International Journal of Architecture and Urban Development
Vol. 14, No. 4, P .Autumn 2024

E-ISSN 2345-2331
Applied Research Article
DOI: 10.71711/ijaud.2024.1182968

Evaluating the geometric component in the optimal design of bending-active gridshell structures

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Recieved 2024.09.04 ; Accepted 2024.12.06

ABSTRACT: Gridshell structures are a type of bending-active structures. In the present study, bending-active grid structures are selected since it is simple to construct curved elements to create exciting and diverse architectural forms with minimum manufacturing energy consumption and minimum wastage of materials, they are strong shells against all kinds of forces and are less addressed in Iran. In this regard, the present study tries to determine the optimal geometric form of grid shells by comparing different geometries. Also, it investigates the geometry of anticlastic, synclastic, and free forms to help improve the structural performance of the bending-active grid shell. The hardness of these shells fully depends on their shape, therefore efficient forming helps to control their hardness and structural behavior. The structural performance of the grid shell is analyzed using Kangaroo Physics and Karamba plugins in Grasshopper software. In constructing bending-active gridshell structures, the shell geometry is drawn based on the changes in numerical variables such as geometric dimensions, opening length, etc., using the digital form-finding method in Kangaroo Physics and Karamba plugins in Grasshopper software and Galapagos optimization, and the final optimal form is designed. Next, the form is investigated against various stresses and loads including bending, shear, etc. The final model, selected by comparing different geometrical modules, shall have the lowest stress and the least displacement so that it can be significantly effective in designing and constructing the optimal forms of temporary bending-active gridshell structures.

Keywords: *gridshell, form finding, types of geometry, bending active, optimization, digital architecture*

INTRODUCTION

The structural behavior of gridshells depends on their geometry. In these structures, the load transfer mechanism is a combination of shell behavior and arch behavior (axial and shear stresses). Also, gridshells are among the structures self-supporting during construction or after completion, meaning they need no additional elements to ensure their stability (Khalil Beigi Khamene, 2015). Designing and implementing curved forms in architecture have received attention with the advancement of form-finding tools and methods in recent decades. Architects and engineers have focused on form-finding strategies, including materials and forces that can discover a system of lightweight structures and provide them to designers, since the 1950s. These lightweight structures became an important part of the work of individuals such as Buckminster Fuller, Felix Candela, Heinz Eisler, and Frei Otto (Chilton, 2000; Otto, 2005). The term "bending-active" was introduced by Knippers and his colleagues to describe beam and surface structures whose geometry is based on the flexibility analysis of surface or vertical elements. (Knippers et al., 2011: 134). The present research seeks a practical method for finding the optimal form of structures using the performance-based design method through finite element analysis (FEA) and optimization using a genetic algorithm. In the present study, bending-active grid structures are selected since it is simple to construct curved elements to create exciting and diverse architectural forms with minimum manufacturing energy consumption and minimum wastage of materials, they are strong shells against all kinds of forces and are less addressed in Iran. In this regard, the present

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study tries to determine the optimal geometric form of grid shells by comparing different geometries. What geometry is suitable for the form-finding of gridshells? And what method is applied to optimize the form? These structures can be made of various materials such as steel, aluminum, wood, etc. For these structures, a very specific erection process was developed to avoid complex joints using the bending capability of slender components. According to this process, two layers of long continuous beams are pinned together on the ground first. The resulting grid allows large deformations in space due to the absence of shear rigidity. It is then elastically deformed by bending to obtain the desired form and finally be stiffened. Next, for example, in the third bracing layer of the beam, the initially straight beams are bent to form a curved stiff surface through this process. Only a few gridshells have been constructed using the active bending method, the most famous of which are the Downland Museum, the Japanese pavilion for the Hanover 2000 Exhibition, and the Cathedrale Ephemere de Creteil, which was constructed with an initially flat grid (Collins & Cosgrove, 2015). Studying bending-active gridshell structures indicated that the elastic instabilities depend linearly on Young's modulus, and having a low Young's modulus is considered a shortcoming and the designer tries to calculate the structure principally (Lienhard et al, 2013). New structural concepts shall be found to take advantage of all the characteristics of composite materials. Most of the slender structures, such as gridshell structures, in structural engineering are designed according to their stiffness and rarely to their strength. Most grid structures have been made of wood because it is the only traditional construction material that can be bent with large deformations without breaking. It also generates a stiffer structure while offering flexibility in curved shapes (Gengnagel et al., 2014).

MATERIALS AND METHODS

In the present study, the required data were by library method and reviewing relevant theoretical studies, and the data were qualitatively and quantitatively analyzed and compared. First, various geometric modules were modeled using software such as Rhino and Grasshopper, and the loads in these models were evaluated by Kangaroo and Karamba physics plugins. Finally, a model with an optimal form was selected based on the choice of material, cost, facilities, and site location. The method proposed in the present study was explained and described by comparing in the form of diagrams and tables. The variables of this parametric model were geometric patterns, and the objective function was based on the structure weight, and the amounts of displacement, stresses, and loads, which were optimized and evaluated. Optimization was carried out by the genetic algorithm through the Galapagos plugin, which is based on the outputs of the Karamba physics plugin.

