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The effects of muqarnas and mortar joints on the acoustic quality of the Jaame mosque of Yazd

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ABSTRACT

The architecture of the Jaame mosque, being the most important place for gathering and worship in the Islamic world, is detailed to the finest of building elements. Several activities take place inside the Jaame mosque in separate or connected order. These activities are the performing prayers led by the Imam, the preaching speech, and the recitation of some of the verses of the Holy Quran. Considering that, it is determining to study the acoustics of Jaame mosques and how architects constructed the space to promote the words of God; hence, this paper analyzes the acoustic qualities of Jaame mosque of Yazd, as one of the architectural and historical masterpieces in Iran. The decorative brickwork used in conjunction with tiles and the muqarnases, Karbandies, and squinches adorning the dome, iwan, and their adjacent spaces, appear to have significant effects on the quality of sound in the building. In this study, we simulated the volume and interior surface of the space and conducted calculations of the reverberation time using EASE. Reverberation time shows a downward trend from low to high frequencies and is controlled in low frequencies to produce a preferable acoustic experience. The median of reverberation time shows 4.32-seconds without muqarnases. This time reduces to 3.33-seconds with the proper arrangement of muqarnases, squinches under the dome, and their distance from the sound source, as well as the brickwork decorations and the configuration of the mortar joints to remarkable effect. The results showed an appropriate distribution of sound throughout the mosque.

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1. Introduction

Mosques as spaces used for worship and lecturing are a good subject as an analysis of the acoustic room based on its internal features and parameters. Due to the lack of sound technologies in the past, transmitting a speaker's voice to the audience was a hard practice; however, mosques were always designed to convey the speech of the Imam to the devotees with the best possible quality. A surface's finish is a fundamental determinant of the behavior of sound waves in space. A dome or column's size and form, breaking space and surface into smaller divisions by adding decorations such as *muqarnas* or *squinches*, and changing the materials of a surface with decorative tiles, could all act as acoustical instruments –besides being aesthetically pleasing. This paper answers how the volume, materials, and surfaces of mosques impact their acoustic qualities.

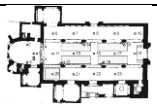
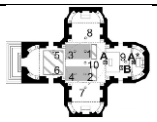
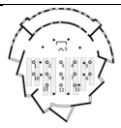
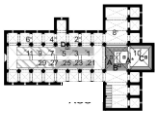
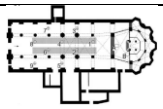
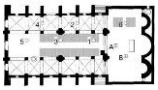
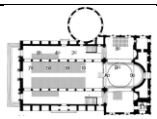
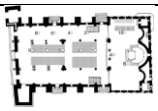
Initially, studying the acoustics of different mosques can point us to the shared architectural features that make such spaces and how other architectural organs affect sound quality. The impact of architectural features has studied in main prayer hall geometry in the eastern province, Saudi Arabia[1], Malaysia [2], Case study of Dog˘ ramacızade Ali Pasa Mosque [3] contemporary mosques[4], and Dome-shape of mosques in Saudi Arabia [5]. Elkhateeb and others studied absorption characteristics of masjid carpets[6]. Abdu simulated the comparison of the acoustical performance of mosques [7]. Othman and Mohammad investigated the speech in Intelligibility in Mosque's Praying Hall [8]. Finally, Orfali simulated the sound system design during Constructing and Reconstructing Mosques [9]. In the following, we will consider some churches with enormous volumes and their acoustical qualities.

Churches are complex rooms from an acoustic point of view. The importance of this aspect of room acoustics has been assessed in Roman Catholic churches [10], Mudejar-Gothic churches[11], Apulian-Romanesque churches [12], Italian Catholic churches [13], and finally simulation of the effect of occupancy and source position in historical churches [14]. Following this idea, we have tried to assess the relationship between reverberation time and characteristics within them. These churches belong to the group of multi-functional objects with respect to acoustics. In contrast to mosques, these have long reverberation times. This is partly due to the absence of absorbing surfaces on the floor –mosques have carpets- different materials and different geometries used in churches. After a brief recap of Reverberation Time-based studies, the Jaame mosque of Yazd is chosen as a case to analyze. The simulation result shows that Jaame mosque of Yazd has good performance; thus we examined its architectural elements - specifically its volume, materials, proportions, *muqarnas* decorations, and mortar joints- and how they affect the buildings acoustic quality. Using EASE the impact of the distance between *squinches* under the dome and the dome's focal point on sound quality, as well as the effect of tile decorations and their proportions and scale, have been analyzed. The purpose of this study is to determine the impact of certain architectural elements in creating an enchanting acoustical environment in Yazd's Jaame mosque.

