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THE ACOUSTICS OF THE LONGOBARD CHURCH OF SANTA SOFIA IN BENEVENTO

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Abstract. This paper presents the results of acoustic measurements carried out in the Longobard church of Santa Sofia in Benevento (Italy). The church is on a central plan, with a diameter of 23.5 m. In the centre there are six columns, placed at the vertexes of a hexagon and connected by arches which support the dome. Around this central hexagon there is a second decagonal ring, with eight pillars of white limestone blocks interspersed with layers of bricks; and two columns immediately after the entrance. The acoustic measurement were done with a sound source on the altar, and the microphone points in the area were seat people. The average value of reverberation time at the frequency of 1.0 kHz was about 1.5 seconds, so the church can be used for good listening of symphonic music.

Keywords: church, acoustic measurements, impulse response, reverberation time

Mathematics Subject Classification: Primary 68-04, 08A72; Secondary 28-04

1 Introduction

Music and architecture are linked by complex characteristics related to the concepts of space, and they are sciences that have evolved together [1, 2, 3]. The composers created their works even taking into consideration the acoustics of the environment in which the music was to be performed. Furthermore, the relationship between music and architecture has always been clear to musicians rather than architects. In the past, architects had no knowledge of indoor acoustics. Towards the end of the 1800s the notions of architectural acoustics began to be clearer thanks to the studies of W. C. Sabine, the father of modern acoustics, who considered the acoustics of the closed environments influenced the composition of the musical works [4]. From the origins of the Christian world, music has always been considered as a means of bringing together the values of faith and as a means of elevation and salvation. The first Christian songs were in Hebrew and Aramaic, then in Greek and finally in Latin. They formed a repertoire that was fully codified only between the 5th century and the end of the first millennium. The typical song was with a single voice sung by males without instruments (because the instruments were associated with pagan festivals). An important liturgical song is the Gregorian chant. The name of the "Gregorian chant" comes from Pope Gregory who

included the accounts in the liturgical reform. Gregorian chants were best performed in the wide cathedrals, in fact the melody of Gregorian chants exploits the advantage of the long reverberation of the Romanesque and Gothic churches.

2 The acoustics of the churches

In the study of the acoustics of large environments, the focus is on aspects related to the physical and geometrical characteristics [5, 6, 7]. The churches are acoustically complex places because of the size of the volumes and the reflecting materials of which the walls are made and the absence of adequate sound-absorbing surfaces. Audience has the responsibility of most sound absorption, consequently acoustic conditions vary between the conditions of empty church and occupied church. One of the most used acoustical descriptors for evaluating the goodness of a room is the reverberation time (measured in seconds). This parameter was introduced at the end of the 1800s by Sabine and is defined as the time interval in which the sound energy decreases by 60 dB after switching off the source. In a room the longer the reverberation time, the greater the contribution of the components of the reflected sound compared to the direct one. The value of the reverberation time is a function of the volume of the room and of the total sound absorption of its internal surfaces. A short reverberation corresponds to a dull room, in which the surfaces absorb most of the sound energy and, as in the open air, the sound coming directly from the source is weakly reinforced. During the celebration of a liturgy different types of sound messages coexist, each of which requires different acoustic conditions. The organ music requires a long reverberation (> 3.0 seconds) but the instrumental music that sometimes requires a reverberation of 1.5 seconds. The readings and sermons require a short reverberation (< 1.0 seconds) to give good speech intelligibility while the Gregorian chants require reverberation 2.0 seconds to encourage a sense of community participation. To have good acoustics for all parts of the liturgy, a church should be transformed into a sophisticated hall of variable acoustics. The ideal values have been developed as indexes based of widely share perceptions. But derive from studies perfomed in concert halls, conference venues and theatres that do not have a high geometric variability. In addition, the churches can vary in size from a few hundred cubic meters to a small chapel; to several hundred thousand for a large basilica [8].

