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Typology and Seismic Stability Analysis of the Vaults of the Historical City of Masouleh*

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ABSTRACT

Vaults are among the most effective architectural innovations for covering ceilings and wide spans, which also serve as decorative elements in various buildings. The aim of the present study was to investigate different types of vaults in the historical city of Masouleh and their performance when an earthquake unfolds. For this, the study raised some questions, as follows: "How many types of vaults have been used in the historical city of Masouleh?" and "Which vaults of Masouleh City demonstrate better structural performance when an earthquake occurs?" Methodologically, the study fell under field surveys. Abaqus finite element software (2022 version) was used to analyze the seismic resistance of Masouleh's vaults; also, data from Bam (2003), Roudbar Manjil (1989) and Tabas (1978) earthquakes were used. Findings indicated that the historical city of Masouleh has 19 vaults, with the so-called steep and gentle Panj-o-Haft vaults being the most common types. Roman vault-construction methods are the most common techniques employed in Masouleh architecture. Findings also suggested that 78% of the city's vaults are structurally strong to withstand earthquakes. The Keshah-Sar and Khaneh-Bar Neighborhoods, meantime, hold the highest number of vaults at 37 and 21%, respectively, and the Reihaneh-Bar Neighborhood holds the lowest number of vaults at 10%. Also, the seismic analysis results of the 19 vaults of the city of Masouleh indicated that the gentle Haft-o-Panj vaults, seen in Roman brick-laying forms in the Asad Mahalleh Neighborhood, had the worst structural performance against earthquakes. Meanwhile, the 45° vault, constructed in Roman styles in the Masjed-Bar Neighborhood, featured the best structural performance against earthquakes.

Keywords: Historical City of Msuleh, Vault, Earthquakes, Traditional Architecture.

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1. INTRODUCTION

A vault[1] has always been one of the most valuable works of art by Iranian artists. Vaults have also been used to cover spans and create mystical concepts in building construction (Rasuli 2014, 160; Bozorgmehr 2006, 17; Pirniya 1990, 202; Pirniya 1973, 146). The historical city of Masouleh is in the province of Guilan, Iran, and has a history of over 10 centuries, which was listed in the National Works of Iran in 1975, and is now being recorded by the UNESCO (Hasanpour Loumer et al. 2023, 59). Because local materials have been used in constructing the historical city of Masouleh and the buildings in the city enjoy good performance status, it is feared that this valuable legacy could sustain serious natural and unnatural hazards. Research in this regard can provide insight into the functioning of architectural elements, such as vaults, when earthquakes occur. Thus, research can help protect and preserve these buildings in the historical city of Masouleh.

For this, the study raised some questions, as follows: “How many types of vaults have been used in the historical city of Masouleh?” and “Which vaults of Masouleh City demonstrate better structural performance against an earthquake?”

2. RESEARCH LITERATURE

Much research has been conducted on Iranian vaults. The following discusses some of them. In an article “Curves and Vault-Curves”, Pirniya (1994) identifies and introduces vaults. For Professor Pirniya, a curve (Chafd in Persian) is geometrically defined to be a curved line or shape, while architecturally denoting a narrow arch (a beam) placed on the portal of a doorway. A vault generally refers to a covering of a space between the walls. Vaults fall under two flat and curved styles based on covering forms.

In the book “A Paper on Vaults and Long Houses”, Ghiyas al-Din Jamshid Kashani (2008) has examined various sketching of vaults and geometric forms.

In the book “Vaults and Arches in Iranian Architecture”, André Godard and Vida Godard (2011) study types of vaults in various areas of Iran.

For Godard, types of vaults and arches in Islamic and Iranian architecture include Tagh Ahang[2], Tagh Tarkeen[3], Tagh Chaharbakhsh[4], Tagh Va Tovizeh[5], Tagh Kajaveh[6], Tagh Karbandi[7]. According to Islamic architecture, vaults are not only applicable and structural elements but they are also aesthetic forms. The type of vault used in the building is usually based on regional climates, building land use and aesthetics.

Pouraminian et al. (2012) did a study “Investigating the Seismic Stability of Iranian Brick-Made Arches (Research annotations)” to conclude that arches and vaults greatly contribute to the bearing capacity of other arches and vaults.

In an article “Investigating the Seismic Safety of Vaults and Cheshmeh[8] in Kashan’s Historical Bazaar Using Finite Element Method”, Momenian and Tahghighi suggested that static analytical results revealed that the studied vaults and Cheshmeh resist gravity loads. However, time-history analytical results demonstrated that vaults and Cheshmeh were not resisting seismic loads and for this, future repair and retrofitting will have to be considered for this historical building.

In the books “Investigating Types of Vaults in Iranian Architecture”, “Vaults and Arches in Iranian Architecture (Architecture discipline)” and “Kolanbou[9]”, Mansouri (2018), Rajabi (2019) and Rabiei et al. (2020), respectively study types of vaults, manners of sketching and the qualities of their components in Iranian architecture.

In the article “Architectural and Structural Form Integration in Forming the Physical Structure of Historical Buildings Using Iranian Arches”, Mehdi-Nejad Jamal al-Din et al. (2021) found that traditional architects proficiently employed the structural and technical features of the building using Panj-o-Haft arches to achieve a beautiful and high-quality spaces. They also demonstrated that the architects managed to use this type of arches to convert incongruities and disharmonies, regarded as threats in pier arrangements, into an opportunity to reveal the aesthetic aspects of space designs.

In an article “Comparative Study of Timurid-era Vault and Dome Using Computational Methods in Kashan Models (Case Study: Goharshad Mosque of Mashhad)”, Fallahi et al. (2022) concluded that the so-called Kashani computations and sketching were not just theoretical-practical exercises; rather, they were rightly employed for creating architectural elements. They also demonstrated the relationship between the computational rules of Kashani models and the geometric system of vaults and domes in Goharshad Mosque.

In the article “Comparing Geometry and The Manner of Sketching in Karbandi Vaults (Case Study: Karbandi Platforms 10, 12, 14, and 16)”, Ayeneh-Chi et al. (2019) examined the differences and similarities in Karbandi sketching techniques. Findings revealed that much research has been performed on different types of vaults across Iran; however, no study has ever examined the vaults of Masouleh and their performance under seismic situations. Studies of this kind can reveal the major role of vaults in structural vaults in Masouleh buildings.