2. Literature Review

In this section, we will compare reverberation time in churches with similar massing's to the Jaame mosque of Yazd –itself in group f [9-14].

Table 1:Comparison of Reverberation Time in Churchs with a volume of more than 10,000 cubic meters[10-14]

Name of church	Volume (m^3)	Floor area (m^2)	Length (m)	plan	RT	Materials
Santa Marina	10708	529	34		3.08	Painted brick, wooden frame
Santi Martina and Luca	11000	475	30		3.29	plaster and stucco, richly decorated, wooden pews
Paul Apostle Church	14000	812	35		8.10	wooden pews, floors of marble or ceramic plates, stained-glass windows
Abbey of Chiaravalle della Colomba	15000	1363	59		6.00	plaster, Painted Brick, wooden pews
Barletta Cathedral	15800	912	46		6.80	wooden roof, marble floor, wooden pews, hard limestone walls
Bitonto Cathedral	16000	858	42		4.30	marble floor, wooden pews, hard limestone walls
Bari Cathedral	30100	1274	46		5.30	wooden roof, marble floor, wooden pews, hard limestone walls
St. Nicholas Basilica	32000	1530	54		5.40	marble floor, wooden pews, hard limestone walls, large painted canvases

The biggest church with 32000 cubic meters of space has a lower reverberation time than many churches with smaller areas. Construction details, surface finishing, and small variations on a given typology may all influence the acoustics of a church. According to Table 1, most churches have rows of wooden benches, walls with gypsum plastering, frescoes and paintings, bricks, and floors covered with marble and stone. Even though many of these churches share common features, other characteristics such as the number of surfaces or the geometry of space, the form of columns and decorations, and the shape of details have as much impact on reverberation time as total volume.

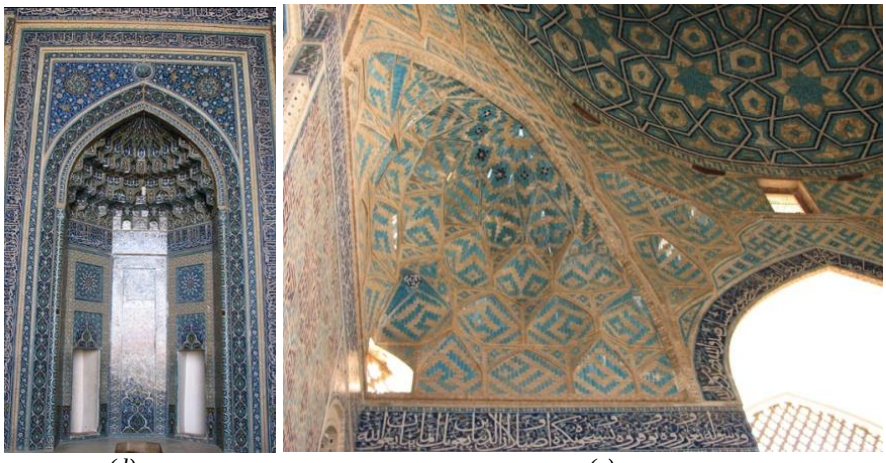
Due to studies on different mosques [1-8], it is clear that there is a correlation between the parameters inside the mosque, such as the form of the plan, the material and its location, and its acoustic qualify. As a result of this study, we can comprehend how to prevent the echo of sound under the dome by appropriate absorbent materials. Also, the mosque with a square plan has a better quality than other forms. The characteristics of the Jaame mosque are examined by

reviewing the obtained data. Furthermore, studying the aforementioned churches revealed how factors other than just materials, but also form and geometry affect reverberation time [10-14]. This helps us understand how muqarnas decorations, squinches, and detailed brickwork decrease reverberation time to make theJaame mosque a desirable acoustic experience.