3 The church of Santa Sofia

The church of Santa Sofia was built by the Duke Gisulfo II and completed by Arechi II. It was built next to a Benedictine abbey, was completed in the year 762, as the Church of the Longobard people, and it was the most daring and imaginative construction of the high Middle age. Arechi II annexed a community of nuns, and entitled the Santa Sofia, that is, to the Holy Wisdom. The church of Santa Sofia is a building of exceptional interest in early medieval architecture. It is of modest dimensions, contained as it is within a circle of only 23.5 meters of diameter, and average height of 8.0 metres, the dome height is 14.0 metres. The general plan is original and entirely new for the time, not derived from Roman or Byzantine examples. The church has a central nucleus consisting of a hexagon whose vertices are placed six columns connected to each other with arches on which the dome develops. Around this central hexagon is a second decagonal ring, with eight pillars of white limestone blocks interspersed with layers of bricks and two columns immediately after the entrance. The pillars are radially arranged, each with the sides differently oriented, so as to make them parallel to the back walls of the perimeter. The course of the external walls is first circular, but at a certain point it is interrupted by star-shaped walls to return again to the circular at the entrance portal. All this creates games of perspectives, decompositions, closures of spaces

coordinated with precise geometrical effects and based on reciprocal relationships, the result of an acute and original constructive intelligence. For example, the extraordinary variety of vaults, due to the unusual coupling of the hexagonal crown with the decagonal one: the succession of quadrangular, then rhomboidal and finally triangular folds is probably a reference to the shape of the tents used by the Lombard people during its long wanderings in Europe. The church of Santa Sofia has not always maintained the same appearance over the centuries. In the twelfth century, the church underwent a first restoration that, leaving intact the original plan, added a bell tower on the left side of the small facade and an elegant portico at the entrance, resting on four columns. The earthquake of 1688, which razed the city to the ground, caused enormous damage even in the church of Santa Sofia. The whole structure was damaged: the central hexagonal dome in wedges collapsed, much lower than the current one and without openings; the Romanesque bell tower overturned on the roof, completely destroying it. With the reconstruction in baroque forms of 1698 (and the further modifications following the subsequent earthquake of 1702) radical changes were made that led to the disappearance of the primitive Longobard configuration and caused the almost complete destruction of the precious frescoes of the IX century. The interventions consisted, among other things, in the transformation of the plant from star to circular, in the demolition and reconstruction in new forms of the central apse, in the tapering of the eight pillars and in the construction of the new façade, which still exists today. There were also two side chapels and the sacristy. The interior was completely plastered and furnished according to the Baroque taste. In 1951 the restoration work began, which, with scrupulous interventions, allowed to bring to light the original Lombard structural structure and then complete the demolished or tampered parts during the baroque transformation. In particular, the two chapels on the side of the façade, the central apse and the circular wall which had incorporated the outer edges of the star walls were eliminated and the walls were rebuilt following the indications provided by the archaeological research [9, 10, 11]. Fig. 1 shows the external view of the church. Fig. 2 shows the aerial view of the church. While Fig. 3 shows the plant and the section of the church with the main dimensions.

Fig. 1. External view of the church.

Fig. 2. Aerial view of the church

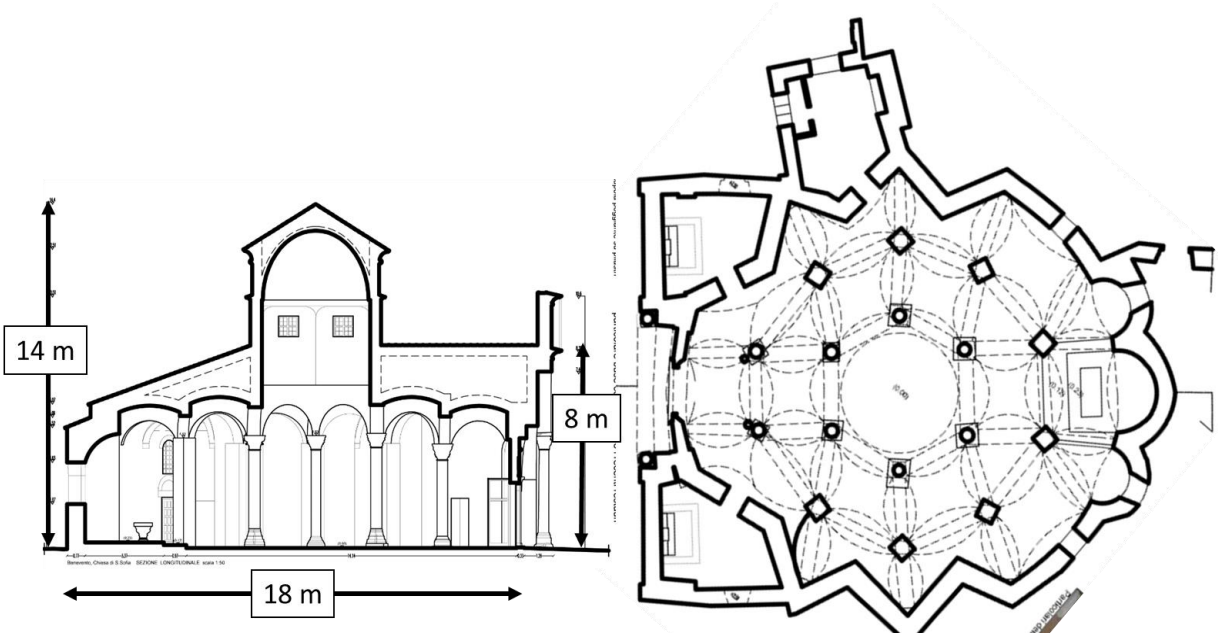

Fig. 3. Plant and section of the church with the main dimensions.