3. METHODOLOGY

In the first step, all the physical features of the 19 vaults of Masouleh City were acquired in a field survey and sketched by using AutoCAD 2023 software. Later, Abaqus Finite Element Method (2022) was used to sketch all the 19 vaults in 3D forms to determine their structural performance. In this software, the features of the earthquakes that occurred in Iran were used. These seismic activities included the 2003 Bam earthquakes (6.6 on Richter scale), the 1989 Roudbar Manjil earthquake (7.4 on the Richter scale) and the 1978 Tabas earthquake (7.8 on the Richter scale), which claimed many life and sustained property losses. In the last step, statistical analytical results were tabulated.

4. UNDERSTANDING TYPES OF VAULTS AND ELEMENTS CONSTITUTING VAULTS

Vaults are the major geometrical elements of Iranian architecture, which are used to cover doorways, porches and arcades (Makki-Nejad 2005, 11). The most basic forms of vaults were used in Egyptian buildings, and reached their peak in ancient Rome and Iranian architecture (Rastegarpour 2014, 52). Vaults feature strong geometric structures (Fuller 1998, 63), used to cover ceilings and portals that withstand much loading; vaults are also used for decoration, in addition to applied structures (Raeis Zadeh and Mofid 2006, 3).

4.1. Types of Vault Classification

Vaults used in Iranian works fall under three classes:
a) Load-bearing vaults: This class of vaults features a circular form with a height greater than a semi-circular radius, falling under oval, egg-shaped and pointed vaults; they are also called goat horn-shaped vaults. These vaults are not so beautiful but they are fully load bearing.
b) Pointed vaults: These vaults are called Shah Abbasi vaults and are highly applied in brick buildings.
c) Decorative vaults: This class of vaults lacks load-bearing capacity and is often employed for decorating facades (Zomarshidi 2018, 28). They are also administered in small spans (Kiyani 2012, 398).
Impost: It refers to a place of the pier from where the vault starts.
Haunch: It refers to a place of the vault that cracks as a result of much load; it features an angle of almost 22.5°.
Pointed ridge: It refers to the place where two halves of the vault meet each other.
Shekargah (Shekangah)[10]: It refers to the distance between the impost and the haunch.
Avargah: It refers to the space between the haunch and the place where the vault collapses under much load; it features an angle of 47.50° (Pirniya 1993, 7).
Span: It refers to the inner space between the two piers on either side of the vault.
Partition: It refers to the vertical distance between the vertical impost and the pointed ridge.
Crown: It refers to the distance between the pointed ridge and the place where the Avargah ends.
Pitch of arch: It refers to the ratio of the partition to the span.

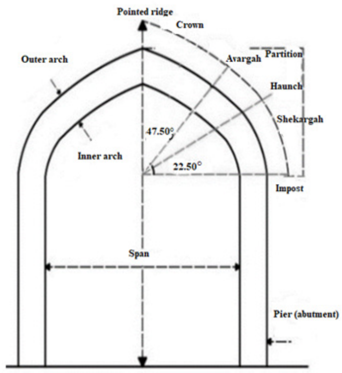
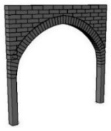
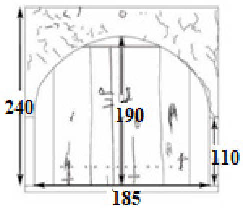
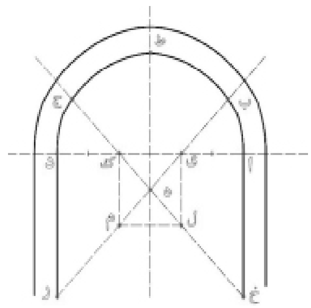


Fig. 1. Structural Components of Vault
(Nazar Mohammadi and Rezvan 2012, 331)

5. INTRODUCING THE VAULTS OF THE HISTORICAL CITY OF MAOSULEH

Masouleh City consists of five neighborhoods, including Khaneh-Bar, Masjed-Bar, Asad Mahalleh, Upper Kesheh-Sar and Lower Kesheh-Sar, covering an area of 160000 m^2 (Hasanpour Loumer et al. 2023b, 2; Zamani-Farahani and Musa 2008, 36; Kakouei et al. 2012, 48; Zamani-Farahani and Musa 2008, 36; Musai et al. 2013, 196; Mansouri 2018, 767; Mansouri 2018, 767; Zamani-Farahani and Musa 2008, 1234; Nasehi, Allahyari, and Zebardast 2017, 15; Memariyan 2012, 219; Ghaffari and Mostoli Zadeh 2013, 113). Masouleh City has 19 vaults in incoming opening sections, which date back to the Zand and Qajar eras. Masouleh's vaults have often been constructed by Roman styles and used local materials, including raw bricks and foothill rocks. First, the physical features of the 19 vaults, including images, dimensions, sizes, geometric sketching, geographical locations, types and names of vaults were tabulated, as noted in Table 1. Later, simulation analyses were performed to determine the functioning of Masouleh vaults and compare them with the seismic features of Roudbar Manjil, Bam and Tabas earthquakes.

