Digitally acoustic reconstruciton of the Roman theatre of Verona at its orginal shape

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***Abstract*—The Roman theatre of Verona became a place of live shows during the 1st century BC. After a florid period of its activity, the theatre has been decommissioned by the barbaric invasions other than by earthquakes and fire that occurred during the Middle Age. Many painters and architects tried to sketch and draw the possible shape of the Roman theatre of Verona, by giving personal interpretations, resulting sometimes deviated from the original configuration. During the 20th century the archaeological excavations brought to the discovery of few construction elements that contributed to obtaining a clearer idea of how the theatre should be erected in the missing parts. The acoustics measurements undertaken with the existing conditions have been compared with the acoustic simulations derived from a digital reconstruction of the original volume size.**

Keywords—Roman theatre, acoustic measurements, digital reconstruction, Ramsete, acoustic parameters.

I. Introduction

The original shape of the Roman theatre of Verona has been subject to many discussions throughout the centuries [1-5]. A variety of hypotheses has been raised by architects and painters, based on their knowledge of the archaeological site [6]. All the possible reconstructions have been achieved on paper drawings, with the exception of a scaled model realized in 1997 by the architect G. Anselmi, built on the track of Palladio's ideas [7-10]. The authors of this paper deal with a faithful reconstruction of the original shape based on the comparison of historical documents, iconographies, publications, drawings, and sketches executed throughout the centuries for the Roman theatre [11-13]. The realization of a 3D model representing the theatre at its original configuration brought to the analysis of the acoustic parameters, which have been compared with the results obtained by measuring the existing conditions [14-29].

II. Historical Background

The greatness of Verona, under an urbanistic perspective, became fame when the city was proclaimed *municipium* (town) by Julius Caesar in 49 BC [1]. The increased number of new neighborhoods brought to the development of public buildings, as the theatre was considered one of them, built on the slope of St Peter's hill [1]. The top of the hill was dominated by a temple dedicated to Jupiter, Minerva, and Juno [1].

Unfortunately, many disasters contribute to the disuse of such important monument, to be included the German invasions in 258 AC [2], river flooding [3], and a heavy earthquake in 1117 [4]. Also, the transformation to a cemetery caused the damage to the marble decorations [2] in combination with the development of the Christianism during the 5th century AC that was favorable to cover the theatre as a place of immoral shows [3]. During the Renaissance, private properties and the St Siro and Libera' church have been erected above the Roman theatre by taking advantage of the solid radial walls of the *cavea* [3], until all the area was bought by A. Monga, who was the first to plan some archaeological excavations [5].

It should be remembered that the painter G. Caroto [6] and the architect A. Palladio represent the first scholars of the 16th century to pay the intention of drawing the original architectural features of the theatre [2].

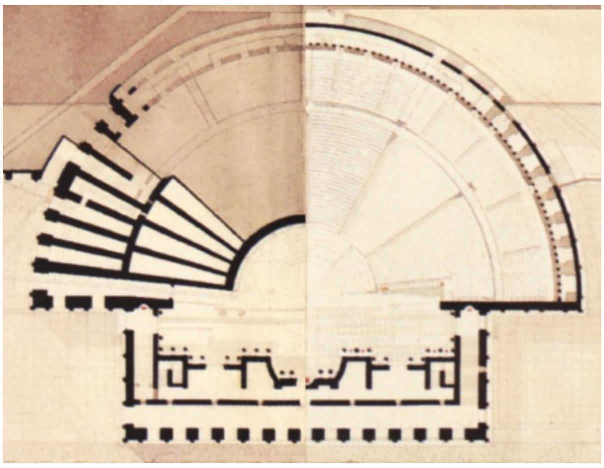

Fig. 1. Plan layout of the Roman theatre of Verona, drawn by E. Guillaume when he arrived in Verona in 1860 [7][7].

Both Caroto and Palladio added some personal interpretation in trying to evoke the internal organization of the theatre other than the configuration of other public buildings located in the same area. As such, the documents produced by accredited scholars of the history contributed to raising some confusion in comparison with the discoveries obtained by the excavations.

The burial of the theatre finished in 1842 when Monga unveiled the steps of the *ima cavea* [5] while E. Guillaume collaborated with Monga in drawings the ruins as they have been found on site [7]. The graphical elaborations by

Guillaume have been collected in a Memoire, as shown in Fig. 1.

The task of gathering information about the site was continued after the Monga's death, in particular by S. Ricci, who undertook a photographic survey of the theatre nowadays representing an inventory book [5].

When the Monga's property has been sold to the local municipality, further works continued in the same area during the 20th century, involving also the demolition of the last residential properties and the removal of filling material that obstructed the cavities [8][9].