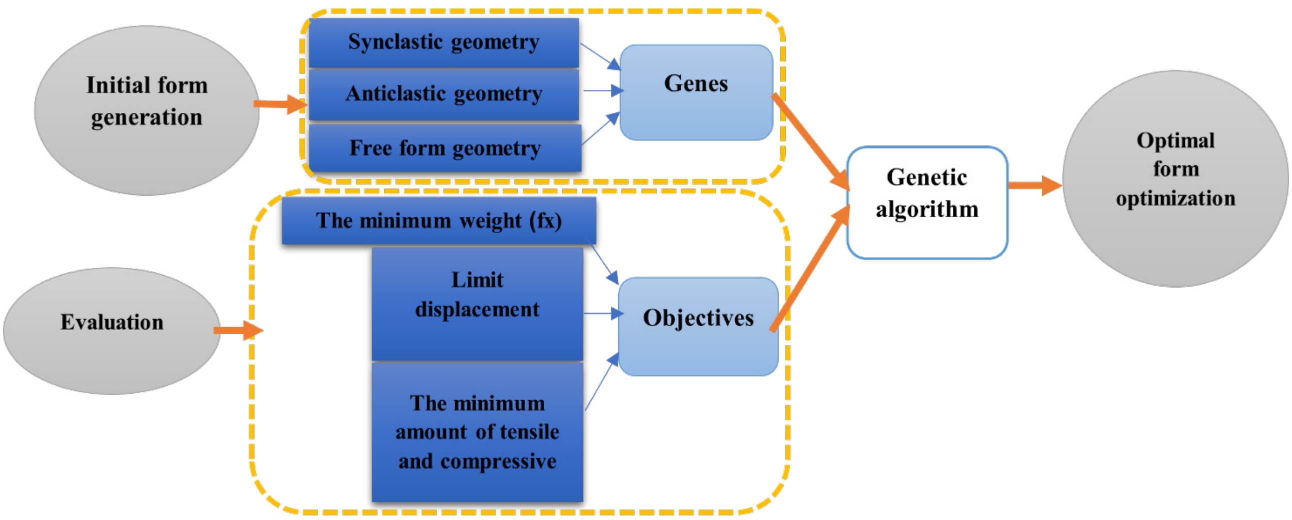


Fig.1: Optimal form generation in the present research

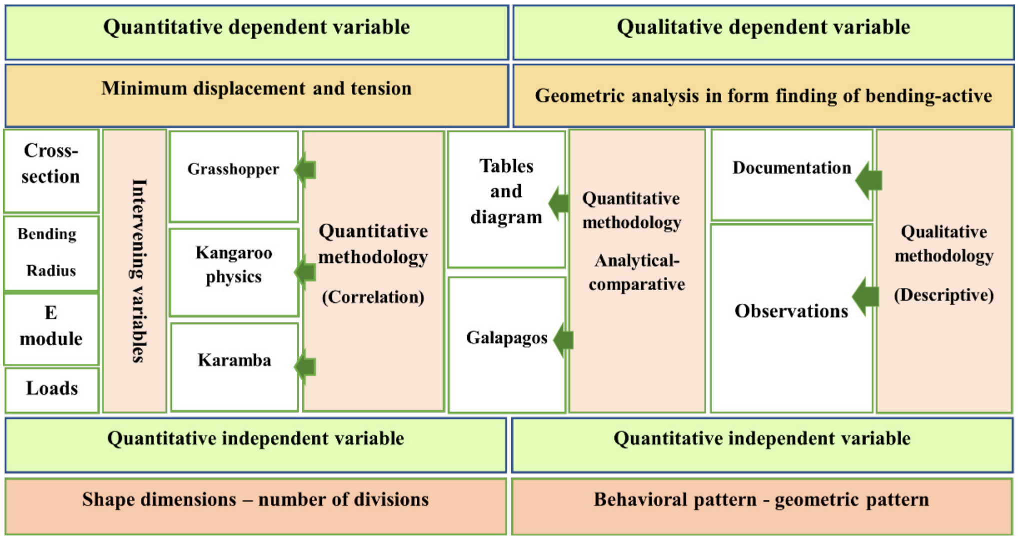


Fig.2: The variables examined in the present research

Research background

Shell structures are regarded as an efficient way to build eco-friendly buildings. They required extensive manual work to make double-curved shapes when materials were not cost-effective. They were popular as concrete or masonry shells in the period (1975-1925). The recent development of digital design and production with a focus on the reduced consumption of materials has helped the generation of gridshell structures, which are a type of double-curved shells, and whose structural system, instead of a single surface, consists of a network of linear members that are often straight members connected to the nodes (Hillersøy Dyvik S, Rønnquist 2021).

Many designers have applied hanging chain models and other physical methods to find the most efficient structural forms acting in tension. For over 40 years, physical models have been promoted as the most appropriate method for finding 3D forms (Kilian & Ochsendorf, 2005).

The use of the hanging frozen fabric method seems to have created a break in the design of shell structures until Edward Cullinan designed the Weald and Downland gridshell near Chichester, London, with improvements in detail design and construction. This process was followed by the completion of the Saville Building project in 2006, designed by Glenn Howells (Lionhard et al., 2013).

The historical development of bending-active forms shows that they have been developed with a behavior-based approach. This approach can be seen in most of the built projects and is known as a construction method so far. In the behavior-based approach, bending is tested initially and directly with the materials and scale, and the system's geometry and its structural behavior are studied experimentally to test the material limitations physically. The emergence of the geometry-based approach lasted until the 20th century, and again in these years, the behavior-based approach has been used in the analysis of bending-active structures. Today, there is another approach called the integral approach that analyzes the elastic bending deformation using numerical modeling, enabling full control of material behavior-based geometry. It also includes the characteristics of materials and their limitations in the numerical analysis model.

Even today, there are numerous examples of bending-active structures developed with a behavior-based approach. Nowadays, the interaction of structure with architecture is an important issue that enables the use of structural knowledge in the field of design. Structure means the arrangement of forces and working with them, and architecture is actually the result of the interaction of various internal and external forces, which leads to the formation of sizes, thicknesses, and forms of structural elements made of different materials and influenced by various force systems. Vitruvius defined architecture as an architectural work that has three attributes: venustas (beauty), firmitas (strength), and utilitas (utility). According to this definition, strength is one of the pillars of architecture, and it can be said that the strength of a building depends on its structure, and the skeleton and structure of a building influence its general form and spatial quality. The design and construction of curvature structures have a long history in architecture. In addition to aesthetic features, these structures have many functional advantages, such as lightweight, easy construction, high stability, and high structural performance. In the past, the form-finding methods used for these structures were limited to physical and computational ones. Today, the advancement of the computer and its capabilities to produce complex forms provide new opportunities for architects (Pillwein et al., 2020).

The construction of gridshells started in the 1960s, and Félix Candela was one of the architects who used mathematical methods for form-finding. He was very interested in presenting mathematical structures in architecture and was one of those who used hyperbolic paraboloid shells in architecture. In his designs, instead of irregular forms, he generated forms with the ability to transfer the loads well (Moore, 1869). Regarding curvature structures, form generation is a constant attempt to achieve integrity in the structure's geometry and architecture, which has once again become the focus of research. Bending active grid structures refer to an approach in structure design whose history dates back to the indigenous architecture of many regions. In indigenous architecture, bendable materials were used to form arches and curved grids with simple geometries, and many experimental construction methods have used this method in indigenous architecture. However, only a few of them belong to the 20th century. This technique has been conventional since the past, especially in the indigenous architecture of different countries and cultures. So, such light structures have been a practical economic solution in architecture (Moore, 2007).

Table 1: Review of research background

Year	Authors	Research title	Results
2014	**Simon Schleicher Riccardo La**	**Paper** Bending-Active Plates Form-Finding and FormConversion	Two methods were compared for detailed analysis of flexural active plate structures and their advantages and disadvantages were discussed based on three case studies. In this paper, a relatively new structural system was presented. It purposefully uses large elastic deformations to produce and stabilize complex geometric shapes based on flat elementary elements. In this system, complex geometric shapes are transformed into simple elements. The paper contributed to the discourse of flexural structure by highlighting two different designs of form finding and form transformation
2015	**YANG JIANG**	**Thesis** Free form Finding of Grid Shell Structure	This thesis presented a numerical implementation to find the funicular shape of lattice shell structures. Form-finding was carried out using two methods: Potential Energy Method (PEM), and Force Density Method (FDM).
2017	**Henrik Green & Daniel Lauri**	**Thesis** Form Finding of Grid Shells a Parametric Approach using Dynamic Relaxation	Structurally meaningful geometry can be obtained with a parametric modeling approach where constraints limit the solution space. A form-finding algorithm was developed for grid shells. The algorithm is based on dynamic relaxation with a dynamic stiffness method, applied along with structural evaluation with the finite element method. This algorithm can form gridshells with arbitrary boundary geometry for steel and fiber gridshells.
2019	**Mohammad Sadra Rajabi, Mohammad Amin Ali Bakhsh**	**Paper** Introduction of gridshell, light steel framing, thermomour, and reinforced concrete superframe systems as innovative structural systems	This study attempted to introduce gridshell systems, light metal framing, and thermomuro superframes as innovative structural systems, in addition to mentioning innovative construction methods of new materials that provide the ground for reducing the weight of buildings and make them resistant against different types of forces, that can be avoided.
2022	**Sanket G. Pathade1, Milind R. Nikhar, Vaibhav. A. Kalmegh**	**Paper** A Review Paper On Behavior of Gridshell Structure	The primary rationale for choosing a grid design is not only the enhancement of performance, and efficiency, or reducing cost, but also for architectural form. Magnificent designs and distinctive buildings can be created based on a gridshell. In this research, first, the grids in a rigid mesh shell were initially examined to study the overall behavior of the structure. According to the FEM results, the stiffness and buckling load of the gridshells can be increased. Material behavior between grid nodes may be modeled more accurately. For typically larger grids, the form-finding is precisely programmed. Due to the bending constraints imposed by the section capacity, they are easier to bend in double curvature.