3. The Jaame Mosque as a case study

With foundations tracing back to 900 years, the Grand Jaame Mosque of Yazd is a masterpiece of Islamic architecture in Iran. A soaring *iwan* (a rectangular hall or space, usually vaulted, walled on three sides, with one end entirely open) and a skyward yet delicately ascending dome set the tone in this majestic building. The vault of the lofty *iwan* is beautifully ornamented with a composition of tile mosaics and arabesque patterns. Tile mosaics skirt the piers of the *iwan*. Adorning the squinches beneath the dome is also *moaghali* tilework. Connecting the *squinches* is a series of *Karbandies*. The main *mihrab* has a beautiful *muqarnas* at its apex and is decorated with tile mosaic and brick. Before the *iwan* is two passages to a series of double-tiered rooms and corridors. The brick body of these corridors is covered with a thin layer of render. Corridors, covered with cross vaults, connect the two *shabestans* to the *iwan* and dome. The eastern *shabestan*, coetaneous with the *mihrab* and dome, consists of aeries of six vault sand is skirted and paved with brick (Figure1)

(a) *(b)* *(c)*



(d) *(e)*

Fig:1 Details of Jaame mosque. a) Eastern Prayer hall, b) A Gallery beneath the dome, For women's prayer space, c) Western Prayer Hall, d) Main Mihrab (consider the muqarnas decorations below the arch), e) Squinches under the dome

1. main entrance
2 .northern entrance
3. northwestern entrance
4. western entrance
5.Gonbad-Khaneh (literally Dome-space)
6. main Iwan
7. eastern prayer hall
8. western prayer hall
9. eastern shabestan
10. western shabestan
11. women worship place

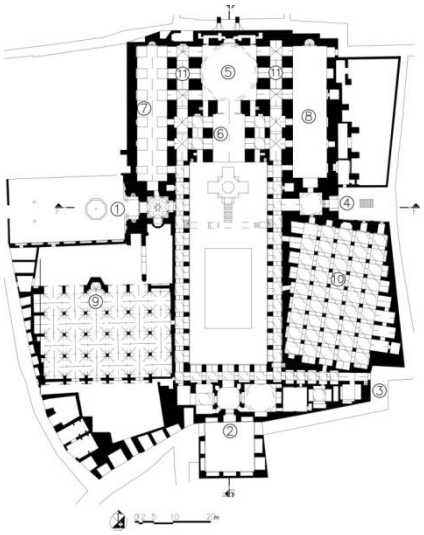


Fig: 2 Plan of Jaame mosque (Simulated parts are highlighted)

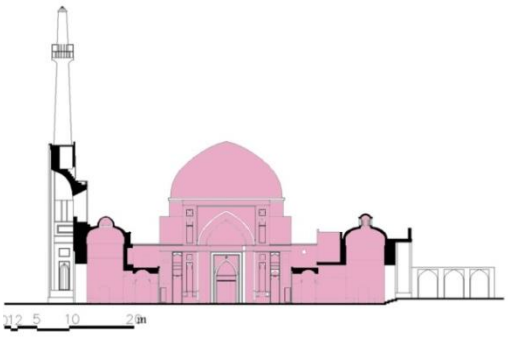
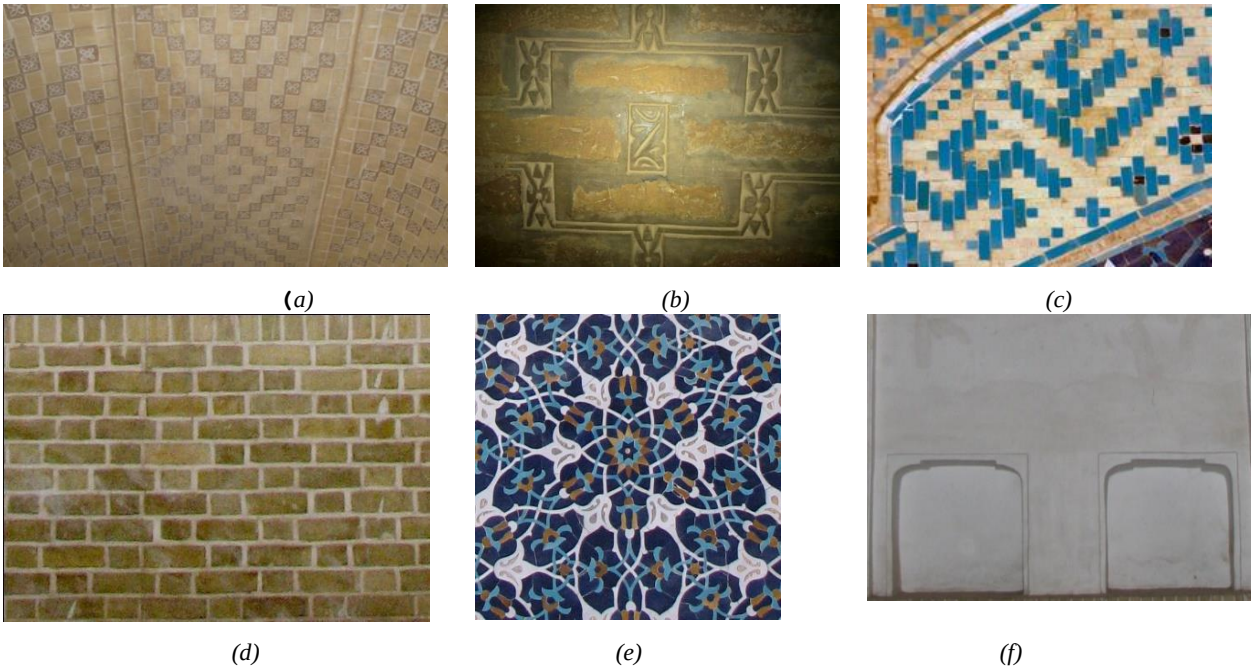