III. ARCHITECTURAL CHARACTERISTICS

The theatre of Verona has been classified by history as a Greek-Roman construction, but it is most likely that the Romans adapted the project to the topography of the site [10][4]. The scenic building is erected only in few parts allowing the reconstruction of the three niches: the circular one at the center (*valva regia*) and the two laterals (*hospitalia*) have a rectangular shape [1][3][7]. The scenic building had a width of 6 m, a height of 27 m and a length of 72 m, reflecting the rules dictated by *Vitruvius* [11].

The *proscaenium* was 9 m wide against the front elevation and 15 m wide against the central niche [3]. The cavea was divided into two main sectors by horizontal corridors (*praecinctio*) [1]. The total capacity was of 3000 spectators, that is actually reduced to 2000 in relation to the existing conditions [2].

The *ima cavea* should have originally 25 steps having a difference of 9 m between the level of the 1st corridor and the orchestra floor [3]. The *summa cavea* instead should be composed of 12 steps [1]. A vertical stone sheet representing a backrest should be erected at the last row of seats of the *ima cavea* and at the beginning of the 2nd *maenianum*, working as a fence because of the level difference of 3 m between the first step of the *summa cavea* and the 1st horizontal corridor [12]. An idea of the architectural organization of the theatre has been given by E. Guillaume in Fig. 2.

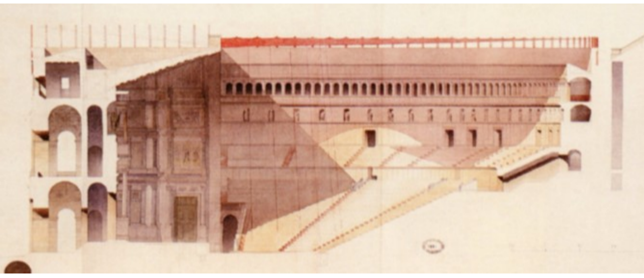

Fig. 2. Longitudinal section, E. Guillaume [7].

Fig. 2 shows the presence of two galleries adjacent to the *parascaenia*; they gave the access to the orchestra; these galleries (*cryptae*) were partially covered [3].

The construction at the top of the *summa cavea* was called *ambulacrum*, being 2.3 m high and characterized by a decking level to be 4 m above the second horizontal corridor [3]. The *ambulacrum* was surmounted by a gallery of 5 m height characterized by arches on the internal elevation [4]. The roof of the gallery was 27 m high; this is the height difference considered with respect of the orchestra level, in accordance with the Vitruvian rules [11]. The theatre was covered by a *velarium* in order to protect people by a shining sun. The velarium was hung by a reticular structure of wooden sticks inserted into the stones of the gallery [13].

TABLE I. summarizes the architectural features of the Roman theatre of Verona.

TABLE I. ARCHITECTURAL CHARACTERISTICS OF THE ROMAN THEATRE OF VERONA AT ITS ORIGINS.

Description	Features
Total capacity (No. of seats)	3000
Number of steps in *ima cavea*	25
Number of steps in *summa cavea*	12
Number of horizontal corridors (*praecinctio*)	2
Stage dimension (m) [L × W × H]	72 × 6 × 27
Presence of *velarium*	Yes
Cavea volume (m^3)	86500
Scenic building volume (m^3)	3000
Total volume (m^3)	89500

IV. MEASUREMENTS

An acoustic survey has been undertaken to understand the behavior of the existing conditions of the uncomplete volume of the Roman theatre of Verona. The analysis of the objective parameters has been done in accordance with ISO 3382-1 [14]. The acoustic survey was carried out with the following equipment:

- Equalised omnidirectional loudspeaker (Look Line);
- Microphones:
  - a) Binaural dummy head (Neumann KU-100);
  - b) B-Format (Sennheiser Ambeo);
  - c) Omnidirectional microphone (Bruel&Kjaer);
- Personal Computer.

The sound source was installed in the center of the orchestra at a height of 1.4 m. The receivers where moved to 11 positions across the *cavea*. The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) having a duration of 15 s in a uniform sound pressure level for the range between 40 Hz and 20 kHz [15].

The measurements were undertaken in unoccupied conditions. Fig. 3 shows the measurement positions of the equipment moved across the *cavea*.

