Introducing a Lightweight Structural Model via Simulation of Vernacular “Pa Tu Pa” Arch

Esmail Zarghami [a], Hossein Bagheri [a,*], Mohsen Vafamehr [b], Bagher Hosseini [b]

[a] *School of Architecture and Urban Design Engineering, Shahid Rajaee University, Qazvin, Iran.*

[b] *Department of Architecture, University of Science and Technology. Tehran, Iran.*

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Abstract

The knowledge of Iranian vernacular structures is based on geometry, and there is a possibility of recreating such structural patterns aimed at producing movable structures. The purpose of this research was to utilize the patterns of vernacular structures to provide a lightweight structural model. The questions raised included how to create various forms based on the structural history of any regions, test their performance degrees, and propose a lightweight structure for them. To this aim, a simulation method was used to simulate "pa tu pa" arch structure via visual programming tools and "Grasshopper" plug-in in "Rhino Ceros" software. Then, to examine the suggested forms generated from the first phase, the structural analysis tools in "SAP2000" software were employed. Assuming various structural connections and examining four types of connections at the structural bases and members, the results indicated that a lightweight structure was feasible with rigid connections. Taking advantage of the mathematical-geometric logic of Iranian traditional structures can lead to production of forms that mark the history of traditional structures. In the current study, connection types were only investigated and parameters such as material types and construction methods can be studied in future research.

Keyword: Vernacular structure, Iranian pattern, "Pa Tu Pa" arch, Lightweight structure, Structural connection

1. Introduction

Lightweight and deployable structures have always appeared as critical tools in designing emergency shelters after accidents. These structural modules can be used as a tool for training, short-term accommodations, temporary housing for low-income people, setting up temporary movable stalls, urban transit applications, and providing shelters in nature. Meanwhile, structures with deployable and vernacular capabilities to be established without expertise have been highly suitable. With the advent of moveable exhibitions, municipal pavilions, and temporary shelters, the architecture of such constructions has become extremely important. By developing such a structural architecture, the background role of each region architecture has emerged to be more challenging. Adoption of an approach that can improve the social and cultural aspects of this type of architecture in addition to utilization of the technical power of international structures capable of leading to ecology-oriented structures with a view on the international arena seems to be essential.

The purpose of the present research was to take benefits of vernacular structural patterns to provide a lightweight structural model while maintaining various forms. The method of creating a form diversity based on the structural history of each region, testing structural performance, and providing a proposed lightweight structure were among the frequent questions raised. This article seeks to answer two scientific questions. 1) How to reproduce structural forms using geometric patterns of vernacular structures? 2) What is the proposed structural form through which type of fitting, thickness and weight are optimal? The first question was answered through simulating the geometric logic of the "pa tu pa" arch using "Rhino ceros" software. The second question was also answered by simulation in the "SAP 2000" software.

* Corresponding Author Email address: hobokaa@gmail.com

2. Review of Literature

2.1 Vernacular structures

The study of vernacular structures associated with vernacular materials and assessment of their capabilities in the contemporary architecture has been among the areas of interest to researchers in this field (Vural et al, 2007). Through examining vernacular and traditional wooden walls, "Vasconcelos" attempted to analyze the shear behavior of timber. He and his colleagues investigated the seismic behavior of traditional unarmed wooden walls. Workshop tests demonstrated wood high plasticity as the main source of resistance to the force of an earthquake Vasconcelos et al. (2013). "Lourenco" was a scholar following his research in the field of analyzing masonry materials used in vernacular structures. He contributed to assessment of force transmission methods in masonry multi-layered walls, masonry arched bridges, and structural behaviors of masonry old tall towers and study of masonry structural connections Lourenco et al. (2009). Investigation of three types of vernacular stone walls by using the workshop and computer analysis methods and finite elements method, as well as comparing the results of the two types of experiments represented good construction practices with aggregates, while the shear strength was found to be within acceptable limits Lourenco et al. (2006).