Fig. 3: Section A-A

4. Research Methodology

This research is a quantitative case study. By analyzing reverberation time in simulated models and exploring differences in acoustic qualities, it aims to establish the relationship of certain architectural elements and reverberation time. Two 3D models of the Jaame mosque of Yazd constructed in SketchUp. These models are then imported into EASE. The volume entered must be completely closed without any holes. Once the room geometry defines, the next step is the assignment of the surface materials. In EASE, acoustic materials principally define by e set of absorption and scattering coefficients, given in a 1/3rd octave resolution. These data can import or enter manually. In this research, data enter mutually. The majority of materials in the part of the mosque that we have studied are bricks under the dome and *iwan*, and gypsum renders in adjacent prayer halls. Also, the floor covers with carpet. In the table below, the absorption coefficient of the materials used in different parts of the mosque (Table2), retrieved from

Marshal Long's *Architectural Acoustics*, is presented [6]. The absorption coefficient of the carpets is calculated based on a study in the research literature[15].Materials used in dome-space and adjacent spaces are shown in Figure 4.



(a) *(b)* *(c)*

(d) *(e)* *(f)*

Fig. 4:Materials of Jamme mosque a)Glazed brick with decorations, b)Detail of the bricks, c)Moaghali tilework (tiles in composition with bricks), d)Bricks, e)Tile Mosaic, f) Render

Table.2: Absorption Coefficient of Materials [6], [15]

Frequency(HZ) / Material	125	250	500	1000	2000	4000	8000
Tile glazed	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Plaster,7.8".gypsum or lime,on Brick	0.01	0.02	0.02	0.03	0.04	0.05	0.05
Brick,Unglazed.Painted	0.01	0.01	0.02	0.02	0.02	0.03	0.03
Brick,Unglazed,Unpainted	0.03	0.03	0.03	0.04	0.05	0.07	0.08
Carpet	0.03	0.04	0.17	0.46	0.76	0.85	0.96

It is well known that the volume of buildings significantly affects their acoustic quality. In mosques are sorted based on their volume [9].

Tables.3:Categorizing mosques based on their volumes [9]

Group	Volume
A	1000 >A
B	1500 >B>1000
C	2000 > C > 1500
D	3000 > D >2000
E	10000 > E > 3000
F	F > 10000

The relationship between volume and Reverberation Time for each group is shown in the following graph (Fig.5).