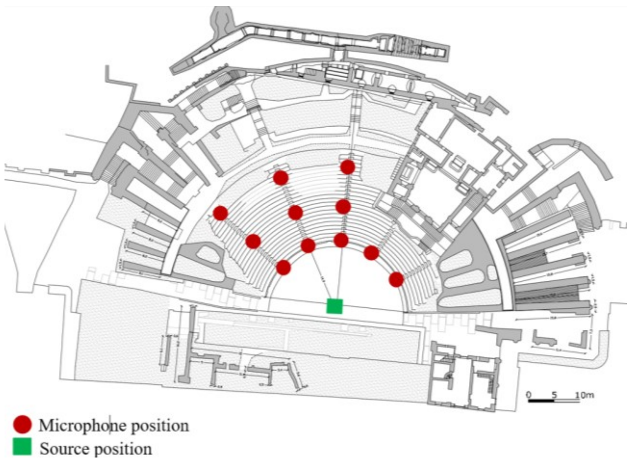

Fig. 3. Scheme of the equipment moved across the *cavea* during the acoustic measurements in Verona.

V. Digital Models

A. Existing conditions and coefficients calibration

Before proceeding with the original reconstruction, a model representing the existing conditions has been realized for tuning process in relation to the absorption coefficients of the materials applied to all the surfaces. The first digital model has been drawn by using AutoCAD at the beginning, where all the entities in 3D-faces have been grouped by considering the existing materials [16]. In a second stage, the model has been exported to Ramsete [17] in order to execute the absorption calibration [18]. Fig. 4 show the reconstruction of the existing conditions of the theatre.

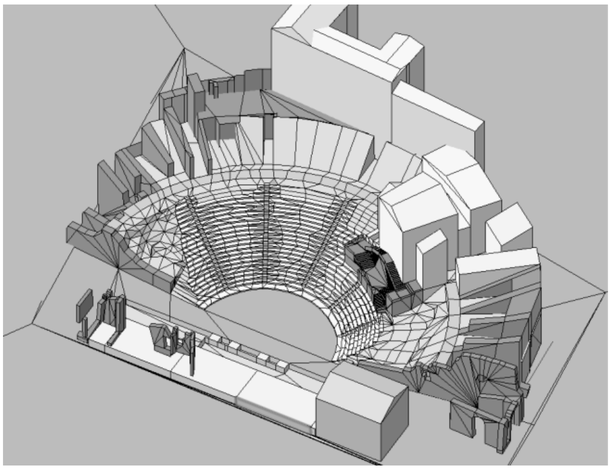

Fig. 4. Digital reproduction of the existing conditions of the Roman theatre of Verona.

The absorption and scattering coefficients considered for the calibrations are summarized in TABLE II. Reference literature for the scattering coefficients is [16][19], while the absorption coefficients have been determined by the calibration process.

The absorbing and scattering coefficients inserted into the model have been compared with the results obtained by the measurement survey. The calibration process consisted of adjusting the values of the absorption coefficients in order to have a minimal drift between measured and calculated acoustic parameters (i.e. EDT, T_{20}, C_{50}, C_{80}, D_{50}). The difference between simulated and measured values does not exceed 5% across all the frequency bands. However, a small variance between the measured and calculated values is caused by physical factors that affected the results during the survey, to be included the wind speed and the reflections from the buildings around the site. Although the sound propagation in the unroofed theatre has been calibrated by considering these acoustic characteristics, the model representing the existing conditions reflects faithfully the real environment.

TABLE II. Absorption and Scattering coefficients used during the digital model calibration.

Materials	Area (m²)	Scattering	Frequency Bandwidth (Hz)					
			125	250	500	1k	2k	4k
Terrain	2623	0.05	0.6	0.6	0.6	0.5	0.6	0.75
Bricks	14190	0.05	0.02	0.09	0.10	0.04	0.1	0.1
Tuff stone	2690	0.05	0.01	0.09	0.10	0.02	0.1	0.15
Gravel	1000	0.50	0.45	0.50	0.45	0.50	0.55	0.7

B. The primordial shape

According to the historical documentation and the archaeological discoveries found by the long campaign of excavations, the original shape of the Roman theatre of Verona has been realized.

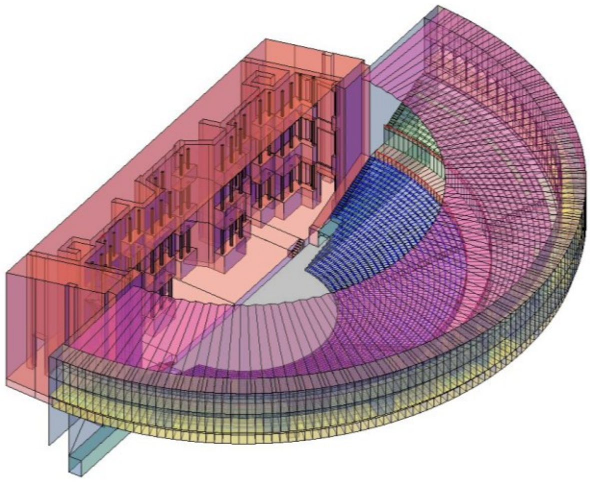

Fig. 5. Digital reconstruction of the original shape of the Roman theatre of Verona.