4 Acoustic measurements

The acoustic measurements were carried out with a spherical omnidirectional sound source located on the altar and 8 microphone points of measurement placed in different positions, in accordance with ISO 3382-1 [12]. The measuremt points were at height of 1.60 m from the floor, in an area occupied to the listeners. The sound source was powered by MLS signal, the processing of impulse responses had been analyzed by the Dirac 4.0 software. Fig. 4 shows the plan of the church with the indication of the source and of the receiver microphone points. The recorded impulse responses were then elaborated with the software Dirac 4.0, and the

several acoustic parameters defined in the ISO 3382-1, such as the early decay time (EDT), reverberation time (T30), the clarity (C80), the definition (D50), and the sound transmission index for speech intelligibility (STI) were analysed. In room acoustic evaluations, the clarity represents the degree to which different reflections arrives and are perceived by the listener, and it is assessed as an early-to-late arriving sound energy ratio. This ratio can be calculated for either a 50 ms or an 80 ms early time limit, depending on whether it relates to conditions for speech or music respectively. The definition considers the early arriving sound energy over the overall sound energy and, similarly to the clarity, it can be calculated for either a 50 ms or an 80 ms early time limit. The Speech Transmission Index (STI) represents the degree of amplitude modulation in a speech signal and it refers to the distortion in speech signals caused by reverberation, echoes, and background noise. In particular, typical suggested values of the different monaural acoustic parameters for both the speech comprehension and music listening are [13]:

- the reverberation time T30 should assume values below 1 second for a clearer perception of speeches, while it may assume greater values, around 2 seconds for music listening preference;
- the clarity C80, expressing the balance between the early and late arriving energy, should have a higher value if the goal is to separate the initial sounds from the diffuse ones and making the discrete sounds stand apart from each other. In a sound field which is not completely diffuse, the clarity C80 is uncorrelated to the reverberation time, and for the purposes of good listening conditions of music is generally reported that C80 should be in the range between -2 dB and 2 dB, while it is expected to be above 2 dB if speech perception is a priority;
- the definition D50 may assume values from 0 to 1, but for a good speech comprehension, it is often accepted that D50 should have values above 0.50;
- the indices STI can take values between 0 and 1, being greater than 0.5 for favourable speech conditions.

The acoustic procedure and post processing methodology were similar to those used in other spaces, such as the large theatre of Pompeii [14], the theatre of Benevento [15], as well as in many other ancient theatres and places [16, 17, 18]. Table 1 shows the optimal values of the acoustic parameters for the different listening conditions, from which it is noted that for an environment intended for speech an optimal reverberation time of less than 1.0 seconds is required. The Fig. 5 shows the average values and standard deviation of the acoustic parameters in the octave band from 125 to 4.0 kHz of the eight measurement points.

Parameters	EDT, s	T_{30}, s	C_{80}, dB	D_{50}
Optimal values for musical performances	$1.8 < EDT < 2.6$	$1.6 < T_{30} < 2.2$	$-2 < C_{80} < 2$	< 0.5
Optimal values for speech performances	1.0	$0.8 < T_{30} < 1.2$	> 2	> 0.5

Tab. 1. Optimal acoustic parameters values for the different listening conditions