Table 1. Physical Features of the Vaults of the Historical City of Masouleh

<table>
<tr><th>No.</th><th>3D Form of the Vaults</th><th>Dimensions and Sizes of the Vaults</th><th>Geometric Analysis of the Vaults</th></tr>
<tr><td>1</td><td>
</td><td>
</td><td></td></tr>
<tr><td></td><td>Name of the Neighborhood, Building Status</td><td>Name of the Vault and Its Administration Method</td><td>Type of the Vault</td></tr>
<tr><td></td><td>Asad Mahalleh
Intact ☒ Exposed to the Serious Danger of Destruction ☐
Destroyed ☐</td><td>Gentle Three-Part Vault
Barrel-Vault ☐ Roman ☒
Concrete ☐</td><td>Bearing............... ☒
Decorative .... ☐</td></tr>
<tr><th>No.</th><th>3D Form of the Vaults</th><th>Dimensions and Sizes of the Vaults</th><th>Geometric Analysis of the Vaults</th></tr>
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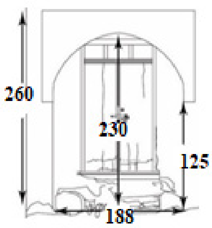
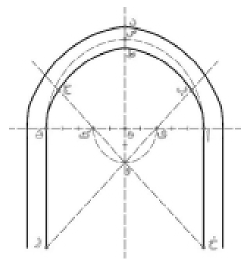
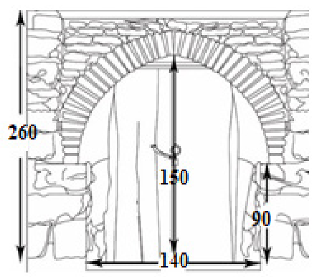
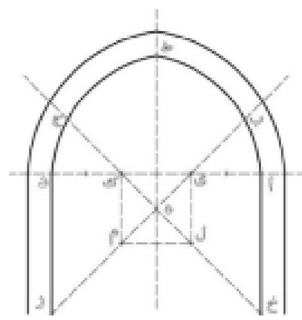
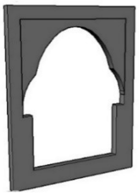
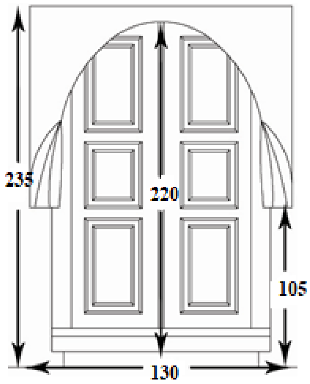
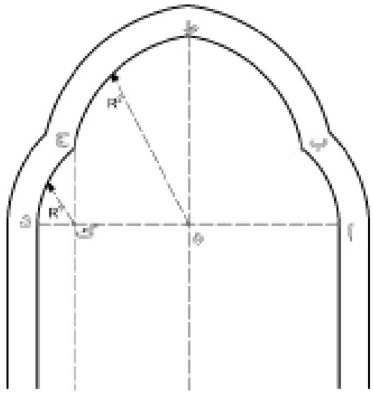
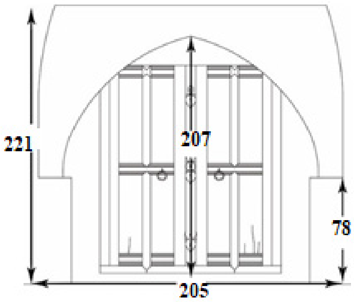
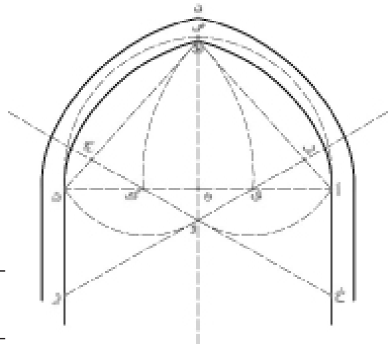
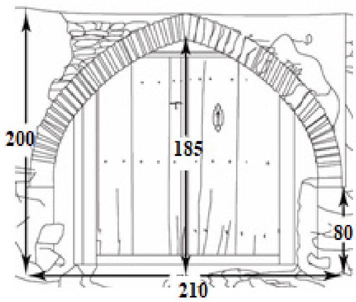
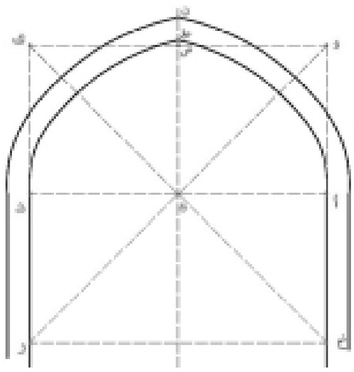
</td><td>
</td><td></td></tr>
<tr><td></td><td>Name of the Neighborhood, Building Status</td><td>Name of the Vault and Its Administration Method</td><td>Type of the Vault</td></tr>
<tr><td></td><td>Asad Mahalleh
Intact ☒ Exposed to the Serious Danger of Destruction ☐
Destroyed ☐</td><td>Gentle Haft-o-Panj
Barrel-Vault ☐ Roman ☒
Concrete ☐</td><td>Load-Bearing..... ☒
Decorative.......... ☐</td></tr>
<tr><th>No.</th><th>3D Form of the Vaults</th><th>Dimensions and Sizes of the Vaults</th><th>Geometric Analysis of the Vaults</th></tr>
<tr><td>3</td><td>
</td><td>
</td><td></td></tr>
<tr><td></td><td>Name of the Neighborhood, Building Status</td><td>Name of the Vault and Its Administration Method</td><td>Type of the Vault</td></tr>
<tr><td></td><td>Asad Mahalleh
Intact ☐ Exposed to the Serious Danger of Destruction ☒
Destroyed ☐</td><td>Gentle Three-Part Vault
Barrel-Vault ☐ Roman ☐
Concrete ☐</td><td>Load-Bearing..... ☒
Decorative.......... ☐</td></tr>
</table>

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
4	 		

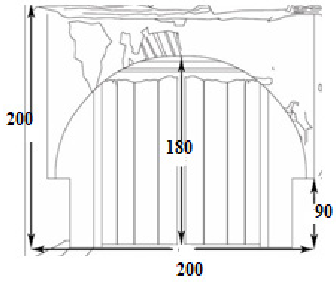
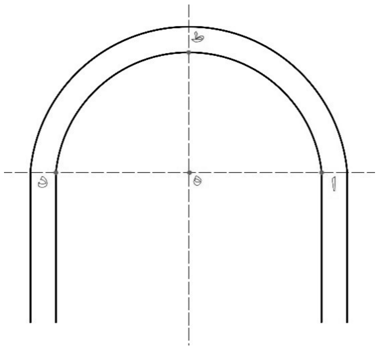
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Reihaneh-Bar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Three-Center three Arches Barrel-Vault ☐ Roman ☐ Concrete ☒	Load-Bearing..... ☐ Decorative......... ☒