By applying the same methodology in using AutoCAD for the realization of the entity surfaces, the digital model of the reconstruction has been exported to Ramsete to undertake the acoustic simulation. During the simulations, the absorption and scattering coefficients have been taken from the model of the existing conditions used for the calibration process.

The sound source has been recreated at the same location of the survey but reproduced at 2.5 m height, while the receivers were 1.3 m high. The number of receivers is 12, homogeneously distributed across the *ima* and *summa cavea*.

Furthermore, other absorbing and scattering coefficients have been added to the materials used in TABLE II. they involve the audience, the cloth for the velarium, and the marble for the scenic building.

TABLE III. Absorption and Scattering coefficients used during the digital model calibration.

Materials	Area (m²)	Scattering	Frequency Bandwidth (Hz)					
			125	250	500	1k	2k	4k
Marble	7316	0.05	0.01	0.01	0.02	0.03	0.04	0.05
Fabric	2971	0.2	0.95	0.95	0.95	0.95	0.95	0.95
Audience	856	0.4	0.65	0.65	0.65	0.65	0.65	0.65

VI. RESULTS

The acoustic parameters obtained by the simulations have been compared with the measured results from the survey. The graphs shown in Fig. 6 to Fig. 10 represent the averaged values of all the receivers' positions.

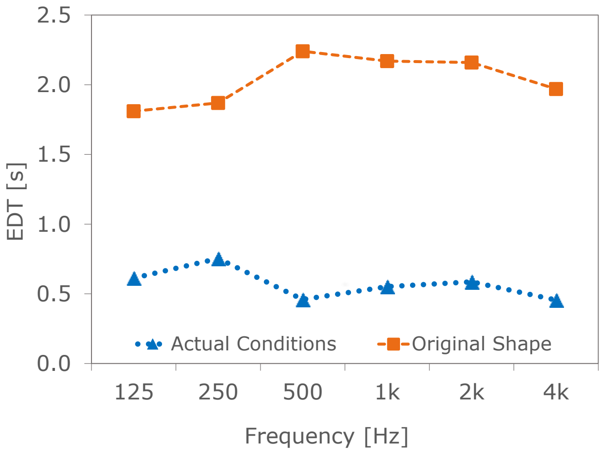

Fig. 6. Compared values of early decay time (EDT).

Fig. 6 shows the results of EDT. In particular, the values related to the original shape result very close to the optimal target of an enclosed space, that would be in the range of 1.8 s and 2.6 s [20]. This noticeable difference is due to the incompleteness of the scenic building that would represent a favorable surface for the early reflections [21]. With the existing conditions, the main contribution in creating the early reflections is given by the orchestra floor, only [22].

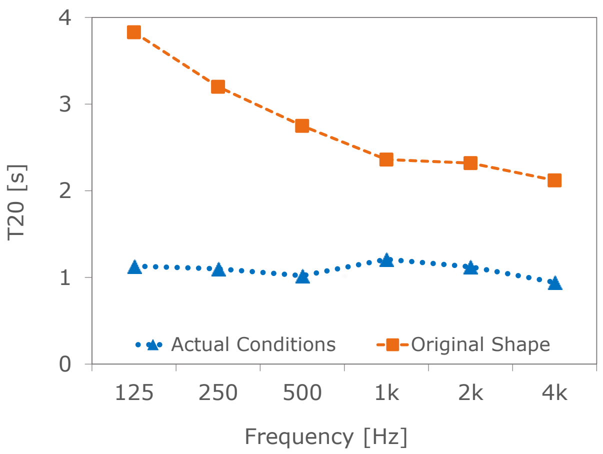

Fig. 7. Compared values of reverberation time (T_{20}).

Fig. 7 shows the values of T_{20} related to the reconstruction model to be close to 4 s for the low frequencies and around 2 s for mid-high frequencies. These results are up to 3 s higher than the measured conditions of the theatre. In fact, the difference between the two configurations is mainly due to the marble material (applied to all the 3D faces, whereas the existing conditions reflect a reduced volume size of the theatre and the presence of materials more absorbing than the marble sheets (e.g. gravel/sand in the orchestra, grass/terrain in some parts of the *ima cavea*) [19].