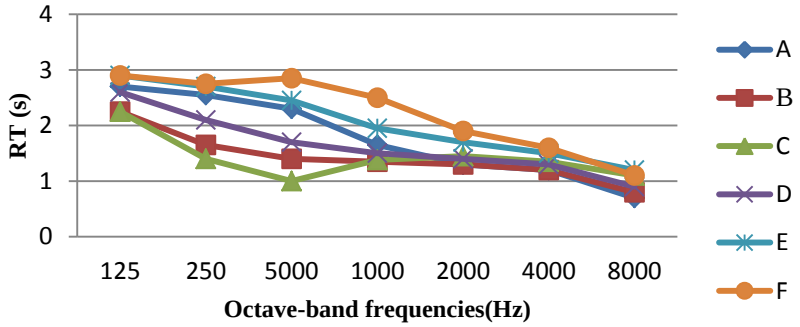
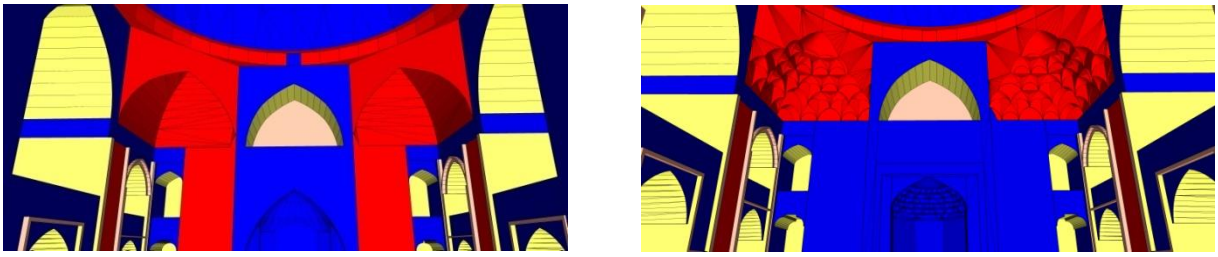


Fig.5: The relationship between Reverberation Time and frequency and a the volume of mosques [9]

The total area of the modeled part is 12795 square meters. The space under the dome plus *iwan* and prayer halls is 68 meters in length and 45 meters in width. Elevation differs in different spaces: The dome has a height of 28 meters, *iwan* 16, and prayer halls each 10. The volume of the simulated dome home and *iwan* adds up to 23629 cubic meters. Since the mosque is situated in the historical core of Yazd, there is not much ambient noise, making it an easier job to control the acoustics of its spaces. Simulating reverberation time in EASE, analyses the absorbing qualities, the number of surfaces, and their formal arrangement, gives us reverberation time in every space and appropriate graphs.

The pictures below (Figure6), two 3D models of the Jaame mosque of Yazd constructed in SketcUp. Different colors have been used in the space according to its usage and area. Also, next pictures (Figure7,8), displaying of the 3D model imported into EASE.



a) *(b)*

Fig. 6: a)Mihrab and dome without squinches and muqarnases, b)Mihrab and dome with squinches and muqarnases

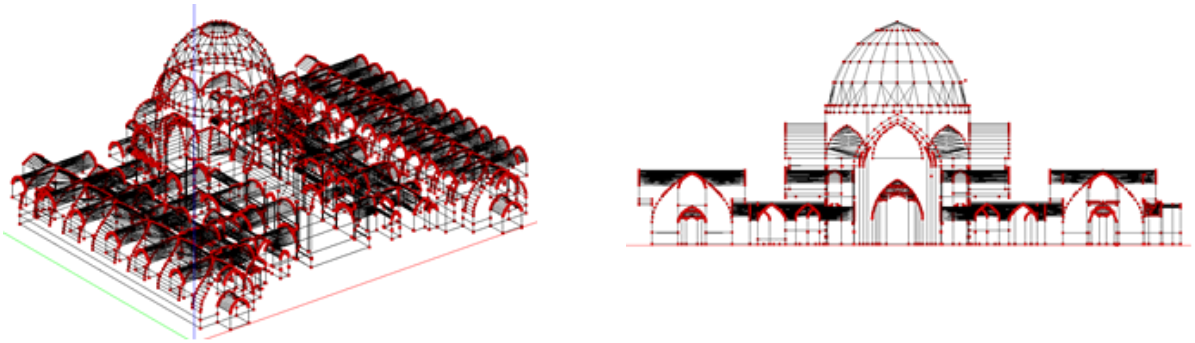


Fig. 7:a)Simulation of the dome and adjacent spaces in EASE showing volume (without squinches and muqarnases), b) Simulation of the dome and adjacent spaces in EASE showing elevation (without squinches and muqarnases)