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
5	 		

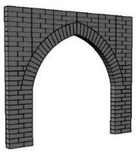
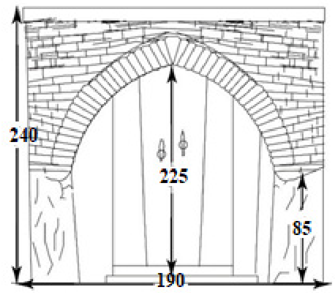
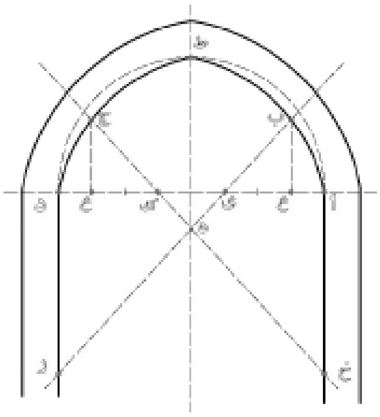
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Reihaneh-Bar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Steep Panj-o-Haft Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing..... ☒ Decorative.......... ☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
6	 		

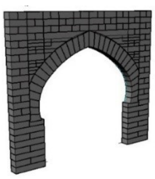
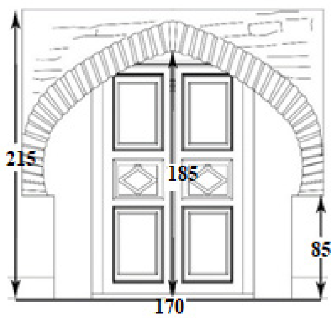
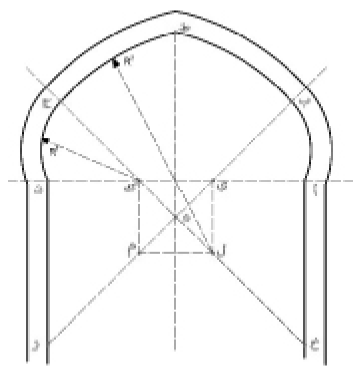
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Masjed-Bar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	45° Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing..... ☒ Decorative.......... ☒

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
7	 		

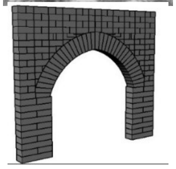
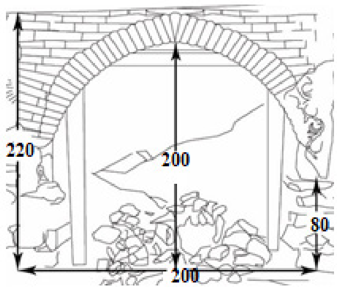
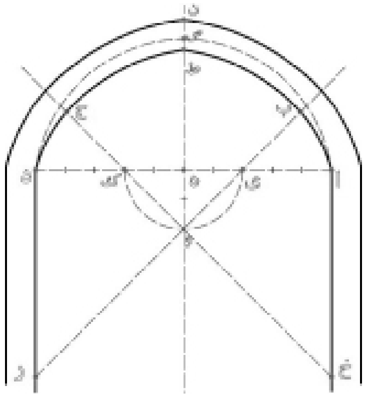
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Masjed-Bar Intact ☐ Exposed to the Serious Danger of Destruction ☒ Destroyed ☐	Tunnel Vault Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative.........☒

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
8	 		

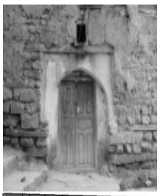
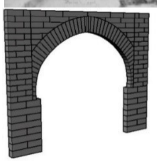
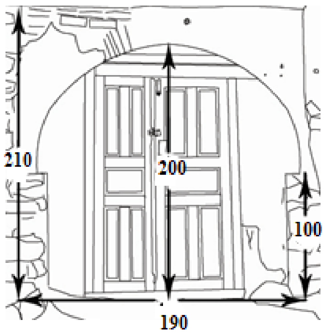
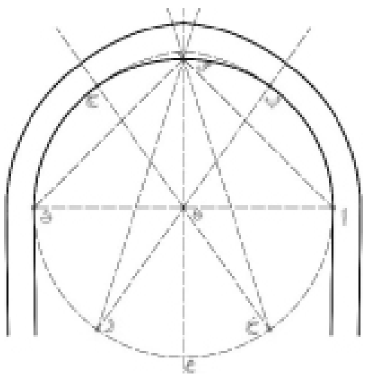
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Masjed-Bar Intact ☐ Exposed to the Serious Danger of Destruction ☐ Destroyed ☒	Steep Four-Part Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
9	 		

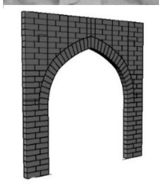
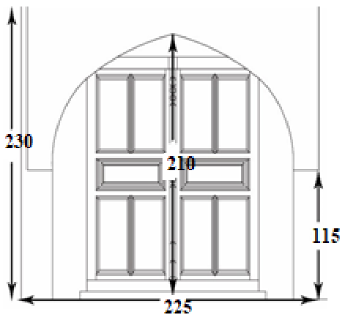
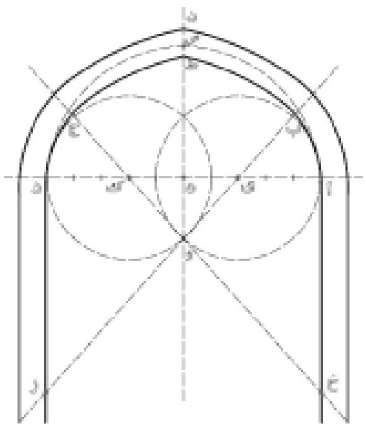
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Khaneh-Bar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Steep Three-Part Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☒

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
10	 		

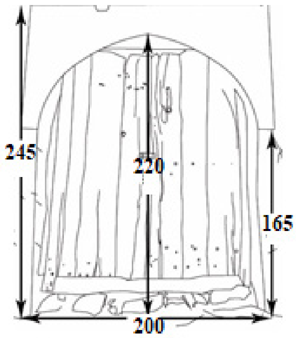
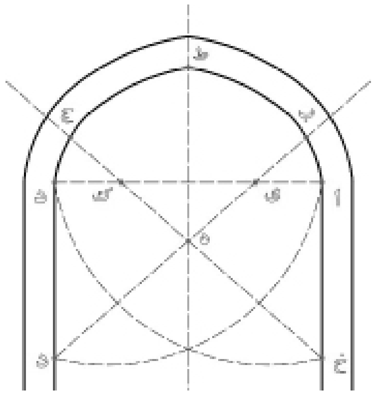
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Khaneh-Bar Intact ☐ Exposed to the Serious Danger of Destruction ☒ Destroyed ☐	Gentle Haft-o-Panh Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
11	 		

