Using a Church as a Temporary Auditorium. Acoustical Design of S. Domenico of Imola

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Abstract. In Europe, many of the ancient buildings, especially sacred architecture, are subject to renovation projects by converting their initial occupation type for temporary exposition. In particular, the demand for assisting to live musical performance is increased considerably in Italy because of the missing of places dedicated to the performing arts. As such, one of the churches of Imola (i.e. San Domenico), located approximately 30 Km far from Bologna, has been requested by citizens to be adapted into an auditorium when necessary. Based on needs expressed by the local population, this paper recommends one of the possibilities of how the acoustical design can be applied to the church in order to adjust the main volume to the realization of transient musical venues, cancelling any undesirable reflections that can lower the quality perception of sound. The actual acoustics has been adapted in order to reach both speech and musical intelligibility, especially focused on sacred music style. Both measured and simulated results have been compared determining the choice of the proposed acoustical solutions in terms of type of finishes and surface area to be covered by the added materials. The suitable treatments in consideration include absorbing wooden panels, curtains and fabric wrap.

Keywords: Acoustic design, Italian church, auditorium, sound perception.

1. Introduction
San Domenico church of Imola assisted its construction throughout five centuries, starting during the Middle Age (i.e. second half of the XIII century) in gothic style and had various expansions till the XVIII century, when Napoleon conquered the lands of northern Italy [1]. Given the historical importance of this church, which testifies the different phases of construction promoted by the power of the clergy and of the state governing alternatively throughout the time, the proposed acoustical project has the intention to do not destroy any of these testimonies and thus it should be considered as not invasive nor permanent operation, but reversible and adjustable to the reverberation time (RT) that each composer requires for his music. The changes and modifications have been designed for temporary venues and hence to be installed and uninstalled easily and in a short period [2].

2. Historical background
In 1249, the Dominicans established in Imola one of the first communities of northern Italy as planned by the development of their religious order. As such, they decided to build a place of prayer (i.e. chapel of S. Nicolò) that became the core of the entire complex, as shown in Figure 1-6.
Because the followers became so many and they felt tight to pray altogether in that chapel, the needs to build a bigger church rise up soon. Between 1280 and 1287 the construction of the church started from the apse, as Figure 2 shows clearly, and the completion of the whole volume was allowed by Pope Benedict XI and occurred in less than a century from that date, as Figure 3 shows below.

During the Renaissance, the development of the press advanced by Gutenberg promoted the circulation of a consistent number of books more freely available; consequently, the necessity of reading in peaceful and comfortable places brought to the birth of a new library dedicated to the monks [2], as shown in Figure 4. After the construction of the chapel of the Rosary on the east side of the transept, the invasion of French soldiers guided by Napoleon transformed the dormitory of the monks into a military barrack (highlighted in red in Figure 5), leaving the church undamaged.

Differently from the convent, that was modified to accomplish the military requirements, the church, fortunately, was not altered and thus it has been maintaining its architectural design since 1718 [2].

3. Geometry and architectural organization
S. Domenico church has a plan layout of a single barrel nave in baroque architectural style, having three framed niches per side, with the symmetrical windows openings above each niche. At the transept level, as demonstrated by Figure 7-8, the cavity on the east side hosts the chapel of the Rosary, surmounted by an elliptical dome in baroque style as well, as shown in Figure 9-10. The apse has a geometry of half decahedron, having a wood choir whose seats are installed along the edges of the perimeter.
If compared with other rooms [3, 4], in which also other physical parameters were evaluated [5, 6] the combination of plaster and stone on the walls and the vaulted ceiling, with the addition of tiles on the floor, makes this main volume very reverberant [7, 8]. Furthermore, the presence of a circular dome at the centre of the Latin cross plan accumulates the sound energy with the effect of a beneficial small delay that strengthens the sound for the last rows of seats placed closer to the entrance [9].
4. Acoustical measurements

4.1. Equipment
The acoustical measurements were undertaken following the methods developed by Farina and Tronchin [10, 11] with the following equipment:
- Equalised omnidirectional loudspeaker (i.e. LookLine), shown in Figure 12;
- Binaural dummy head (i.e. Neumann KU-100), shown in Figure 13;
- B-Format microphone (i.e. Soundfield MK-V), shown in Figure 13;
- Personal Computer connected to a loudspeaker and two receivers.