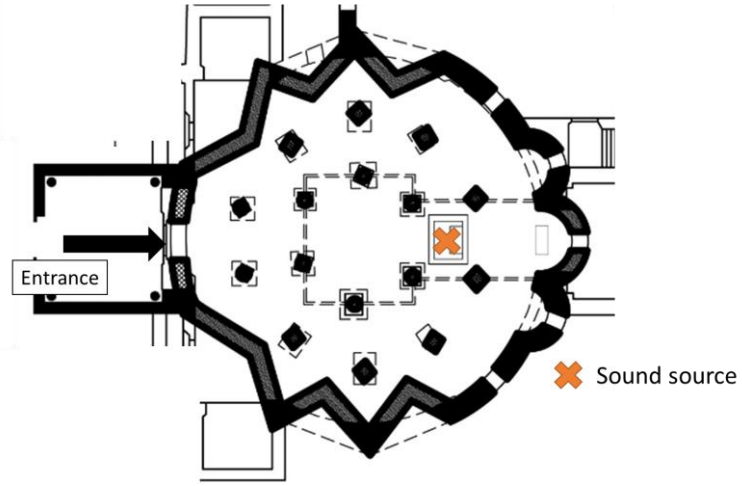

Fig. 4. Position of the sound source on the altar

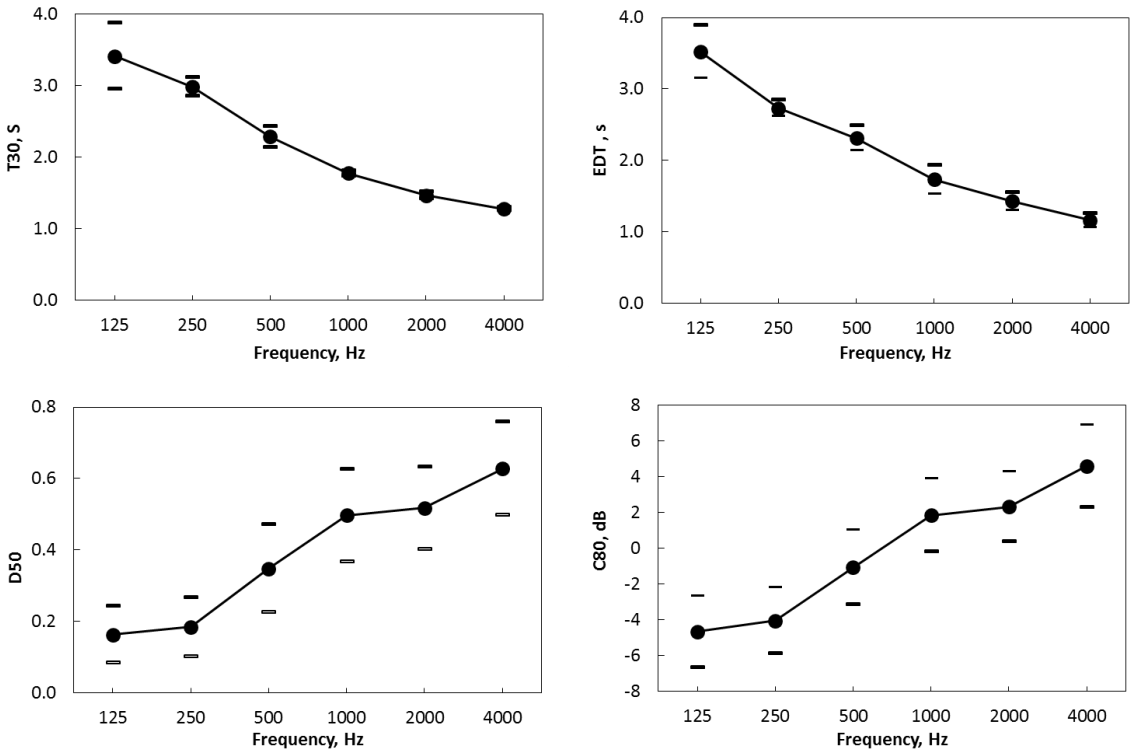

Fig.5 Average values of the acoustic parameters measured and standard deviations.

5 Discussion

The values of EDT and T30 at the low frequencies and around 3.5 seconds while at medium frequencies and on the order of 1.5 seconds. T30 and EDT decrease rapidly as the frequency increases. The values of the standard deviation are small at medium frequencies, while at 125 Hz the value of the standard deviation is greater, the spatial parameters at this frequency chenge with the measuremnt positions. So for D50 and C80 the values of the standard

deviation vary significantly, this variation means that the acoustic parameters D50 and C80 change from point to point.The value of C80 reflects the trend of the reverberation time is less than - 2 dB at low frequencies at medium frequencies is around 0 dB. Similarly for the value of the definition which is greater than 0.5 for frequencies above 0.5. The average value of the parameter STI = 0.5. The room does meet the criteria of good listening for the music and the speech.

6 Conclusions

This paper has discussed the acoustic characteristic of the Longobard church of the Santa Sofia in Benevento. The church built as a place of prayer for the nearby monastery; the church has been rebuilt many times because of the damage due to the numerous earthquakes. This place has good characteristics for listening to music and for understanding speech. The modest volume makes the acoustic characteristics are optimal.

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