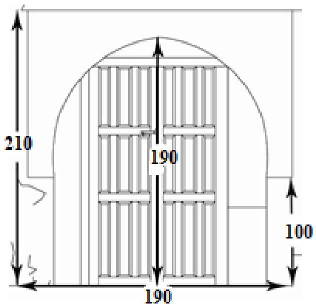
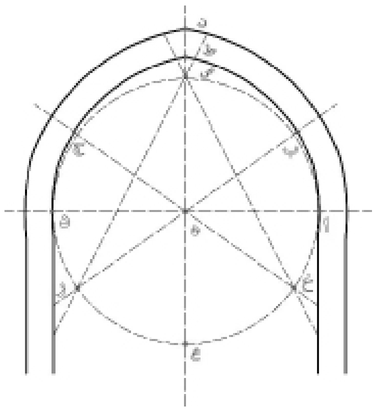
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Khaneh-Bar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Simple Cloverleaf Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
12	 		

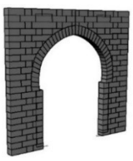
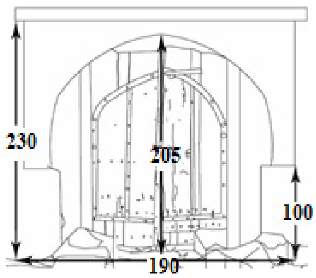
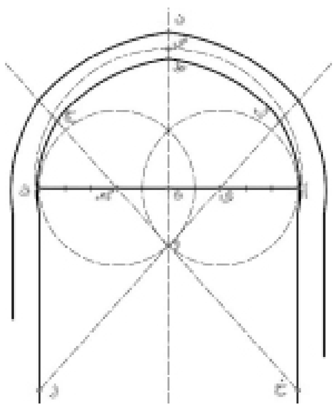
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Khaneh-Bar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Steep Panj-o-Haft Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
13	 		

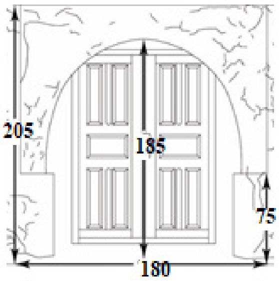
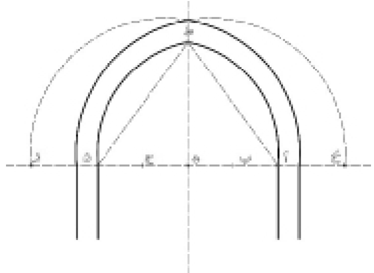
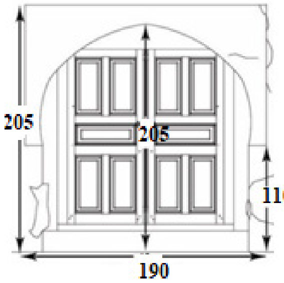
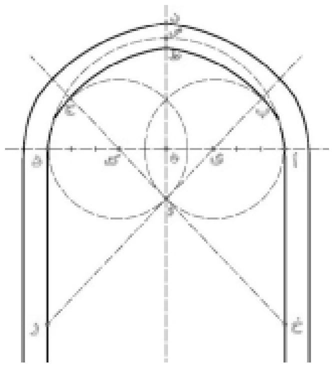
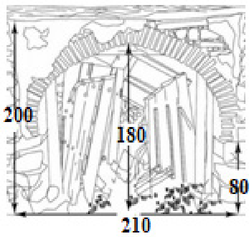
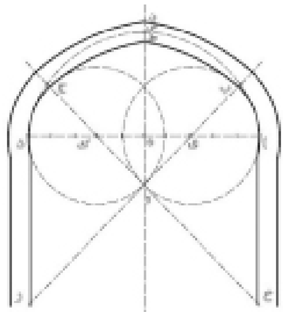
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Kesheh-Sar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Steep three Part Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

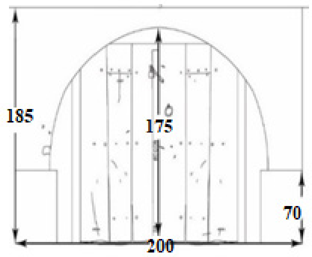
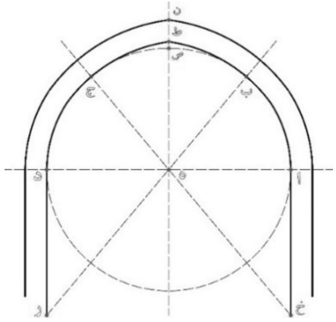
No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
14	 		

Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Kesheh-Sar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Steep Cloverleaf Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
15	 		

Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
Kesheh-Sar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☒	Steep Panj-o-Haft Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
16	 		
	Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
	Kesheh-Sar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Chamaneh Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐
No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
17	 		
	Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
	Kesheh-Sar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Steep Panj-o-Haft Barrel-Vault ☐ Roman☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐
No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
18	 		
	Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault
	Kesheh-Sar Intact ☐ Exposed to the Serious Danger of Destruction ☒ Destroyed ☐	Steep Panj-o-Haft Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☐

No.	3D Form of the Vaults	Dimensions and Sizes of the Vaults	Geometric Analysis of the Vaults
19	 		
Name of the Neighborhood, Building Status	Name of the Vault and Its Administration Method	Type of the Vault	
Kesheh-Sar Intact ☒ Exposed to the Serious Danger of Destruction ☐ Destroyed ☐	Equilateral Barrel-Vault ☐ Roman ☒ Concrete ☐	Load-Bearing.....☒ Decorative..........☒	

5.1. Parameters Used and Seismic Analysis Results of the Vaults of Masouleh Historical City

The next section uses the 2022 Abaqus finite element software and the seismic features of Roudbar, Manjil, Tabas, and Bam to examine the 19 vaults of the historical city of Masouleh.