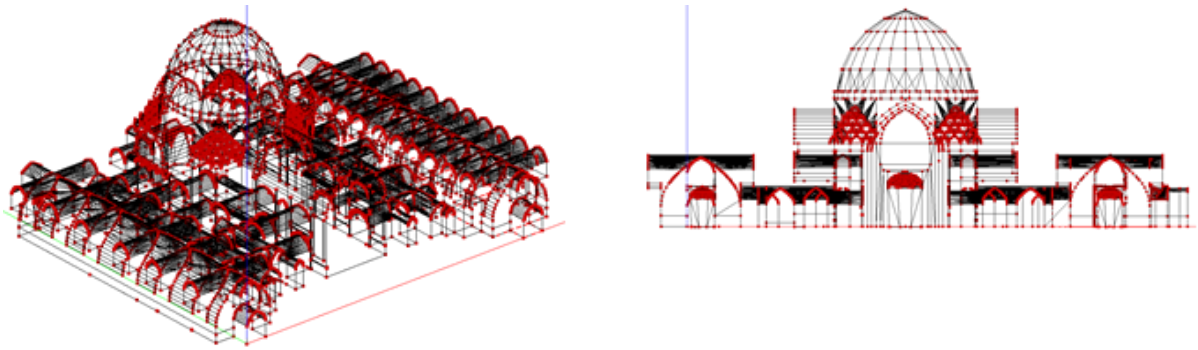


Fig.8:a)Simulation of dome and adjacent spaces in EASE showing volume (with squinches and muqarnases), b)Simulation of dome and adjacent spaces in EASE showing elevation (with squinches and muqarnases)

5. Result and discussion

The simulated space does include decorative *muqarnases* on the *mihrab, squinches* under the dome, and *Karbandies* in the western and eastern prayer halls. Because acoustic design very much depends on the absorbing characteristics of the space, materials were carefully chosen in the simulation. Both simulations have different area surfaces; the table4 shows how they differed in this aspect.

Table. 4: Total area of each material in both simulations

Material(m^2) / Analysis	Tile	Plaster,7.8".gypsum or lime on Brick	Brick, Unglazed, Painted	Brick, Unglazed, Unpainted	Carpet	Average Absorption Area	Room Surface Area
Mosque without muqarnas	1275.26	6745	2151.50	860	1633	1261.01	12664.76
Mosque with muqarnas	1315	6762	2225.20	860	1633	1369.68	12795.2

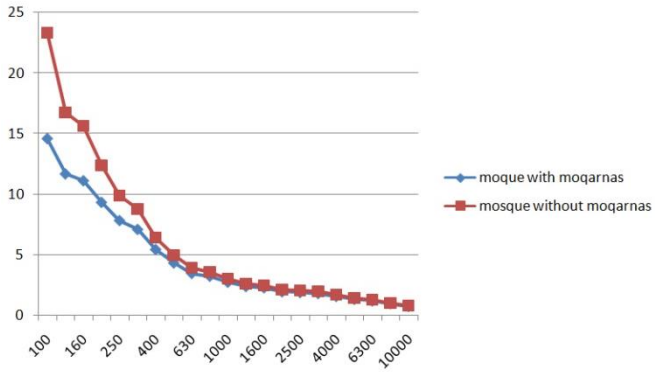


Fig. 9: Comparing Reverberation time in mosques with and without muqarnases

Table. 5: Comparing Reverberation time in mosques with and without muqarnases

Frequency(HZ) / space	125	250	500	1000	2000	4000	8000
Mosque without muqarnas	16.76	9.89	4.94	2.99	2.10	1.67	1.03
Mosque with muqarnas	11.68	7.84	4.35	2.76	1.98	1.60	1.00

It is expected that due to the increase in total surface area and the number of surfaces, reverberation time will decrease. According to Table 3**Error! Reference source not found.**, the

Jaame mosque is in group f; thus its reverberation time graph should be calculated as per Fig.5 and EASE analysis. Also, reverberation time should be evaluated in 300 to 4000 frequencies as people mostly speak in this range [17]. By comparing Fig.5 and Table. with Fig.5, reverberation times in both calculations show a 5-second variance in low frequencies. This variance reveals that *muqarnases* on the *mihrab* and under the dome have significant impacts on absorbing sound in low frequencies (Figure 6-7). Materials of said elements, such as the *mihrab's* tilework and brick and glazed brick of the *squinches* beneath the dome, absorb low frequencies conveniently. By excluding complexities, we analyzed how the massing of the dome affects the sound. An increase of reverberation time in low frequencies is due to a concentration of sound waves by the dome.