Theoretical foundation

Mesh design process in the gridshell

Classification of gridshells

According to the definition of gridshells, any grid surface with a curvature and a very low depth-to-span ratio can be considered a gridshell. Therefore, gridshells are one of the structural systems with a great variety. The gridshells can be classified in terms of grid geometry, load transfer type, form, and the establishment of structure. At the beginning of the design process, a continuous form may be defined for the gridshell. To avoid excessive stress, the structure should have a rounded form with curvatures as homogeneous as possible. Then, according to the range of curvatures, the geometric features of the beams are selected (mainly the outer radius). According to the features of the beam, a grid is drawn on the form (geometric step) and then, the resulting form of the gridshell (mechanical step) is calculated. After form-finding steps, the third layer of beams (bracing layer) is modeled and the stresses in the structure are evaluated in serviceability limit state (SLS) and ultimate limit state (ULS) per construction rules. You may sometimes have to change the mesh or form of the gridshell to reduce the stresses. When a concentric form and appropriate stresses are designed, the membrane can be designed according to the three-dimensional form obtained from the numerical steps.

Step1: Geometric step

The intersection of diagonal and straight lines in different plans (regular quadrilaterals, circles, ovals, etc.) forms different gridshells. The number of lines can be reduced or increased. The greater the number of linear members the heavier the structure and the higher the load it can bear. Different geometric modules can be used to construct gridshells. However, the most widely used modules, which are considered basic patterns, include square, diamond, triangular, and hexagonal grids. Other patterns can also be obtained by combining basic patterns.

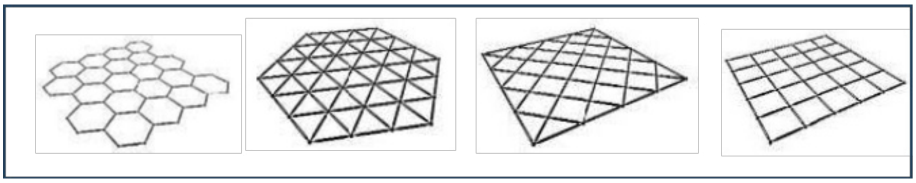


Fig. 3: Basic patterns for grid geometry

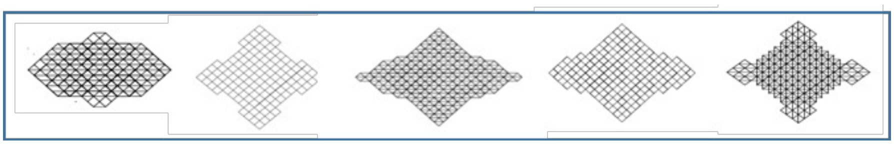


Fig. 4: Composition of modules

Step 2: Load transfer type

In fact, a gridshell can be considered a shell with large openings. The remaining strips or grids structurally behave like the shell. In shells, engineers see countless load transfer paths, while in gridshells, internal forces are transferred through members and as a result, more limited paths. Since the shear force cannot be transmitted through the grids, some braces can be considered to create shell behavior. For this purpose, one of the most common techniques is the use of a continuous covering layer in grids using diagonal bracing which triangulates the grids. In this type of system, the grid structure allows it to transfer the loads in two or more than two directions. In other words, unlike structures transferring loads to supports in only one direction, this system transfers loads through several paths and in several directions. Therefore, in terms of load transfer, gridshells can be classified into two-way, three-way, and four-way gridshells as the main classes (Mansoori et al., 2019,706).

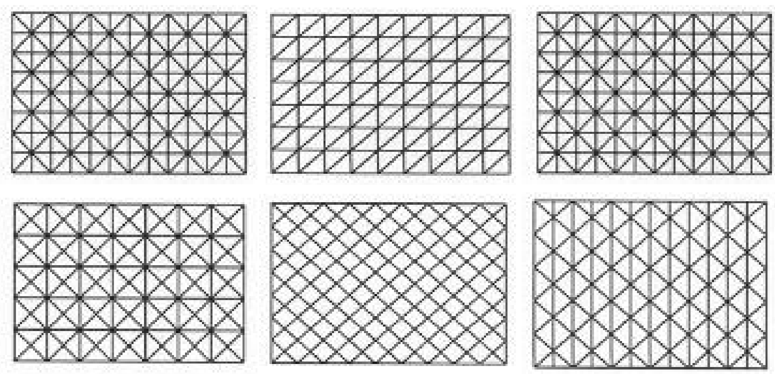


Fig. 5: Load transfer patterns in gridshells, two-way patterns (middle), three-way patterns (right) four-way patterns (left) (Hoshiar, 2009)

Step 3: Mat form

Gridshells, like other shells, can be classified into different classes in terms of the structure mat curvature and form. The five main classes are as follows: 1. Zeroclastic: flat sheets; 2. Monoclastic: Singly-curved sheets and cylindrical sheets; 3. Synclastic: doubly-curved sheets; 4. Anticlastic: doubly-curved sheets (in opposite directions); and 5.Free-form: sheets with different curvatures. It is noteworthy that in such shells, different grid geometries and different load transfer types can be used. To more accurately know synclastic gridshells, first, the shells obtained from surfaces of revolution and then, those obtained from surfaces of translation or ruled surfaces must be examined

The synclastic shells obtained from surfaces of revolution are classified into the following classes:

1. Sphere and circular domes; 2. Ellipsoid of revolution or spheroid; and 3. Paraboloids of revolution. The synclastic shells obtained from surfaces of translation or ruled surfaces include: 1. Elliptic paraboloids; and 2. Paraboloids of translation (Farshad, 1992, 8).

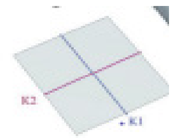
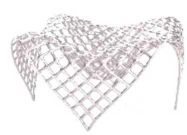
Synclastic shells

To better understand synclastic shells, it is necessary to first study and understand the structural forms of slender shells. Shell evokes protective surfaces found in nature such as bird eggs, sea shells, mollusk shells. turtles, human skulls, seeds, and those nests built completely instinctively by certain birds (Melaragno, 1991,120).

Shells are thin structures with often curved surfaces that transfer loads to the supports only by tension, pressure, and shear. Shells are very efficient in structures and exterior coverings of buildings, where the applied load is uniformly distributed. Since the shells are often very

thin, they have little bending strength and are not suitable for bearing concentric loads (Moore, 1998, 197).
The shell can carry relatively large loads if the loads are uniformly distributed on it. An egg is the best example of a shell in nature. Although it is thin, it can withstand a large amount of uniform distributed load due to its form. The high strength of shells is due to their forms and not their mass. Shells are very optimal in the use of materials because they withstand loads through their form rather than by bending behaviour. There is a great variety of forms that can be used in constructing a slender shell. In fact, theoretically, the shell can take any form, whether it is mathematically definable or not. Dome, cylindrical, vault, conical, and hyperbolic paraboloid shells are the most famous shell forms (Gulabchi & Amiri, 2016, 441).

Table 2: Classification of gridshells based on geometric characteristics (Source: Authors).

Class	Geometry	Characteristics	Image
Zeroclastic	flat sheet	K1=0 K2=0	
Monoclastic	Singly-curved sheet	K1=0 K2>0	
Synclastic	Doubly-curved sheet	K1>0 K2>0	
Anticlastic	Doubly-curved sheet (in opposite directions)	K1<0 K2>0	
Free-form	There is no specific formula for curvature. The sheet has different curves.	k1 and k2 are the curvature of the lines in the x- and y- directions towards the z axis, respectively.	