Table 2. Criteria Used in the Finite Elements Modeling of the 19 Vaults of Masouleh City

No.	Standard Unit of Meas-Urement Signs	Standard Unit of Measurement
1	C	Cohesiveness
2	f	Inner Friction Angle
3	η	Volumetric Expansion Angle
4	E	Modulus of Elasticity
5	ρ	Mass Density
6	ν	Poisson's Ratio
7	Load	Gravity Superimposed Load Assumed to be Equal based on the the Load-Bearing width of the Vaults
8	σ_t	Allowed Tensile Strength of Materials
9	σ_c	Allowed Compressive Strength of Materials

Table 3. Criteria used in Finite Elements Modeling of the 19 Vaults of Masouleh City

No.	Criterion of Measurement	Unit	Unit Sign	Data
1	C	Pa	Pa	1.00E+05
2	f	Degree	Degree	20
3	η	Degree	Degree	15
4	E	Pa	Pa	7.00E+09
5	ρ	Kg/m^3	Kg/m^3	1850
6	ν	-	-	0.2
7	Load	KN	KN	60
8	σ_t	Mpa	Mpa	0.2
9	σ_c	Mpa	Mpa	2.5

Table 4. Hypotheses used in Finite Element Modeling

No.	Hypotheses in Static Analysis
1	The Vault-in-Vault is Clamped
2	A Linear Elastic Behavior is Considered for the Elements
3	Materials are Isotopes.
4	The Superimposed Load Applies an Equivalent of 60 kN Force to the Vault, in addition to the Vault itself
5	The Allowed Strain of Masonry Materials is 0.002.

Table 5. Finite Element Modeling Required Results

No.	Required Results
1	Investigating the Deflection of all Vaults under Equal Static Loading
2	Investigating the Maximum Compressive Stress and Comparing it with the allowed Compressive Stress under Equal Static Loading Conditions
3	Investigating the Maximum Tensile Stress and Comparing it with the Allowed Tensile Stress under Equal Static Loading Conditions

Table 6. Order of Masouleh's Vault Performance via Maximum Seismic Deformation (Yellow Color: the Worst Performance; Blue Color: the Best Performance)

Vault No.	Highest Changes (m)	Highest Changes (mm)
S1	5.17E-04	0.517
S2	5.08E-04	0.508
S5	3.98E-04	0.398
S17	3.94E-04	0.394
S10	3.82E-04	0.382
S4	3.78E-04	0.378
S18	3.41E-04	0.341
S3	3.24E-04	0.324
S16	3.21E-04	0.321
S9	3.19E-04	0.319
S7	2.82E-04	0.282
S15	2.65E-04	0.265
S11	2.60E-04	0.260
S13	2.58E-04	0.258
S19	2.30E-04	0.230
S8	2.17E-04	0.217
S14	1.85E-04	0.185
S12	1.83E-04	0.183
S6	1.77E-04	0.177

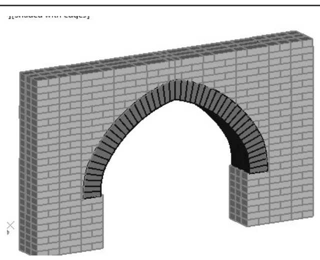
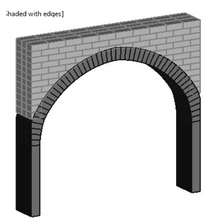
Minimum Deformation under Static Loading	Maximum Deformation under Static Loading
	
S6 Vault	S1 Vault

Table 7. Performance of Masouleh Vaults in Terms of Tensile Stresses in Earthquakes (Yellow Color: the Worst Performance; Blue Color: the Best Performance)

Vault No.	Pa	MPa
	Stress (T)	Stress (T)
S2	194700.000	0.195
S17	126100.000	0.126
S5	121900.000	0.122
S1	118200.000	0.118
S7	109400.000	0.109
S4	92600.000	0.093
S10	88870.000	0.089
S3	87780.000	0.088
S18	87470.000	0.087
S16	86600.000	0.087
S19	80890.000	0.081
S15	79690.000	0.080
S9	71790.000	0.072
S11	68370.000	0.068
S13	67970.000	0.068
S8	63970.000	0.064
S6	52210.000	0.052
S12	49110.000	0.049
S14	40990.000	0.041

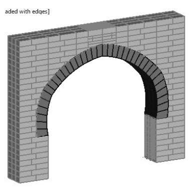
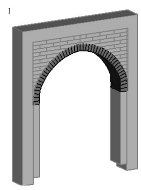
Minimum Tensile Stress under Static Loading	Maximum Tensile Stress under Static Loading
	
S14 Vault	S2 Vault

Table 8. Performance of Masouleh Vaults in Terms of Compressive Stresses in Earthquakes (Yellow Color: the Worst Performance; Blue Color: the Best Performance)

Vault No.	Pa	MPa
	Stress (C)	Stress (C)
S1	236200.000	0.236
S2	226500.000	0.227
S4	213900.000	0.214
S18	213200.000	0.213
S5	211500.000	0.212
S17	195100.000	0.195
S8	183900.000	0.184
S16	181500.000	0.182
S7	173900.000	0.174
S13	170800.000	0.171
S19	169900.000	0.170
S10	167900.000	0.168
S3	164800.000	0.165
S9	163700.000	0.164

Vault No.	Pa	MPa
	Stress (C)	Stress (C)
S15	162600.000	0.163
S11	152600.000	0.153
S6	138500.000	0.139
S14	122400.000	0.122
S12	115400.000	0.115

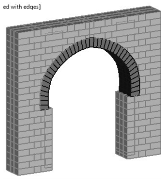
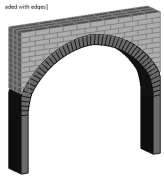
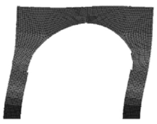
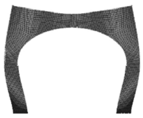
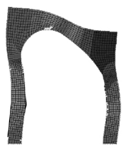
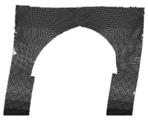
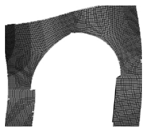
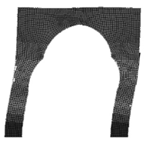
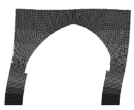
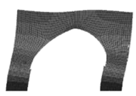
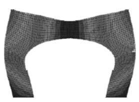
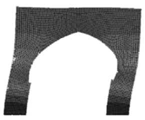
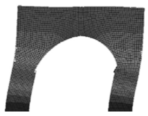
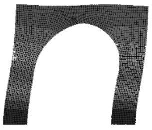
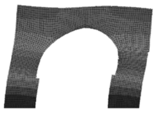
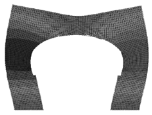
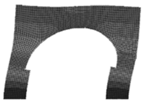
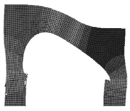
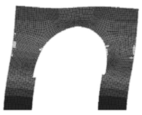
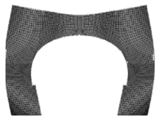
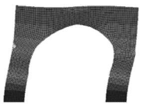
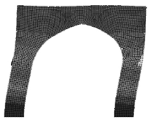
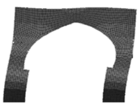
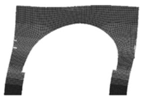
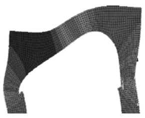
Minimum Compressive Stresses under Static Loading	Maximum Compressive Stresses under Static Loading
	