In the next step, we examined how a simplified dome, convergence, and *squinches* beneath the dome affect reverberation time. We altered the distance between the *squinches* and the dome's focal point. Small changes in reverberation time in low frequencies were witnessed. This showed that increasing the distance of decorations, for example, *muqarnases* or *squinches*, from the dome, slightly improves reverberation time.

Table. 6: How the distance of the squinches from the focal point affects RT

Frequency(HZ)	125	250	500	1000	2000	4000	8000
Current State	11.68	7.84	4.35	2.76	1.98	1.60	1.00
Shifting squinches0.5 m	11.67	7.84	4.35	2.76	1.98	1.60	1.00
Shifting squinches 1 m	11.67	7.84	4.35	2.76	1.98	1.60	1.00
Shifting squinches 1.5 m	11.66	7.83	4.34	2.76	1.98	1.60	1.00
Shifting squinches 2 m	11.65	7.83	4.34	2.76	1.98	1.60	1.00
Shifting squinches 2.5 m	11.65	7.83	4.34	2.75	1.98	1.60	1.00
Shifting squinches 3 m	11.64	7.82	4.34	2.75	1.98	1.59	1.00
Shifting squinches 3.5 m	11.63	7.82	4.34	2.75	1.98	1.59	1.00

After analyzing the resultant reverberation time from both simulations, we examined how the distance of the *squinches* from the focal point under the dome and the source of the sound –e.g., the Imam- affect sound (Table 6). We divided the distance into seven, 50 cm phases. *Squinches* were placed at a distance of 0.5 meters to 3.5 meters from the focal point. The following table shows how distance affected reverberation time (Figure 10).[16]

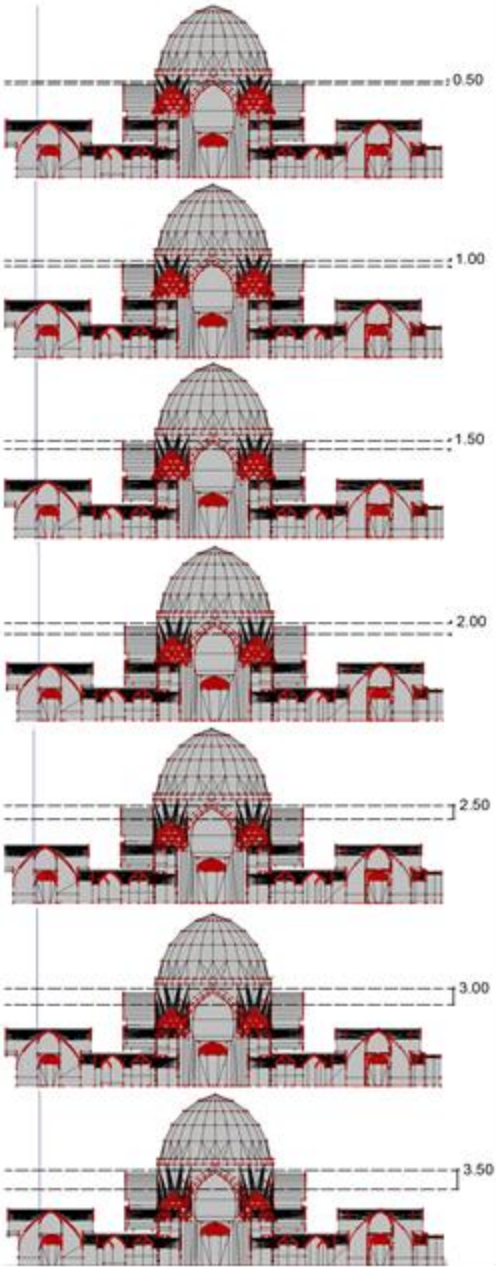


Fig.10: Simulation of different distances of squinches to the focal point (dome-space and adjacent spaces in EASE)