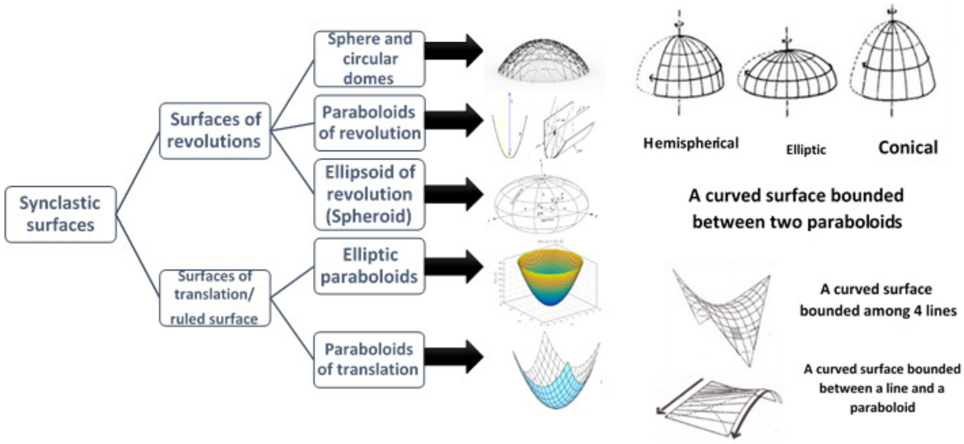


Fig. 6: Typology of synclastic gridshells based on their geometries (Source: Authors).

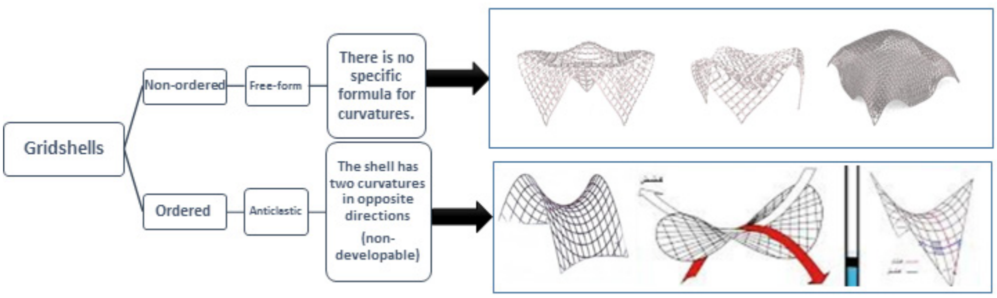


Fig. 7: Typology of anticlastic and free-form gridshells based on their geometries, (Source: Authors).

According to Table 1, ten modules are selected from the existing free-form, synclastic, and anticlastic modules. In the present research, first, the selected modules are geometrically and numerically analyzed using the Kangaroo physics plugin in the Grasshopper software, and their geometries are optimized by changing parametric variables. Next, the model with the lowest stress, least displacement, and highest strength is selected to create a gridshell with the optimal structural performance in the Karamba plugin. Also, it is tried to reduce the weight of this gridshell structure by choosing suitable materials to make it have the best performance in bearing all kinds of loads and stresses. In the present research, the correct selection of variables such as dimensions, proper geometry, and appropriate cross-section plays a significant role in improving the structural performance of gridshells (Moore, 1998,198).

Digital form-finding

Digital form-finding is done in the preliminary by changing parametric variables such as dimensions, span length, height, etc. to select the optimal form in Grasshopper software. Then, the final form is selected in the Kangaroo Physics plugin, which can analyze the form and determine support points. Next, in the construction phase, the final materials must be chosen using Karamba plugin, numerical analysis, and determining stresses, etc. The final materials selection requires considering all factors, including Young's modulus, displacement, deformation form, and minimum stress and force. Optimal solutions may be strongly influenced by the initial grid. In the proposed method, the initial grid initialization consists of a uniform grid provided by the coherent mapping technique and produced by Spring Bourne et al. The reason for using coherent grids in this research is the almost constant angle between the edges. This avoids twisting points, provides homogeneous curvature distribution, and makes it possible the displacement of joint points and the adaptation of boundary conditions to the site by parametric design. These are all the limitations related to the material and geometry of the grid system. This computational form-finding model has become one of the basic interfaces that helps coordinate design and various factors. While this fully geometric model is an abstraction of the actual shape, and additional deformation due to dead load is neglected, there is currently feedback on the wide range of form-finding possibilities offered by this process. In the finite element analysis (FEA) method, Karamba plug numerically and graphically provides the user information, such as weight, displacement of nodes, stresses, etc. Gridshells are delicate structures, and their design requires preventing buckling and bending (Lefevre, Douthe, & Baverel, 2015).

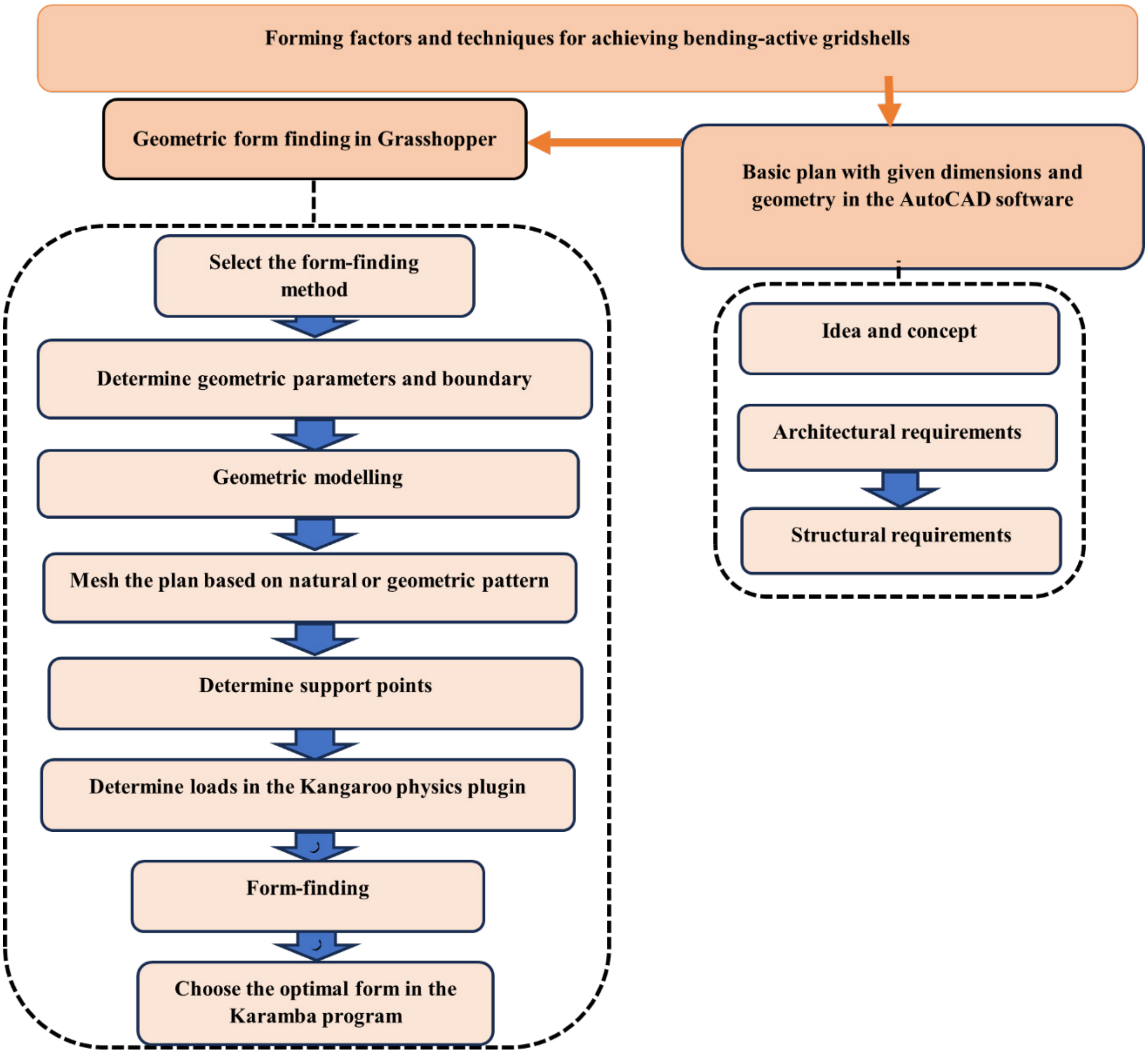
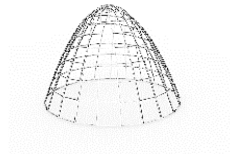
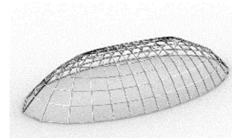
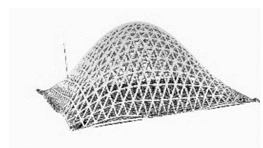
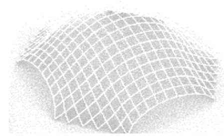
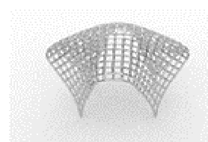
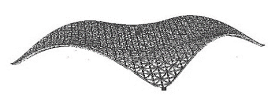


