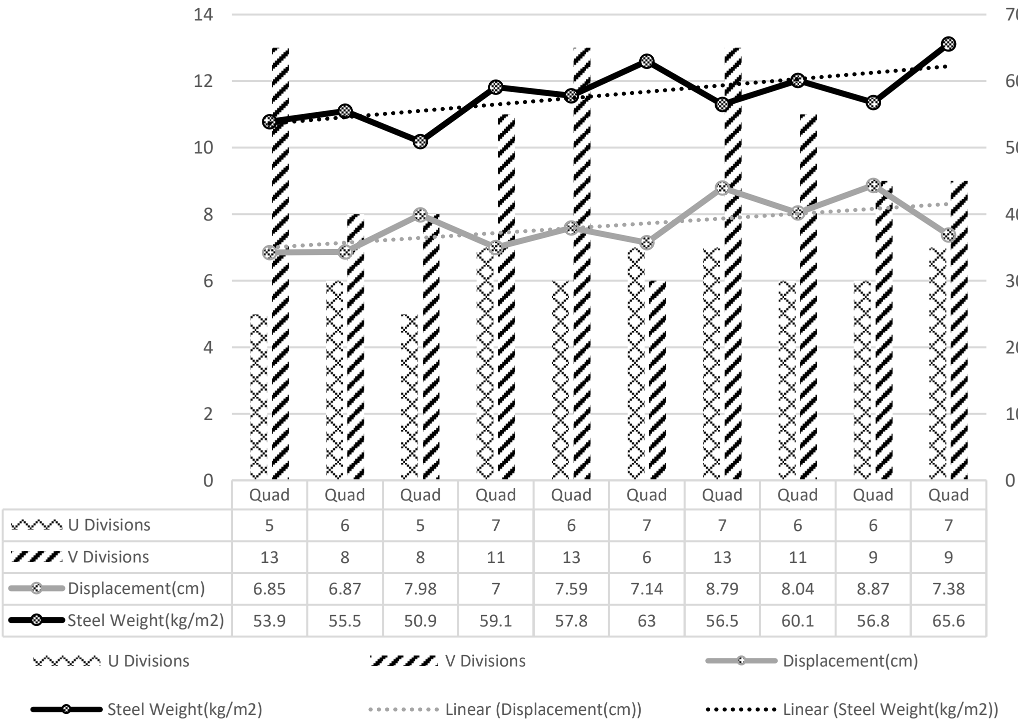
3.1.3. Analysis on shell Type III

On shell Type III, 832 different grids are generated by implementing the six geometric patterns among which 827 grids are less than 250 kg. The same coefficients α=0.6161 and β=3.7840 are used here as well. The best ten generated grids on this shell are introduced in Figure 8. It is seen in the figure that Triangle B and Triangle C are the most frequent patterns among the best ten ones on shell Type III. Moreover, there is no meaningful relation between the variables *u* and *v* with displacement and steel weight in the generated grids on this shell as well.



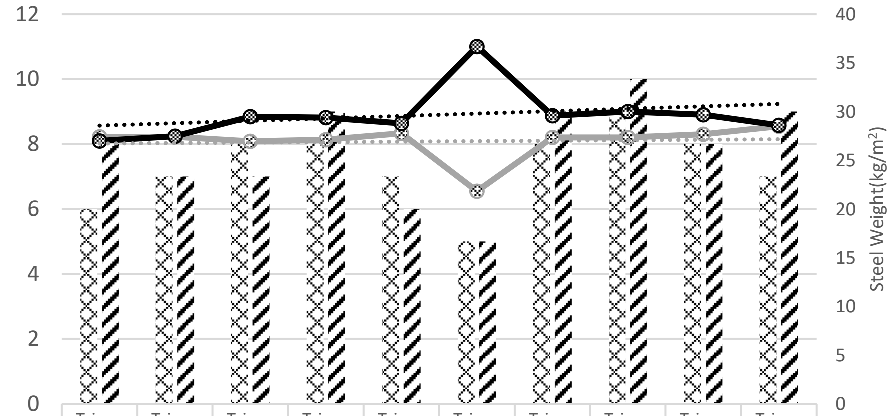
	Voronoi	Triangle B	Triangle B	Voronoi	Diamond	Triangle C	Triangle B	Voronoi	Diamond	Triangle B
U Divisions	2	6	6	3	4	4	4	4	4	6
V Divisions	2	22	23	2	6	9	14	2	5	14
Displacement(cm)	7.59	8.15	7.64	8.9	7.53	8.71	6.59	8.75	8.92	7.93
Steel Weight(kg/m2)	104.8	125.2	134.1	139	146	143.7	164.5	158.4	160	169.8

Figure 6. The 10 best generated grids on shell Type I



	Quad	Quad	Quad	Quad	Quad	Quad	Quad	Quad	Quad	Quad
U Divisions	5	6	5	7	6	7	7	6	6	7
V Divisions	13	8	8	11	13	6	13	11	9	9
Displacement(cm)	6.85	6.87	7.98	7	7.59	7.14	8.79	8.04	8.87	7.38
Steel Weight(kg/m2)	53.9	55.5	50.9	59.1	57.8	63	56.5	60.1	56.8	65.6

Figure 7. The 10 best generated grids on shell Type II



	Triangle B	Triangle C	Triangle C	Triangle C	Triangle C	Triangle C	Triangle B	Triangle C	Triangle C	Triangle C
U Divisions	6	7	8	8	7	5	8	9	8	7
V Divisions	8	7	7	9	6	5	9	10	8	9
Displacement(cm)	8.23	8.23	8.09	8.14	8.33	6.55	8.21	8.21	8.3	8.55
Steel Weight(kg/m2)	27	27.5	29.5	29.4	28.8	36.7	29.6	30	29.7	28.6

Figure 8. The 10 best generated grids on shell Type III

3.2. General analysis

Now, let us compare all the 1,517 generated grids on all the three designed shells together. To this end, the same coefficients α = 0.6161 and β =3.7840 are considered. The obtained results show that all the best ones are the ones from shell Type III which illustrates the efficiency of shell Type III in comparison with the other designed shells. Hence, the related figure to this result is the same as Figure 8. An interesting point in the obtained results on the three shells here is that among the best ten grids on each shell, the displacement and steel weight move in opposite directions, i.e., when displacement increases the steel weight decreases and vice versa. It can be seen through the Figures 6 to 8.

4. CONCLUSION

This article studies the impact of structural features in the design of gridshells. So, structural variables were applied to consider their effects during the design process. Then, given a large space to be covered by a gridshell structure. A framework first proposed by designing three different shells, and then geometric patterns generated on each shell including triangular, quadrangular, and Voronoi. As the framework was based on Rhino, several plug-ins in Rhino were used. An approach was proposed to determine the best gridshells. Taking into account the relative displacement (d) and steel weight (w) of the generated gridshells, the cost function $f(d,w) = \alpha w + \beta d$ was considered in which the coefficients α and β were determined respectively by dividing the minimum steel weight and displacement by the maximum ones. Moreover, w and d were not the raw steel weight and displacement in each gridshell, and instead were the relative ones resulted from dividing the steel weight and displacement of each grid by the maximum ones. The numerical results showed that among the best 10 grids on each shell, always the steel weight and displacement move in opposite direction, and that there is no meaningful relation between the density of the faces in a grid with its displacement and steel weight.

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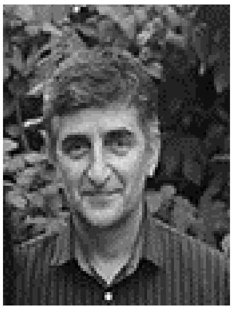

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