In another way of dealing with vernacular structures, "Cardinale" provided a renovation method based on vernacular practices with the capacity of being employed in the same projects after studying the methods of vernacular structures of the two Basilica and Puglia regions Cardinale et al. (2013)."Origami" is known as one of Japan's handicrafts, many patterns of which were developed by Doctor "Takshomi" Gilewski et al. (2016). This model is utilized in various fields such as sculpture, manufacturing toys, robotics, and medical and architectural applications Sorguc et al. (2009). In addition, Origami, currently known as a folded structural type, has been adopted from the traditional art accounting for a model of deployable and moveable identity-based structures Quagila et al. (2014). All these functions have been called as origami forms by "Stewart", representing the interdisciplinary natures of mathematics, engineering, biology, and many other fields using origami forms sorguc et al. (2009). Similarly, adoption of such limited forms of arched structures can be expounded in the field of architectural form finding by using computer software and plug-in Block et al. (2006). The use of vernacular materials and focus on form finding is a dominant approach adopted by a similar research study Davis et al. (2012) and Xiaoxin and Kelly (2019) in rural Chinese village revitalization. However, the structural strength of traditional buildings has not always been proven (Cromley, 2008).

2.2 Iranian vernacular structures

"Beruk" in his study focused on form finding through decorative structures. With the structural model of mosque porches in Muslim countries, he attempted to differentiate the models used in each context of architecture. He introduced "Muqarnas" patterns as capital of Islamic architectural designs (Beruk, 2011). On a similar study, "Dabbour" focused on netted patterns (Dabbour, 2012). In a newer approach, researchers have highly regarded the form-based use of Islamic-Iranian motifs and nodes. By modeling and computer programming Islamic units of motifs, "El-Said" could generate miscellaneous motifs based on Islamic-Iranian motifs (El-Said, 2001). In addition, several other investigations have followed the same approach without the aid of computers (Critchlow, 1976). In fact, in such applications, the method of producing forms has been well received by architects.

Generally, the above-mentioned researches have pursued an approach based on formal and structural patterns in the traditional architecture. Based on the contents of any forms of traditional architecture Khorsandi et al. (2019), "Tehrani" provided a kind of strategic advantage of traditional architecture. Through studying Iranian arches and domes, he contributed to understanding of the behaviors of traditional structures Tehrani et al. (2012). Additionally, "Abbolghasemi" emphasized understanding of patterns instead of form applications (Abolghasemi, 2006). Focusing on structure is the result of developing a content approach to Iranian structures collected by Me’marian in his book entitled "The Qualitative and Quantitative Understanding of Material Strengths of Vaulted Structures" (Memarian, 2012). Through computer-drawing techniques, he provided further understanding of structural functions and structures of traditional forms. With the help of a three-member family, "Khazali" designed a shelter with minimum cost. Using his desired computer-designed structure, he established a shelter in a village of "Tonekabon" City in "Mazandaran" Province, Iran, within two days. The form resulted from his structural members led to formation of a bamboo dome with very simple endemic details that has not been proven in this research. However, research Biswajit et al. (2019) showed excellent behavior in terms of lateral drift and ductility capacity without any significant drop in lateral load capacity even under large lateral drift for vernacular structure Assam- type house.

In whole, study of traditional Iranian structures has more in formal aspect and less attention has been paid to measuring structural factors Toghyani et al. (2020). The main contribution of this study is the attention to identity in the structure, which has been tested by redesigning the geometry of the Iranian arch. According to the studies conducted and the aim of this research, which was to produce lightweight structures with various forms from traditional structures, a completely content-based approach based on geometric and mathematical logic of vernacular structures was considered. Relevantly, an Iranian type of structure was selected and investigated. The following table presents the existing approaches to dealing with the recognition and application of Iranian traditional structures.

Table 1
A summary of approaches to dealing with the recognition of traditional structure

Approach	Elements		Researcher
Form-based	Decorative patterns	Netted, Muqarnas, Yazdi Category	Broug, 2008 Dabbour, 2012,Embi and abdullahi, 2013
	Sacred patterns	Mandala, light, silence	Ardalan and Bakhtiar, 2000 Pennick , 1994
	Motifs & nodes	6 and 8-angled star, octagon,	Ogluo, 2010,Shefaee, 2002,soori, 1988
Content-based	Domes and vaults		Tehrani, 1994 & Abolghasemi, 2006
	Framing		Memarian,2012,Bozorgmehri,2006,Sherbaf, 2006,Lorzade, 2005
	Load patterns		Critchlo,1976,Memarian, 2012
	Geometry of patterns		Tehrani, 2012 Pirnia, 1990 Sherbaf, 2006

3. Research Methodology

The research method was based on simulation. First, to reproduce a form of traditional structures, computer simulations were utilized by using visual programming tools and Grasshopper Plug-in in Rhino Ceros software. Then, to examine the forms produced from the first stage, computer simulation with structural analysis tools was employed in "SAP 2000" software.