After that, the impact of bricks, mortar joints, and detailing was assessed. In our simulations, lattice brickwork, brick surfaces, and mortar joints were not analyzed. Bricks and mortar joints act like perforated panels in low frequencies. Ghaffari has shown this in the mosques of the bazaar of Tabriz. With simulations and fieldwork, he calculated a desirable 4.3 to 5 seconds reverberation time in these Qajar mosques[17]. Since ebbs were excluded from brick decorations and because of software limitations in creating details like mortar joints, we can presume that reverberation time in lesser frequencies must be lower. In every 1 square meter of brick surface,

by including mortar joints, the total surface area will increase by 1.4 square meters. Per Sabine's reverberation time formula, for an entire area of 3085.20 of glazed and unglazed brick and a 0.4 square meter increase in every 1 square meter of brick surface, reverberation time in lower frequencies will decrease by 10% (Formula 1).

$$T = 0.16 \frac{V}{\sum \alpha S} \tag{1}$$

Descending reverberation time in low frequencies as in Table7 shows acoustic comfort in this environment. Including mortar Joints in simulations decreased reverberation time in frequencies 300 to 4000, to a minimum of 1.44-seconds and a maximum of 7.05-seconds. Median reverberation time in the Jaame mosque, calculated by the formula 2 is 3.33 seconds. Comparing to Table 5, this number has a 1-second variation in median reverberation time. This median reverberation time shows us that even though the mosque has many parallel walls echoing sound and a dome converging waves, the intensity of low voice is substantially decreased, resulting in a desirable acoustic experience[17].

$$RT_{SPEECH} = \frac{RT\ 250 + RT\ 500 + RT\ 1000 + RT\ 2000 + RT\ 4000}{5} \tag{2}$$

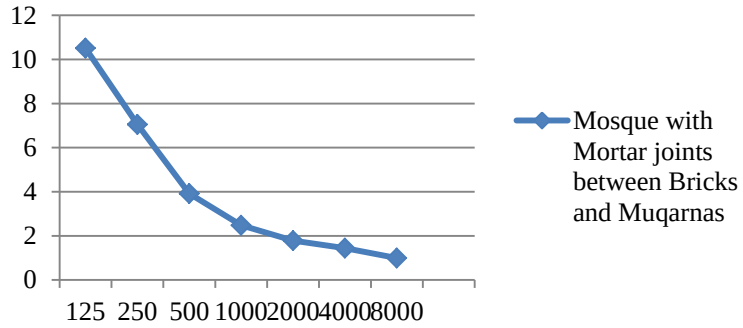


Fig.11: Diagram of Reverberation Time including aforementioned 0.4 square meter increase

Table 7 Reverberation time including 0.4 square meter increase on brick surfaces (mosque with muqarnas)

Frequency(HZ) / Place	125	250	500	1000	2000	4000	8000
RT in mosque with muqarnas	10.51	7.05	3.91	2.48	1.78	1.44	0.99

6. Conclusion

Considering all parameters analyzed in this study, it can be said that the Jaame mosque of Yazd has a desirable acoustic environment. Two examinations were executed to establish this. First, the mosque was modeled without *muqarnases*, *squinches*, and brick decorations on the body of

the dome-space and adjacent spaces. The resulting reverberation time in low frequencies was considerably long. The absence of the above-mentioned features causes sound waves to converge, subsequently increasing reverberation time in low frequencies. By adding *muqarnases, karbandies*, and absorbing surfaces such as decorations and mortar joints, reverberation time in lesser frequencies was substantially lowered. This also stopped sound waves from converging. Even though *muqarnas* and *Karbandies* are constructed of reflective materials, namely tiles and glazed brick, due to an increase in total surface area and their form, reverberation time decreases. Adjusting the distance of these elements from the focal point of the dome also impacts reverberation time. Basically, as *muqarnases* and *Karbandies* near the floor, reverberation time decreases. Analyzing the impact of said surfaces on reverberation time, and comparing the acoustic qualities of a mosque to a church, it can be claimed that because congregations tend to sing more, longer reverberation time is preferable. On the other hand, sermons and speech are more common in mosques; thus space should be designed so that everyone can grasp the imam's preaching. Mortar joints, *muqarnases,* and *Karbandies[18]* break sound waves, preventing focus on one point, thus reducing reverberation time as well as creating a superior acoustic experience for the faithful. Details, massing, form, and materials as well as recesses –such as women's praying space- dovetail to control sound and reverberation time, producing a desirable acoustic environment for all.

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