Fig. 8: Bending-active gridshell structure form-finding algorithm (Source: Authors)

Table 3. Geometric classification of gridshells based on the calculated loads and displacement (Source: Authors)

No	Class	Maximum shear load N	Maximum bending force Nm	Materials	Load transfer path	Minimum displacement Cm	Figure
Model 1	Hemisphere (synclastic) A shell with two curvatures in the same direction	0.18	16.47	Wood	ways 2	596.24	
Model 2	Hemisphere ((synclastic Geodesic	0.45	10.22	Wood	ways 3	336.96	
Model 3	Elliptic hemisphere (synclastic)	0.45	13.60	Wood	ways 2	258.85	
Model 4	Elliptic hemisphere (synclastic)	0.44	11.01	Wood	ways 3	220.25	
Model 5	Synclastic shell	8.61	2.85	Wood	ways 3	16.991	
Model 6	Anticlastic shell	1.44	61.04	Wood	ways 2	330.15	
Model 7	Anticlastic shell	0.045	0.035	Wood	2ways	13.99	
Model 8	Anticlastic shell	1.51	0.81	Wood	4ways	14.97	
Model 9	Free-form shell	13.33	2.89	Wood	4ways	9.05	
Model 10	Free-form shell	0.174	0.017	Wood	4ways	11.69	

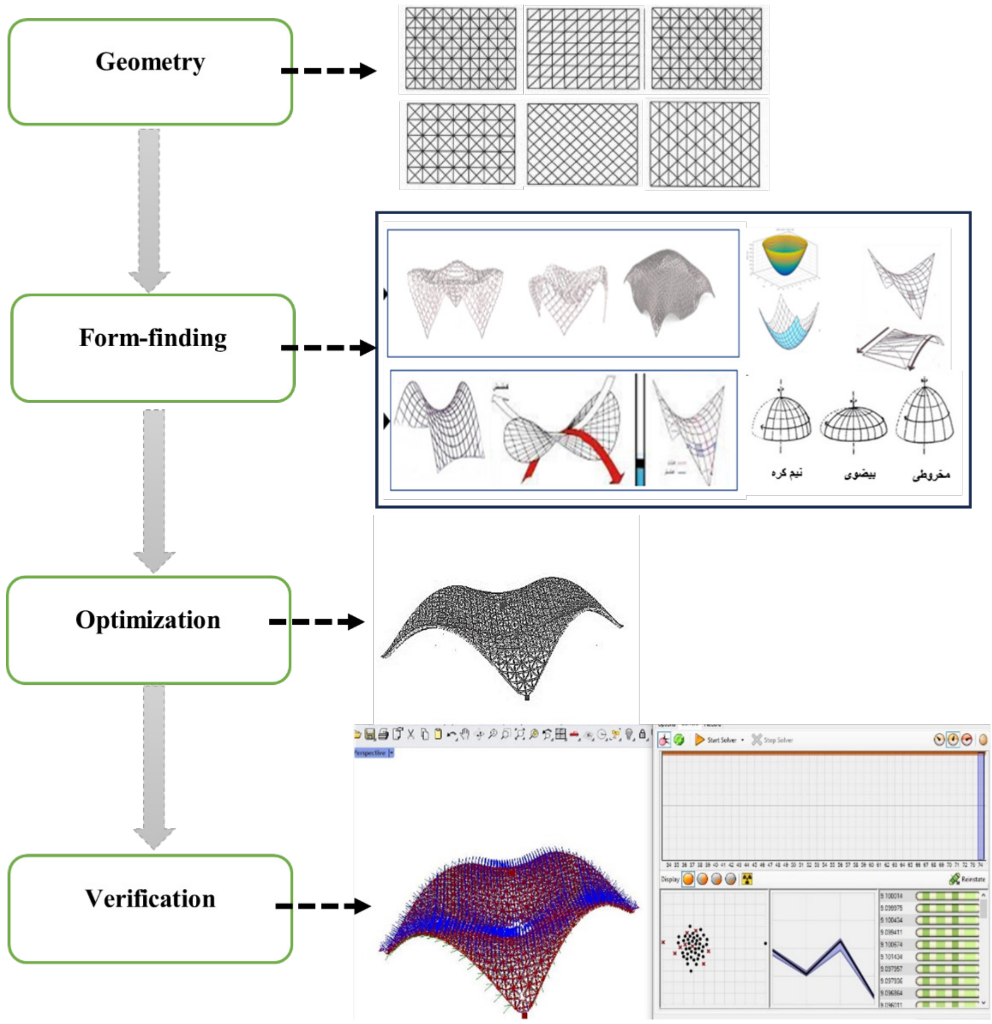


Fig. 9: How to achieve the optimal form (Source: Authors)

RESULTS AND DISCUSSIONS

Table 2 compares and structurally analyzes three synclastic, anticlastic, and free-form geometries using the Karamba plugin. As seen in this table, the free-form geometry is the best form of gridshell structures with the least displacement and the lowest shear load in the Karamba plugin. Also, wood is considered the optimal material for the examined forms. Therefore, wood can be considered the best material in bending-active gridshell structures. Comparing various types of synclastic gridshells indicates that the hemisphere with an elliptic plan has less displacement than the hemisphere with a circular plan. So, it can be said that the plan geometry plays a significant role in structural form optimization. Now, comparing the types of two-dimensional plans makes it possible to create an optimal bending active gridshell of high strength. Therefore, the amount of displacement must be limited within a certain range. The displacement is directly proportional to the applied loads and inversely related to the structure stiffness, indicating that the structure stiffness must be increased to reduce the displacement. As a result, the stiffness of each element of the structure depends on its material, and it is a function of the radius of the cross-section and its length. Also, the stiffness of the whole system depends on the structure geometry. As a result, according to Diagram 7, which compares the number of paths, the gridshell structure with four paths has a better possibility of transferring loads to the members and minimizes the shearing force. Also, in free-form shells, there is a higher degrees of freedom compared to synclastic and anticlastic structures, and the efficiency and strength of the structure increase with the increase in the number of paths.