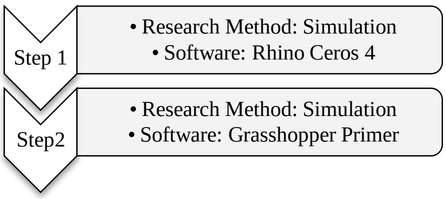

Fig. 1. Procedure of the Research Method

3.1 Work procedure

By defining "pa tu pa" arch parameters in "Rhino" software, the structure plan was created. Then, to define the arch variables, and change the form content, Grass Hopper plug-in capable of being installed on Rhino Software was utilized. All the main parameters of the arch design were defined within the software setting under the name of "Slider". By changing each parameter, the arch underwent a change of shape.

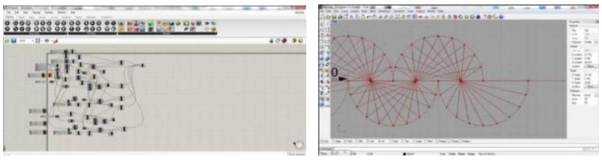

Fig. 2. Taking advantage of "pa tu pa" arch in designing structural forms by using form programming within "Grass Hopper" plug-in

3.2 Form reproduction via visual programming

The studies of Iranian traditional structures reflect application of a geometric-mathematical system. Marquee cover was intended in the current study. Accordingly, the geometric structure of "Pa tu pa" arch was examined through a random sampling method. The characteristics of conformity bearing forces at the center of load endurance and force divided by the structural set were among the factors to choose this arch.

3.3 "Pa Tu Pa" arch

This arch is as one of the widely used sorts of Iranian "Chafds" (Golabchi and Dizaji, 2014). An arc in the ancient Persian language is architecturally called a narrow archway placed on the head of a doorway. The method for calculation and geometric drawing of them has been presented in various references. Due to its high rise, this kind of "Chafd" is one of the most stable "Chafds". An example of this "Chafd" can be observed in "Allah Allah" dome of "Sheikh Safi al-Din Ardabili" Mosque.

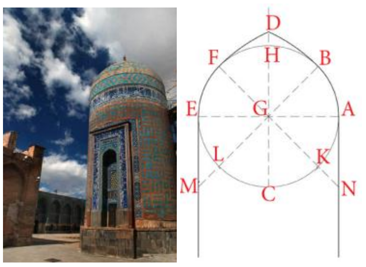

Fig. 3. "pa tu pa" arch application method: Allah Allah dome of Sheikh Safi al-Din Ardabili Mosque

3.4 Hypothesis test and structural analysis

Table 2
Introducing loading of structure

load	amount	reference
Gravity	25 k/m2	6th chapter of National Building Regulations
snow	150 k/m2	Region 4 of Tehran City
Earthquake	______*	2800 Iran Standard Regulations
wind	61.3 k/m2	6th chapter of National Building Regulations

*Due to lightness of the structure and thus less force of earthquake than that of the wind, it can be concluded that the structure should be designed to bear the wind load. After allocation of the parameters affecting the structural analysis, computer analysis was conducted. The existing structure was analyzed by using program "SAP2000" V14. Following this, the static and dynamic loads of the structure were defined but not presented due to the large number of calculations; its documentations are still available.

3.5 Requirements and restrictions

Before allocating sections to the members, all lateral, wind, earthquake, snow, and living and dead loads were calculated. Analysis of the structure behavior against the lateral wind is presented as an example. Violet represents tension and blue displays suction in a structure. All the color spectra in between are allocated to the relative amounts of tension and suction against wind. After assigning loads, the initial requirements were defined for modeling in the software setting as follows:

1) All sections were shaped as hollow circles.
2) All sections were of steel material of ST37 type.
3) All members had a 200-mm diameter.
4) The criteria for election of diameter and section shape included calculation of basic loads
5) and user’s experience.
6) Selection of a circle shape for the sections was for reasons such as convenience of working with round
7) steel sections, modulation of torsion torque effect, reduction of effective snow load, and requirements
8) for architectural designs.
9) Selection of identical diameters was for the two reasons of operational and manufacturing requirements as well as architectural standards.
10) Two groups of members were conjoined to build a module and to perform the executive calculations, one group was assumed with full members without interruptions, while the other members were disrupted
11) at joints.
12) All the thicknesses presented by the software analysis were based on the sections present in the Iranian market.
13) The resulting proposed structure consisted of circles with a radius of 5 m after calculating their overlapping with a height of 9 m.
14) The area of the structure was 200 m2.
15) The structure volume of coverage was 1,800 m3.