S12 Vault	S1 Vault

Table 9. Horizontal and Vertical Oscillation of Vaults in an Oscillation Period under the Effect of Free Vibration

Vault No.	Time	Changes in the Horizontal Axis Direction	Changes in the Vertical Axis Direction	Vault No.	Time	Changes in the Horizontal Axis Direction	Changes in the Vertical Axis Direction
S1	Horizontal Period of the Template 0.0996 Vertical Period of the Template 0.0178			S2	Horizontal Period of the Template 0.0185 Vertical Period of the Template 0.0160		
S3	0.0821 Vertical Period of the Template 0.0176 Horizontal Period of the Template			S4	0.1110 Vertical Period of the Template 0.0203 Horizontal Period of the Template		
S5	0.0857 Vertical Period of the Template 0.0181 0.0181			S6	0.0456 Vertical Period of the Template 0.0124 0.0124		
S7	Horizontal Period of the Template 0.0704 Vertical Period of the Template 0.0152			S8	Horizontal Period of the Template 0.0632 Vertical Period of the Template 0.0149		
S9	Horizontal Period of the Template 0.0632 Vertical Period of the Template 0.0149			S10	Horizontal Period of the Template 0.0967 Vertical Period of the Template 0.0177		

Vault No.	Time	Changes in the Horizontal Axis Direction	Changes in the Vertical Axis Direction	Vault No.	Time	Changes in the Horizontal Axis Direction	Changes in the Vertical Axis Direction
S11	Horizontal Period of the Template 0.0758 Vertical Period of the Template 0.0165			S12	Horizontal Period of the Template 0.0497 Vertical Period of the Template 0.0131		
S13	Horizontal Period of the Template 0.0967 Vertical Period of the Template 0.0177			S14	Horizontal Period of the Template 0.0559 Vertical Period of the Template 0.0141		
S15	The Horizontal Period of the Template 0.0643 The Vertical Period of the Template 0.0145			S16	The Horizontal Period of the Template 0.0803 The Vertical Period of the Template 0.0162		
S17	The Horizontal Period of the Template 0.0666 The Vertical Period of the Template 0.0140			S18	The Horizontal Period of the Template 0.0661 The Vertical Period of the Template 0.0148		

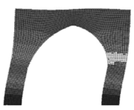
Vault No.	Time	Changes in the Horizontal Axis Direction	Changes in the Vertical Axis Direction
S19	The Horizontal Period of the Template 0.0643 The Vertical Period of the Template 0.0147		

Table 10. Introducing the Worst and the Best Vaults in Masouleh in Terms of Horizontal and Vertical Simulation and Vault Performance under Oscillation from the Effects of Seismic Free Vibration

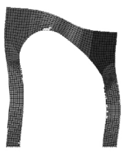
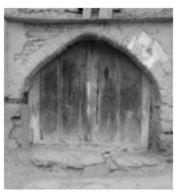
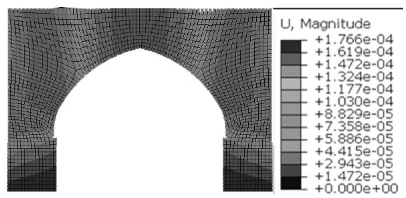
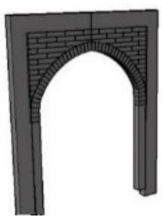
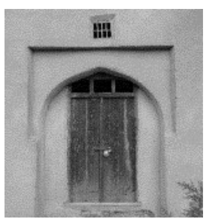
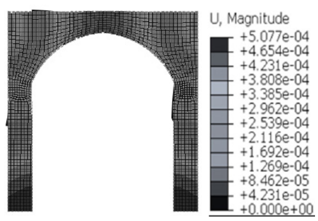
Vault No.	Time	Changes in the Horizontal Axis Direction	Changes in the Vertical Axis Direction	Vault No.	The Worst Time	The Highest Changes in the Horizontal Axis Direction	The Highest Changes in the Vertical Axis Direction
S2 Vaults (the Best Vault in Terms of Resistance against Free Vibration)	Horizontal Period of the Template 0.0185 Vertical Period of the Template 0.0160			S1 Vault is the Worst Vault in Terms of Resistance to Free Vibration	Horizontal Period of the Template 0.0966 Vertical Period of the Template 0.0178		

Table 11. Analyzing the Performance of the Historical City of Masouleh Subjected to Bam, Roudbar, Manjil and Tabas Earthquakes (Yellow Color: the Worst Performance and Blue Color: the Best Performance)

Vault No.	Bam Earthquake	Roudbar and Manjil Earthquake	Tabas Earthquake
	Vault Moment of Failure	Vault Moment of Failure	Vault Moment of Failure
1	23.17	5.8	2.64
2	23.56	2.06	1.51
3	23.42	6.41	7.12
4	23.22	2.06	2.58
5	23.3	5.83	6.65
6	24.65	6.46	-
7	23.41	6.46	6.65
8	23.57	6.45	8.64
9	23.57	6.56	15.92
10	23.53	2.06	8.18
11	24.22	6.47	8.38
12	24.82	6.46	13.18
13	23.6	9.85	-
14	24.34	10.05	11.7
15	23.57	6.46	8.64
16	23.42	6.25	6.65
17	23.57	6.46	11.7
18	23.6	6.46	18.36
19	23.57	6.46	6.64

Table 12. Introducing the Best and the Worst Vaults of the Historical City of Masouleh based on Seismic Simulation Analyses

Vault 6: The Best Performance against Earthquakes like those of Bam, Tabas and Manjil		Rangge of Static Chnages in Vault No. 6
 	Vault 6: Having the Best Performance and the Lowest Formal Changes against Static Loads	
Vault 2: The Worst Performance against Earthquakes like those of Bam, Tabas and Manjil		Rangge of Static Chnages in Vault No. 2
 	Vault 2: Having the Worst Performance and the Lowest Formal Changes against Static Loads	

In the following, Table 13 and Figures 1-4 demonstrate types of vaults, their construction procedures, the frequency of vaults and load-bearing and decorative vaults in the city of Masouleh.