Fig. 10: Comparison of the ten selected models in terms of the minimum displacement

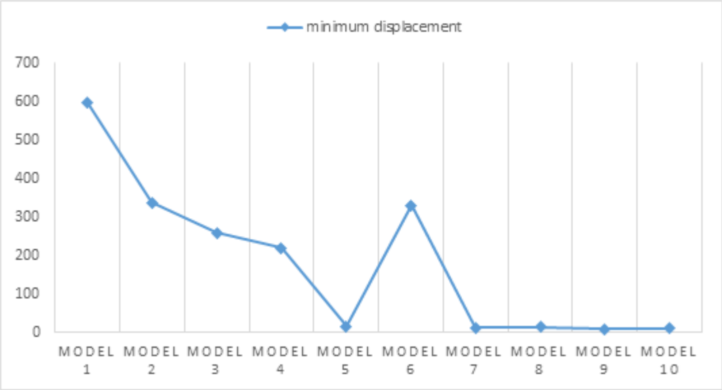


Fig.11: Comparison of the ten selected models in terms of the minimum displacement

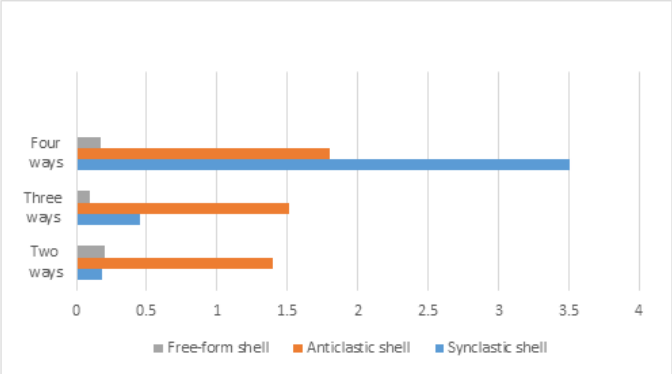


Fig. 12: Comparison of the number of paths in terms of the shell geometry performance improvement

Figure 11 compares the three geometries studied in terms of the number of load transfer paths. In these geometries, the loads are transferred in two or more than 2 directions. In other words, unlike structures transferring loads to supports in only one direction, this system transfers loads through several paths and in several directions. The geometric and structural analysis of the 10 models studied indicates that increasing the number of load transfer paths is a method of optimizing the geometric form of bending-active gridshell structures. Among the models studied, the model with 4 load transfer paths is considered the optimal one. The greater the number of load transfer paths, the better the structural performance of the bending-active gridshell will be to minimize the displacement. Because 4 ways make it possible for the structure to better transfer the loads to the members, and minimize the shear load. Moreover, comparing free-form geometry with synclastic and anticlastic geometries indicates that free-form geometry provides more degrees of freedom to enhance the structural performance and strength of the structure than two other geometries.

Figure 13 shows the ranges of tensile and compressive stresses for Model 9, as the model with the optimal form, in blue and red, respectively, using finite element analysis. The stress analysis indicates that most parts of the structure are under tensile stress. The Karamba plugin delivers compressive stresses with negative values and tensile stresses with positive values to the user. The lower the stress tolerated by a member, whether it is tensile or compressive, the higher its structural performance. Moreover, that member can be optimally designed using less materials. The most optimal form of a shell is achieved when the loads are transferred through axial stresses.

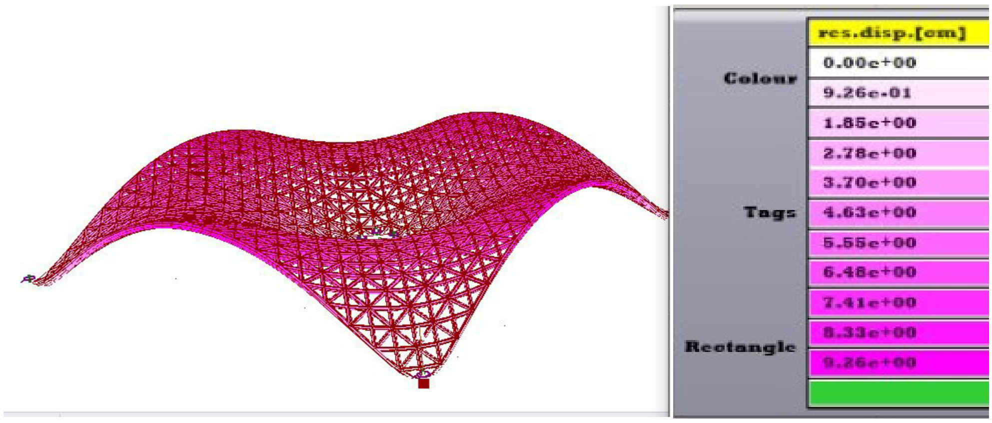


Fig. 13: The ranges of the compressive and tensile stresses of the structure of Model 9, as the model with the optimal form, using the Karamba plugin, (Source: Authors).

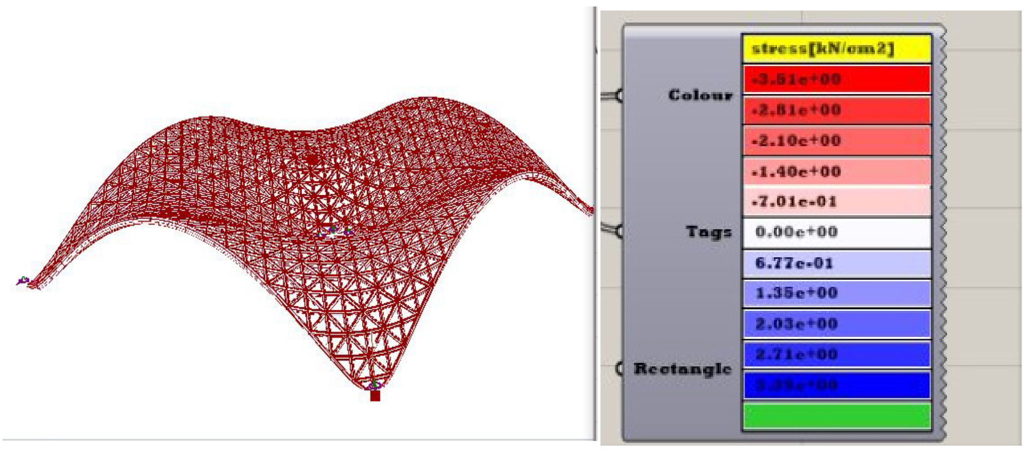


Fig. 14: Analysis of the gridshell structure in the Karamba plugin (bold pink shows the maximum amount of displacement in the selected material (i.e. wood)) (Source: Authors)

Figure 14 shows the structural analysis of Model 9, as the best model for the bending-active gridshell structure. This model has a free-form geometry, the least amount of displacement, and the lowest level of shearing load and stress and transfers the load through four paths. Also, Figure 15 shows the parametric modeling and simulation of Model 9, as the most optimal form with a free-form geometry. In modeling, the designer can create a variety of exciting and efficient geometric forms for gridshell structures by changing materials and structural variables such as geometric dimensions, opening height, cross-section length, the location of supports, geometric stiffness, and connections between members.

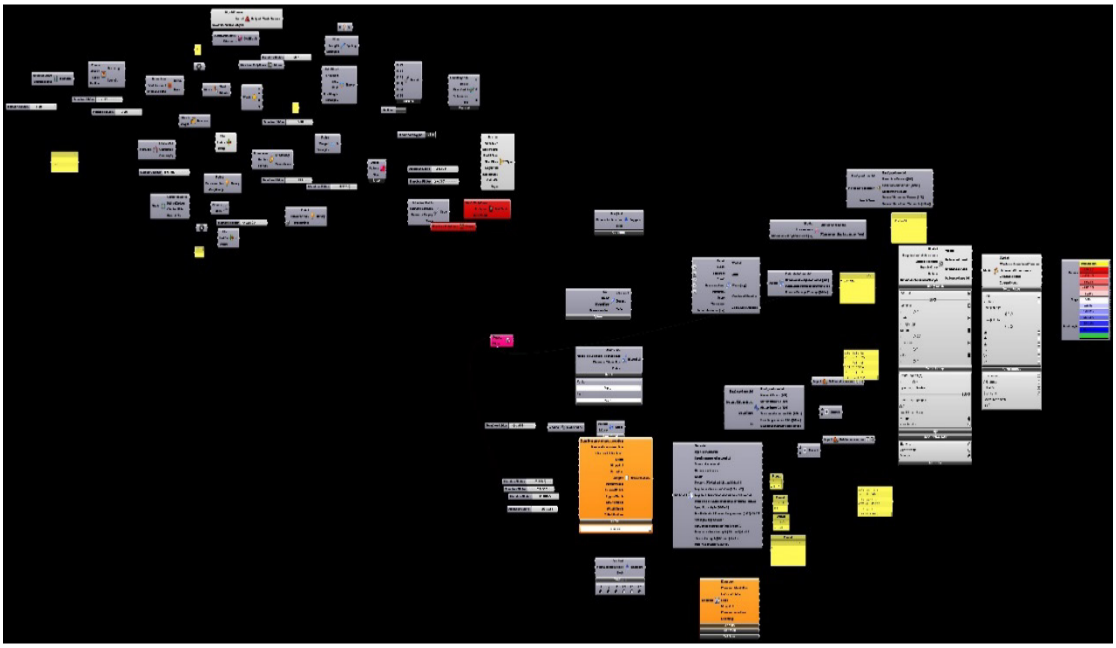


Fig. 15: Parametric modeling analysis of the optimal form of Model 9 in structural analysis in the Karamba plugin (Source: Authors)