By allocating sections, sizes, shapes, and thicknesses of the members, as well as defining the loads on the structure, analyses of 4 different types of the proposed structure were conducted. Finally, the analyses led to thicknesses and numbers of members and the total weight of each type of joints in the proposed structure. The stress ratios are presented as a graphic picture.

3.6 The application process in "SAP 2000"

The task was performed in the software setting in 6 steps:1) Modeling; 2) Measuring with a hypothetical section; 3) Applying the tent cover load by using fibers of lightweight and light-passing polymer composites; 4) Controlling the results of stress ratios (definitions of type, material, coverage load, and the software output resulted from loading); 5) Obtaining member sizes, and; 6) Obtaining the results of each size specifications (weight, unit length, Poisson's ratio etc)

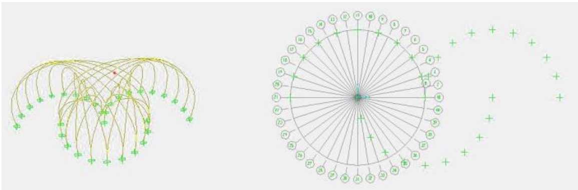

Fig. 4. Structural modeling in the software setting and initial testing of the sections of the proposed structure

Ultimately, the outputs of the structural characteristics were provided for all 750 members; however, to summarize the outlines of this part of the study, the weight per unit length and characteristics of one of the structural members were provided as an example.

4. Results

At the first stage, through mathematical logic simulation of "pa tu pa" arch, the results of form diversity were collected by changing parameters such as arc height, rising, and span. All the similar form-main arch ratios created a reference to vernacular structures. The result was generation of over 200 different types of forms, from which a 2- module sample is presented in this section. However, the forms resulted from combination of two modules and developments of the proposed structural modules were disregarded in this scope.

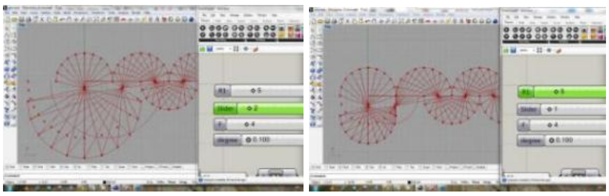

Fig. 5. The form diversity of the visual programming of the geometric pattern of "pa tu pa" arch

In the second phase, it was attempted to test the stress ratio by allocating fixed steel sections. Through studying the software output, it was found that all the structure members had a stress ratio below 1 (stress ratio $\leq$ 1). This means that the ratio of the load applied to a member bearing capacity has never been greater than allowed, and the structure will thus be stable. This stability is also based on the loading conditions defined. By determining the bearing capacity of the proposed structure, the analyses could explore the diversity of connections to test the amount of weight loss. The results obtained for four types of connections are as follows:

5.1 Type 1 (fixed base connections and fixed members)

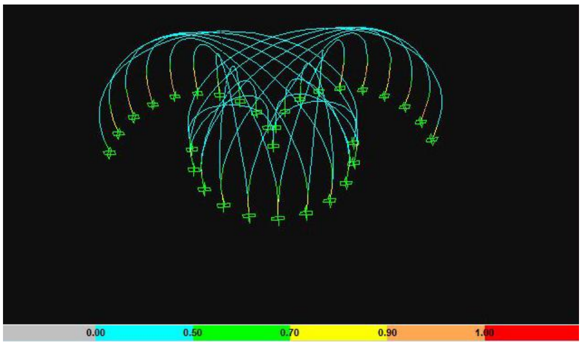

Fig. 6. The software output for stress ratio amount in type 1

The results of the analysis of the structure of type 1 indicated that no member was in critical condition. All members were obtained with a diameter of 200 mm accompanied with two types of thicknesses, since members of the same diameter made it easy to build the structure and integrate the architectural design. After analyzing the stress ratio, the structure type and weight were evaluated.