The excitation signal to measure the impulse response (IR) of the room was an exponential sine sweep (ESS), having a frequency range set between 40 Hz and 20 kHz. The IRs acquired by the microphones were stored in a 20 bits 96 kHz sample rate soundboard (i.e. Layla).

4.2. Sound source positions
The sound source was located in 2 different positions:
- At the junction of the two wings of the cross, and
- Onto the presbytery stage.

Figure 11-13 gives a schematic view of source and microphone positions. The loudspeaker was not installed along the median axis in order to avoid focal effects owed to the surmounted circular dome, which have a strong influence on the subjective acoustic perception [12]. As such, the selected two spots simulate the location of two random musicians playing onto the performing stage.

The measurements were performed similarly to those conducted on musical instruments [13, 14] aiming to consider also the effect of vibrating panels, [15, 16, 17] in order to consider, during further analysis, also their nonlinear components [18, 19, 20] similarly to the loudspeakers.

4.3. Microphones positions
The dummy head and the B-Format microphones were moved coupled in 32 positions across the nave in order to represent as much as possible all the audience seats [21], which has also been simulated in further similar studies [22].

Figure 11. Source and receiver positions.

Figure 12. Omnidirectional sound source.
4.4. Measured results

The data analysis, based on measured parameters summarised in Table 1, shows that the RT resulted between 4s and 6s [23] mainly at low frequency bands, which is significantly high, and hence not matching the criteria neither for live music nor for speech intelligibility [24]. Also the other acoustical parameters resulted out of the target range, demonstrating that the perception of sound and speech, with these acoustical features, is very difficult to be understood by listeners [25], requiring a proper acoustic design, considering a multi scale analysis in a sustainable perspective [26].

Table 1. Values of measured acoustical parameters.

| Hz    | 63  | 125 | 250 | 500 | 1000 | 2000 | 4000 |
|-------|-----|-----|-----|-----|------|------|------|
| $T_{20}$ | 6.3 | 5.9 | 5.6 | 5.00 | 4.6  | 4.0  | 3.0  |
| EDT   | 7.5 | 6.9 | 6.4 | 5.6 | 5.0  | 4.0  | 2.7  |
| $C_{50}$ | -11.5 | -11.1 | -10.8 | -10.2 | -9.7 | -8.8 | -7.1 |
| $C_{80}$ | -8.6 | -8.1 | -7.8 | -7.1 | -6.6 | -5.6 | -3.8 |
| $D_{50}$ | 6.6 | 7.2 | 7.7 | 8.7 | 9.6  | 11.6 | 16.2 |
| Ts    | 522 | 478 | 445 | 384 | 345  | 284  | 202  |
| G     | 10.2 | 9.8 | 9.4 | 8.6 | 8.1  | 7.3  | 5.8  |
| STI   | -   | 0.37 | 0.38 | 0.41 | 0.43 | 0.47 | 0.55 |

Another great contribution that influences the acoustical results is the presence of the chapel of Rosary, opened laterally to the transept, which behaves like a big resonator giving back the delayed reflections after bounced at the boundaries surfaces of the chapel [27].

5. Architectural-acoustics design

Aiming to adapt the acoustics to musical performances, the proposed project takes into account also the preservation of the archeitectonic elements that characterize a palimpsest of architectural styles overlapped throughout the centuries. As such, the proposed measures can be considered as completely reversible. When the church hosts the musical performance, the temporary conversion to an auditorium has been planned to have a capacity of 410 seats allocated along the nave [28], as shown in Figure 14.
Two fire exits have been introduced between the 2nd and the 3rd niches of the nave, separating by a corridor the rows of seats into two areas: one closer to the stage and the other one arranged onto the stalls, along all length of the nave. Beneath the highest seats of the sloped stalls, a cloakroom and a box office can be allocated. Services and washrooms have been assigned to the western extension of the church, externally to the auditorium.

5.1. Stage and acoustic shell
The stage would be covering all the transept area of approximately 80m² and raised up to the level of the presbytery with a light structure of a wooden frame, where an orchestra of 50 elements can be comfortably distributed over the space. The raised stage would have a double purpose: it will improve the sight from the audience seats and also it will stand for a resonance box because of its light wooden frame, solving partially the booming effect at low frequencies [29].

In order to reinforce the sound towards the audience and avoid undesirable delayed reflections, an acoustical shell would be added. The slightly curved geometry, as the section of Figure 14 highlights, has the function of cutting off the focal effect created by the circular dome above the stage, changing in this way the directivity of the emitted sound that was spread out in various directions otherwise [30]. The shell was designed to be made of painted wooden panels on the lower part and synthetic transparent glazed sheets on the upper portion. All the panels will be assembled onto a metal frame tensed in a reticular configuration [31].