CONCLUSION

What makes it necessary to examine flexible structures, such as bending-active gridshell structures is their good performance against lateral forces. Today, in addition to their desirable performance compared to complicated forms made with straight-line members, they have a simpler construction method, and reducing form-finding limitations makes them a suitable option. The steps of the optimal bending-active gridshell structure construction are as follows. First, the structure plan algorithm is designed parametrically in the Grasshopper plugin. Regarding the gridshell geometry, the architect can simulate any model in the Grasshopper plugin. The structure plan plays a significant role in finding the optimal form of the structure. After designing the structure plan, the architect deals with the structure's performance and looks for the optimal geometry to build a strong and efficient structure. The present study compared three synclastic, anticlastic, and free-form geometries using the Karamba and Kangaroo Physics plugins in the Grasshopper software, and indicated that free-form geometry is the best optimal form for the design of bending-active gridshell structures since it minimizes both the shear load and the displacement of the structure. Also, this study compared three different geometries using Galapagos software to help architects to design the gridshell structure form. The rectangular cross-section was considered for the structures in the comparison since it provides more optimal and suitable structural performance. In this study, Model 9 was identified as the best model with the least stress. The Karamba plugin provides the user with numerical and graphical information such as weight, displacement of nodes, stresses, etc. Gridshells are delicate structures, and the prevention of buckling and bending must be considered in their design. For this purpose, the structure should not be exposed to large displacements. On the other hand, more flexible structures such as bending-active gridshell structures show better performance against lateral forces. Therefore, the amount of displacement must be limited to a certain range. The Karamba plugin shows that the structure displacement is directly and inversely related to the loads and the structure stiffness, respectively. So, if the goal is to reduce the amount of displacement, the structure stiffness should be increased. The stiffness of each element of the structure depends on its material, and it is a function of its length and the radius of its cross-section. The stiffness of the entire system and thereby, the displacement of the whole structure depends on the stiffness of each element and the topology and geometry of the structure, i.e. the cross-section and the moment of inertia. In the present study, the Galapagos software was used to select the proper cross-section with the least displacement and deformation. Comparing the 10 selected models indicated that Model 9 is the most optimal model with a free-form geometry since it has the most optimal structural performance, the lowest axial stress, and the least displacement.

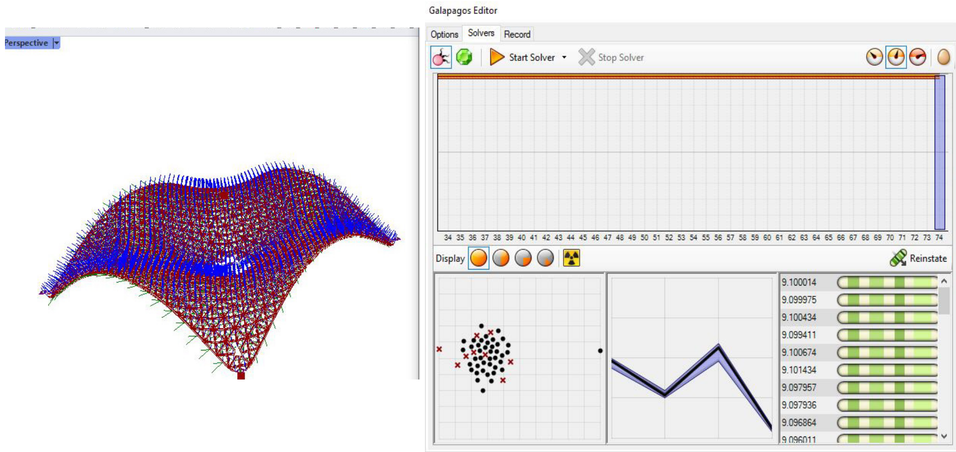


Fig. 16: Optimal form analysis of Model 9 in the Galapagos software (Source: Authors).

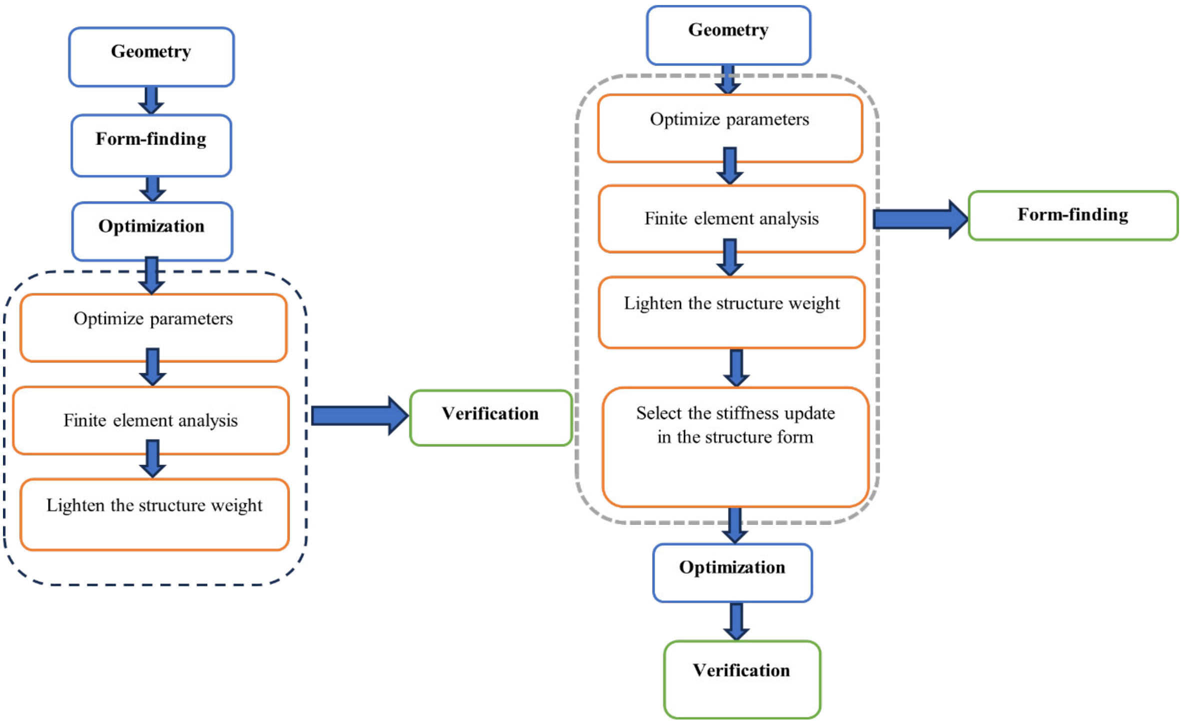


Fig. 17: How to reach the verification step for selecting the optimal bending-active gridshell form (Source: Authors)

AUTHOR CONTRIBUTIONS

Overall, the authors contributed to all aspects of the research. S. Sadeghi performed the literature review, and experimental Modeling, analyzed and interpreted the data by modeling software and the conclusions, and prepared the manuscript text.M. Rahbar helped in the literature review and manuscript preparation and Data analysis and modeling and physical models, identified the right strategy to achieve results. k. taghizadeh azari performed Making replicas and Introduction of foreign articles and case examples and helped in edition this paper and H. zabihi research method and revised the literature of the text.