Table 3
Specifications of type 1connections

Type	Base connection	Member connection	Member thickness(mm)	Number of members	Total weight (ton)
1	Fixed	Fixed	5 & 8	690	9.862

With fixed base connections, the structure had 690 members and a weight of 9.862 tons. According to the span covering the structure and the height provided, the structure was shown to be very light compared to similar covering structures.

5.2 Type 1 (fixed base connections and joint members)

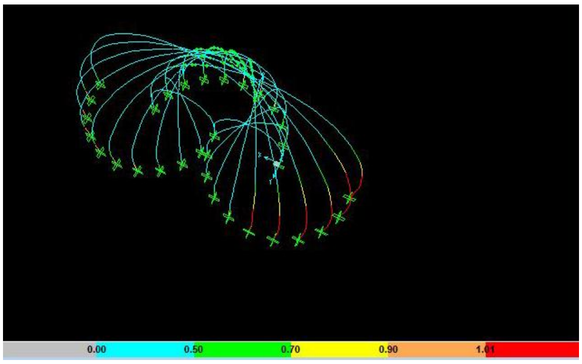

Fig. 7. The software output for stress ratio amount in type 2

By changing the fixed into joint members, a slight critical condition (1.003) in the stress ratio occurred to the ends of the original arcs. With regard to light weight of the structure, this situation was the result of side stress and wind load. This stress occurred in members that were almost vertical. Table 4 presents the data of Type 2.

Table 4
Specifications of type 2 connections

Type	Base connection	Member connection	Member thickness(mm)	Number of members	Total weight (ton)
2	Fixed	Joint	7.1	750	13.406

The number of members in the second type of joint connections has become greater than that of the first type. By increasing the number of members and connections, weight gain was to be expected in the structure. The structure weight rose from 9 tons in type 1 to 13 tons in type 2. In fact, the 4 tons of the structural weight gain was the result of the utilization of joint connections. It seems that at fixed bases, providing member connections with joints would increase stress amount in the structure. On the other hand, the weight enhanced.

5.3 Type 3 (joint base connections and joint members)

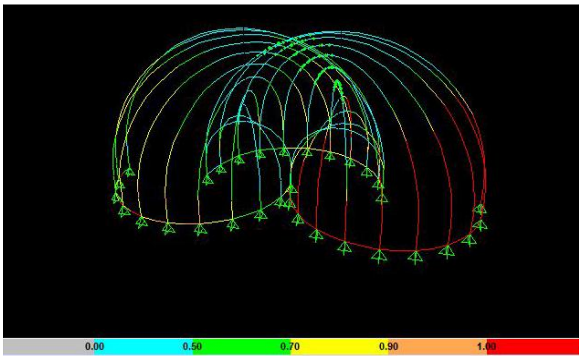

Fig. 8. The software output for stress ratio amount in type 3.

With the weight gain of type 2 caused by the increased number of members and their joint connections, this assumption arises that the incremented stress in members is caused by the fixed connections at the bases. Therefore, the third hypothesis was based on connections and joint members. The results were indicative of an increase in stress in the main base members. In fact, this increase in stress was associated with a greater amount than the structure capacity, and thus the amount of the stress ratio slightly augmented (1.01) compared to that of type 2. Indeed, the amount of the stress enhancement in the critical members was only 0.09% in comparison to that of type 2; however, it had taken additional number of members. Type 3 has three different thicknesses for its members.

Table 5
Specifications of type 3 connections

Type	Base connection	Member connection	Member thickness(mm)	Number of members	Total weight (ton)
3	Joint	Joint	7.1&4.5 & 6.3	750	10.478

In this case, the number of members was 750, i.e. it was not different from type 2. The only different parameter between types 2 and 3 was the base connections. By changing the connections from fixed to joint connections, the structural weight reduced from 13 to 10 tons. Thus, a structure with joint connections at its base and members leads to a weight loss. Three tons of weight reduction due to a change in the base connections was significant. It seems that a lighter structure can be achieved with joint connections at the base and fixed connections for the members.