Keeping the principle of transparency, the shell has been intended to be open to the lateral sides of the stage, leaving the visibility of the stucco decorations onto walls and vaults.
5.2. Acoustic treatments

The reversible approach of the acoustic design is given by different types of treatments:

- Installation of wooden panels. The acoustic panels (drawn in red) are composed of 2 layers of plywood (i.e. 5mm thickness) separated by a 50mm gap filled with batt insulation (i.e. glass wool). Acoustic panels have broadband absorption, mainly spread over the mid-frequency bands;

- Placement of heavy curtains. Heavy curtains (drawn in blue) have been thought in line with the popular feast decorations settled during religious events. As such, the curtains have the purpose of shielding some reflecting surfaces (e.g. glass of windows) and also of separating different volumes, like the chapel of Rosary from the main hall. Heavy curtains are very absorbing at mid-high frequencies [32];

- Fabric wrap. Heavy fabric (drawn in yellow) has been chosen to wrap the columns with the purpose of reducing the overall RT. Having a cream colour, this treatment should not have a strong visual impact [32].

Figure 15. Acoustical design with applied wooden panels (red), curtains (blue) and fabric wrap (yellow)

From the transversal section on the left side of Figure 15, it is possible to see how the curtains separate the main hall from the chapel of Rosary. Wooden panels are necessary also on the back wall, where the main entrance is located, so that longitudinal standing waves can be neutralized [33].

Figure 16. The acoustical design represented in longitudinal section.
These interventions have also been evaluated in a cost-optimal perspective, in order to keep the costs as reasonable as possible, as in case of energy refurbishment of buildings [34].

6. 3D modelling and simulations
The aforementioned acoustical treatments were included in a digital 3D model (see Figure 17), realized with Ramsete software, which calculates the ray-tracing reflections based on pyramidal (instead of conical) spreading. The source and receiver positions were reproduced at the same location of the real measurements.

![Figure 17. 3D model by using Ramsete](image)

![Figure 18. Comparison of measured and simulated results](image)

By applying the acoustical treatments as discussed into Section 5, the booming effect at low frequencies is now controlled, and also the clarity index is lowered [35]. Based on the results obtained, the acoustics of the temporary auditorium is more suitable for sacred musical performances, as planned initially by the project intentions, but it is acceptable also for other forms of classic music [36]. Table 2 below summarizes all the acoustical parameters.

| Hz   | 63  | 125 | 250 | 500  | 1000 | 2000 | 4000 |
|------|-----|-----|-----|------|------|------|------|
| T_{20}| 2.8 | 2.9 | 2.4 | 2.0  | 2.6  | 2.6  | 2.3  |
| EDT  | 2.5 | 2.7 | 2.2 | 1.8  | 2.3  | 2.3  | 2.1  |
| C_{50} | -6.1 | -6.5 | -5.7 | -4.8 | -5.9 | -6.0 | -5.5 |
| C_{80} | -3.7 | -4.0 | -3.2 | -2.1 | -3.4 | -3.4 | -2.9 |
| D_{50} | 19.5 | 18.4 | 21.0 | 24.9 | 20.6 | 20.2 | 22.0 |
| Ts   | 187 | 199 | 168 | 140  | 175  | 175  | 161  |
| G    | 6.8 | 6.6 | 5.8 | 4.8  | 5.7  | 5.7  | 5.3  |
| STI  | -   | 0.54| 0.58| 0.63 | 0.57 | 0.57 | 0.59 |

The Figure 19 to 22 summarize a few maps of the main acoustical parameters, showing the difference between measured and simulated values after the applied acoustical treatments [37]. From this comparison it is possible to see the improvements in terms of sound quality, as shown by the contour levels over all the plan layout [38-40].
7. Conclusions
Given its historical background, Italy has a huge sacred architectural patrimony (e.g., churches and convents) dislocated even in small towns like Imola. On the other side, the lack of concert halls and auditoria stimulates the local authorities to incite the refurbishment of ancient buildings and the transformation into new places for listening to live music, in order to accomplish the needs of the population. The proposed idea to convert San Domenico church into an auditorium for temporary venues seemed too hard in absence of an appropriate acoustical design. As such, the authors gave some suggestions to reduce external noise and the RT [41-45] and match the target of classic music [46-50], in particular the sacred style.

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