ACKNOWLEDGEMENT

This article is taken from Sahar Sadeghi's doctoral thesis titled "Explanation of the form-finding components of active bending grid shells in temporary architectural structures" under the guidance of Dr. Morteza Rahbar and the advice of Dr. Katayoun Taghizadeh Azari and Dr. Hossein Zabihi at the Islamic Azad University of Tafarsh Branch.

In addition, I would like to thank my supervisors and advisors, Mr. Dr. Morteza Rahbar, the supervisor, and Ms. Dr. Katayoun Taghizadeh Azari and Dr. Hossein Zabihi, the advisors, who gave me great help and guidance in the process of my thesis research, and in line with these consultations and guidance over several years. Research, effort and hard work reached new and practical results in the field of designing and formulating active bending mesh shell structures, which are less common in the field of architecture. It has been discussed and these results have been summarized and compressed in the form of an article.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work . In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication or falsification, double publication and, or submission, and redundancy, have been completely witnessed by the authors.

REFERENCES

Adriaenssens, S., Block., Ph., Veenendaa. D., Williams. Ch. (2014). “Shell Structures for Architecture”, London.

Aftokharzadeh, S. (2006) “Nature's geometry against Euclidean geometry”, *Architecture and Construction Magazine*, 8 .

Bulenda, T. and J. Knippers. (2001). “Stability of grid shells.” *Computers & Structures*. 79(12): p. 1161-1174.

Bendsøe, M.P., A. Ben-Tal, and J. Zowe. (1994). “Optimization methods for truss geometry and topology design”. *Structural optimization*,7(3): p. 141-159.

Celina, P. (2007) “Past and Future of Grid Shel Structures”. Massachusetts: Massachusetts institute of technology.

Collins M , Cosgrove T. (2016). “A Review of the State of the Art of Timber Gridshell Design and Construction”, Department of Civil Engineering and Materials Science, University of Limerick, 261.

Du Peloux, L., Baverel, O., Caron, J.-F., & Tayeb, F. (2013). “From shape to shell: a design tool to materialize freeform shapes using gridshell structures.“

Fazel, A. (2012) “Form finding and structural optimization of grid shell structures based on evolutionary genetic algorithm”, Tehran: University of Tehran.

Fritzsche, J.C.(2013). “Gridshell efficiency optimization”. Graduation Thesis, Eindhoven: Technical University Eindhoven.

Gengnagel C, Lafuente E. (2011). “Structural Application of Bio composites in highly elastic Structures”**.** *Conference Proceedings IABSE - IASS Symposium 2011*, Taller Longer, Lighter, London ..

Gengnagel C, Lafuente E. (2014) “Active Bending in Hybrid Structures Conference Paper”. *Conference Proceedings IABSE - IASS Symposium Departement of Structural Design and Technology* [KET] Faculty of Architecture, University of the Arts Berlin, Taller Longer, Lighter, London.

Gengnagel, Ch., Alpermann, H., Lafuente Hernández. (2014). “Active Bending in Hybrid Structures”, Departement of Structural Design and Technology [KET], Faculty of Architecture, University of the Arts Berlin, Conference Paper

Gholamzadeh, E., Metini, M., Eslami, Y., Talischi, Gh. (2022) “Formal interpretation of synclastic shells in nature and architecture”, *Journal of Fine Arts-Architecture and Urbanism*, 26(2) pp. 51-64

Golabchi M & Taghizadeh K. (2011) "Skins and folded sheet structures". Tehran: First edition, Tehran University Press, 78-80.(in Persian)

Gulabchi, M., Amiri, M. (2016) “Elements of Instruments for Architects” Tehran: Tehran University Publications Institute.

Hoshiar, N. (2009) “A collection of preliminary and advanced design tips for astronaut structures”, Shahid Bahonar University, Kerman .

Kilian A , Ochsendorf J. (2005) “Particle -spring systems for structural form finding”. *Journal of the International Association for Shell and Spatial Structures*, VOL. 46 .n. 147.

Kim, J. & Park, K. (2018). “The Design Characteristics of Nature-inspired Buildings” *Civil Engineering and Architecture*, 6(2): 88-107.

Liddell I. (2015). “Frei Otto and the development of gridshells”. *Case Studies in Structural Engineering*, 4, 39-4

Lienhard J, Alpermann H, Gengnagel C and Knippers J. (2012) “Active Bending, a Review on structures where bending is used as a self-formation process” *IASS-APCS Symposium 2012, From Spatial Structures to Space Structures*, Seoul 2012 .

Lionhard J, Alpermann H, Gengnagel C, Knippers J. (2013) “Active bending, a review on structures where bending is used as a self-formation process”. *International Journal of Space Structures*, 28(3-4):187-96.

Mansoori M., Kalantar N., Creasy T., Rybkowski Z. (2019). “Adaptive Wooden Architecture, Designing a Wood Composite with Shape-Memory Behavior," In: *Bianconi F., Filippucci M. (eds) Digital Wood Design, Lecture Notes in Civil Engineering*, vol 24, Springer, Cham. https://doi.org/10.1007/978-3-030-03676-8_27.

Margulios, I. (2013) “Architect, engineer, structure”, Mahmoud Gulabchi, first edition, Tehran, Tehran University Press.

Matini, M. (2013). “Using nature patterns to design flexible structures in architecture”, *Journal of Fine Arts - Architecture and Urban Planning*, Volume 20, Number 1, University of Tehran, Tehran.

Moore F. (2007) "Understanding the behavior of structures", (M. Golabchi, translator) Tehran: Tehran University Press, 213

Moore F., (2009) “Understanding the Behavior of Structures”, translated by Golabchi Mahmoud, Tehran University Press, third edition, Tehran .

Moore, F. (2007) “Understanding the behavior of structures” (M. Gulabchi, translator) Tehran: Tehran University Press

Pillwein S, Leimer K, Birsak M & Musialski P. (2020) "On elastic geodesic grids and their planar to spatial deployment". preprint arXiv:2007.00201

Salvador, M. (2002). “Structure in architecture”, translated by Mahmoud Gulabchi, Tehran: Tehran University Press.

Taghizadeh, K. (2015). “Teachings of natural structures, questions for architects”, *Fine Arts Journal*, 28 (11), pp. 75-84.

Taghizadeh, K., Matini, M., and Kakui, E. (2018) “Flexible structures; A solution to reduce the functional problems of moving shells” *Journal of Fine Arts-Architecture and Urbanization*. 24 (2), pp. 39-48.

Tang, G. (2013) “Timber gridshells: beyond the drawing board”. *Proceedings of the Institution of Civil Engineers-Construction Materials*, 166(6), 390-402.

Tang, G. (2013). “Timber gridshells: beyond the drawing board”. *Proceedings of the Institution of Civil Engineers-Construction Materials*, 166(6), 390-402.

Tibert, A. and S. Pellegrino. (2011). “Review of form-finding methods for tensegrity structures”. *International Journal of Space Structures*, 26(3): p. 241-256.

Winslow, P., Pellegrino, S., & Sharma, S. (2010). “Multi-objective optimization of free-form grid structures”. *Structural and Multidisciplinary Optimization*, 40(1-6), 257.

Yang, X.-S. (1970), “Optimization Algorithms”. Vol. 356, pp. 13-31).