Table 13. Introducing the Statistics of the Vaults used in the Historical City of Masouleh

Fig. 1. Types of Vaults used in Masouleh

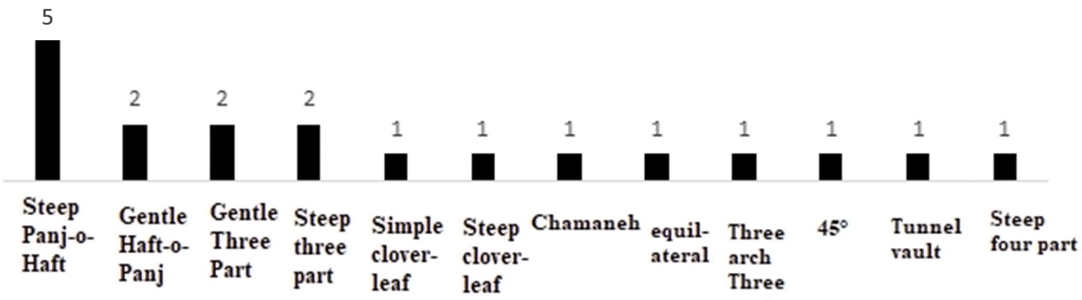
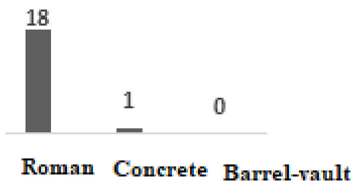
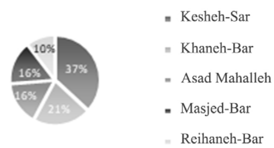
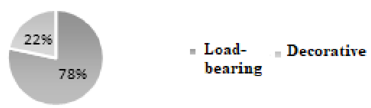


Fig. 2. Types of Vault Construction Methods in Masouleh	Fig. 3. Frequency and Types of Vaults in Masouleh Neighborhoods	Fig. 4. Type of Load-Bearing and Decorative Vaults
		

6. CONCLUSION

A vault is an arch-shaped ceiling constructed to transfer the weights of vertical loads to abutments or buttresses over a span, which lies between two abutments. Vaults feature different types, the most common of which include parabolic-shaped, semi-circular, oval, pointed and elliptical vaults. Vaults were used in the Mesopotamia 2000 years ago. Meanwhile, the oldest Iranian vaults were used in Choghazanbil temple 1350 B.C. Throughout history, Iranian architects have created impressive vaults with large spans in specific climates. Architects of Guilan used to construct buildings by using wooden structures based on moderate and humid climates. The craftsmen of the historical city of Masouleh used to construct buildings in the city by using wooden, stone and raw materials, while following Iranian architecture principles and using local materials, based on climatic needs. The diversity of using materials in the city of Masouleh helped form and employ various vaults in this historical city. In total, the city features 19 types of vaults, including steep Panj-o-Haft vaults, gentle Haft-o-Panj, gentle and steep three -part, simple cloverleaf, steep cloverleaf, Chamaneh, equilateral three-arche-three-center, 45° tunnel vaults, steep four-part, etc. Out of this, the steep Panj-o-Haft and gentle Haft-o-Panj accounted for the highest frequency of the vaults., with the simple and steep cloverleaf vaults holding the lowest number. In general, raw bricks were used in 18 Masouleh vaults and concrete was used in one building, built in the contemporary era. The majority of Masouleh's vaults are built using the Roman style. In this connection, Kesheh-Sar, Khaneh-Bar, Asad Mahalleh, and Masjed-Bar Neighborhoods have the highest numbers of vaults. The performance results of Masouleh's vaults against earthquakes like those of Roudbar, Majd, Tabas and Bam cities indicated that 17 vaults, out of the 19, were found to feature fully safe and stable conditions against destructive earthquakes. Seismic analyses also suggested that the 45° vault (Fig. 6), constructed in Roman styles in the Masjed-Bar Neighborhood, outperformed other vaults in terms of stability against earthquakes, and the gentle Haft-o-Panj (Fig. 2), located in the Asad Mahalleh Neighborhood, held the poorest seismic performance compared to others. In sum, study results were found to reveal good and safe options for constructing new buildings in the historical city of Masouleh. Also, the results could help preserve the vaults and lay the ground for prospective comparative research on Masouleh's vaults and those of Abyaneh in Isfahan.

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CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

MORAL APPROVAL

The authors commit to observe all the ethical principles of the publication of the scientific work based on the ethical principles of COPE. In case of any violation of the ethical principles, even after the publication of the article, they give the journal the right to delete the article and follow up on the matter.

PARTICIPATION PERCENTAGE

The authors state that they have directly participated in the stages of conducting research and writing the article.

ENDNOTE

1. Also, Chafteh, Chafd, Chaft in Persian curved, bent; In building construction, a structural member consisting of an arrangement of arches, usually forming a ceiling or roof
2. It is one of the oldest vaults, which is constructed by moving a chafd on two parallel walls. At a glance, this vault looks like a cradle and resembles half of a cylinder
3. In the inner space of the Tarkeen vaults, cracks can be seen compared to the vaults used in its administration.
4. Made of four sections
5. This vault is made by making plaster rainbow shapes on the ground and then loading them and administering the vaults according to the pattern of the rainbow styles.
6. This type of vault transfers all incoming loads from its main cover to the vault bodies
7. It is a set of diagonal vaults that cut each other and use their intersection (sides) to make the vaults to create a cover.
8. A kind of arch
9. A type of vault
10. It refers to an angle of 22.5 of the curved line (beam) on the vault.

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