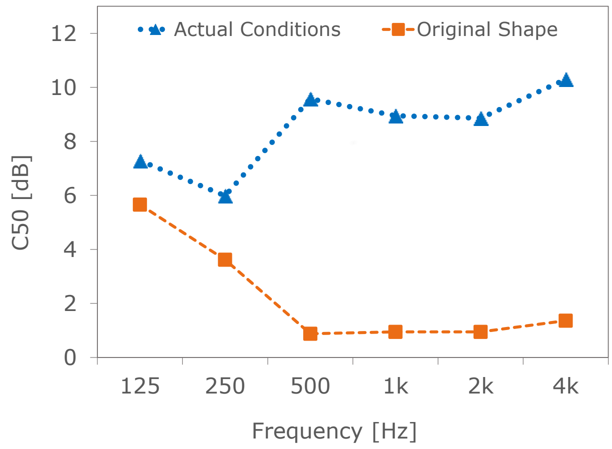

Fig. 8. Compared values of speech clarity index (C_{50}).

A visible difference between the measured results and the simulated values has been found to be approximately 9 dB from 500 Hz onwards, as shown in Fig. 8. This means that the speech understanding could be difficult for the actual configuration, due to the lack of any vertical reflecting surface such that would be contributing to support the voice energy [23].

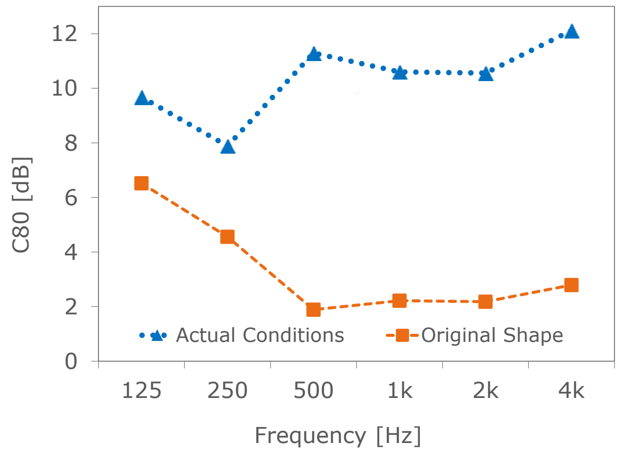

Fig. 9. Compared values of musical clarity index (C_{80}).

Fig. 9 shows that the values of C_{80} obtained by simulations are found to be within the optimum range of -2 dB / +2 dB, as defined by literature [20][23]. This target has been achieved between 500 Hz and 4 kHz, while the values at low frequencies result up to 4 dB higher than the upper range limit. Overall, the measured C_{80} result worsened inside the existing theatre, compared to the values obtained by simulations.

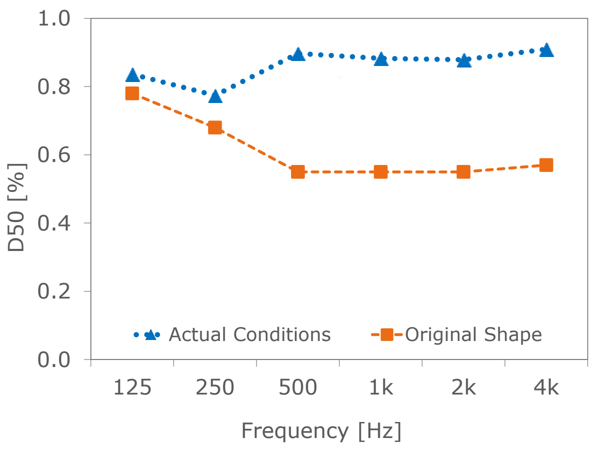

Fig. 10. Compared values of definition (D_{50}).

Fig. 10 indicates a speech suitability is attributed to the existing conditions, while the values of D_{50} around 0.5 (i.e. 50%) indicates a speech and musical suitability of the original shape [24].

VII. Conclusions

This paper deals with the acoustic study of the Roman theatre of Verona as it would be during its splendor time. The analysis of the historical documents has been undertaken by involving different studies on dimensions, structural and architectural typologies, and historical events that include natural and human disasters other than the excavation works happened during the 20th century. Two digital models have been realized: the first one reflects the existing conditions which has been used to calibrate the measured results with the absorbing coefficients applied to the surface elements; the second one reflects the shape and the volume of the Roman theatre as it would be designed by the architect of that time. The comparison of the two acoustics environments highlights a worsening of the listening conditions, because of the incompleteness of the scenic building, that would be representing a strong reflecting surface for the early reflections, and of the coronating constructions (i.e. *summa cavea*, *ambulacrum*) that would be contributing to making this performing arts space suitable for speech and music shows.

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