5.4 Type 4 (joint base connections and fixed members)

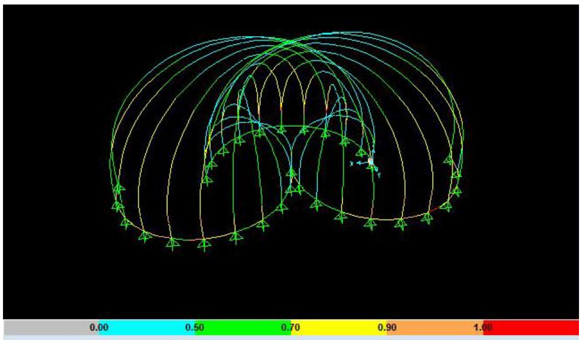

Fig. 9. The software output for stress ratio amount in type 4

With the fixed connections of members, the number of members declined and a subsequent weight loss occurred to the structure. Concerning the critical stress, no member was entangled in the critical condition owing to the joint position of the members. In addition, the stress distribution was more desirable. Table 6 presents specifications of type 4.

Table 6
Specifications of type 4 connections

Type	Base connection	Member connection	Member thickness(mm)	Number of members	Total weight (ton)
4	Joint	Fixed	7.1&4.5 & 6.3	690	10.285

The weight in type 4 has dropped approximately 200 k compared to that of type 3. Moreover, the number of members has decreased to 690 members. Hence, this weight loss of the structure can be significantly related to the reduction in the number of members. However, when the connections were fixed, the critical stress was highly reduced, and the structure laid in a more favorable condition based on loading performance.

5.5 Comparison of the structural behavior

With regard to determination of different thicknesses for each type of structure, as well as structural weight optimization, optimal sizes and thicknesses of members were presented for each type based on the structural analyses, which can be observed in Table 6 according to lightness priorities.

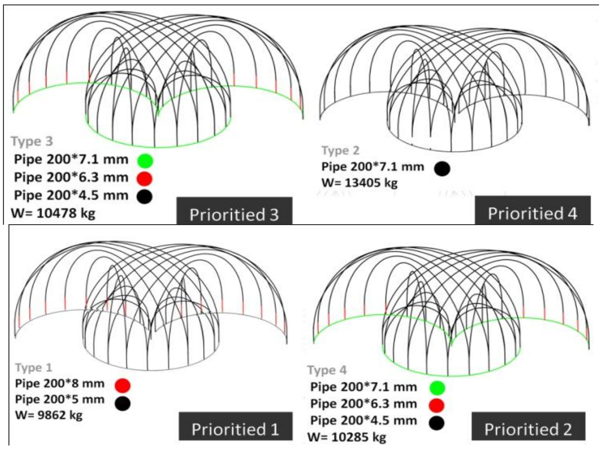

Fig. 10. Prioritization of four structural types based on less weight.

5. Conclusion

The results show that Iranian arches can be reproduced. This is possible by studying the mathematics and geometry of the arch, and the modeling method can be used. Analyzing the loading of "Pa tu pa" arch shows that if the geometries of traditional structures are designed with today's materials, despite lightening the structure, aspects of the identity of the structure have also been considered.

Structural analysis expresses that the most effective method of reducing the weight of the proposed structure is to decrease the number of members with respect to a fixed shape, size, and section material. This strategy is feasible in fixed connections. This is while joint connections are highly efficient in the coordinated behaviors of structures. However, this behavior was not considered in the present study, and only the structural lightness was targeted. Utilization of the mathematical logic of Iranian traditional structures can lead to production of forms bearing a historic sign of traditional structures. One of the easiest and best ways to achieve this is using computer simulations that do not incur high costs compared to the laboratorial method.

Due to the geometry-based aspect of these structures, a very simple and clear structural logic will be required to analyze the generated forms as in the present study, the geometric logic of "Pa tu pa" arch structures was studied, and the arc was found to be useful in the structural analyses. Taking advantage of the existing technical possibilities such as type of material, construction method, and plenty of connections will contribute to enhancement of structural efficiency. In the current investigation, connection methods were examined, resulting in lightness of the proposed structure with the aid of rigid connections.

limitations of research are that the nonlinear analysis must conduct to observe the goodness of the system subjected to extreme events such as earthquakes (Ghasemi and Nowak, 2017). Also one of the most acceptable probability-based approaches is Load Resistance Factor Design (LRFD), which measures the safety level of the structures in terms of the reliability index (Ghasemi and Nowak, 2018) which has not been considered in this research. So in future research, studying the effects of material types and another geometry of Iranian patterns on the proposed structural lightness can be addressed. This field of study can be developed via analysis of variables such as natural ventilation, light, and radiation.

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