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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 wooden 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 The authors of this paper deal with a faithful reconstruction of the original shape based on the comparison of historical documents, iconographies, publications, drawings, and sketches executed throughout the centuries for the Roman theatre [11-13].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 measurements undertaken with 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 the main gods (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 during the 16th century, the painter G. Caroto [6] and the architect A. Palladio represent the first scholars having the intention to draw the original architectural features of the theatre [2].

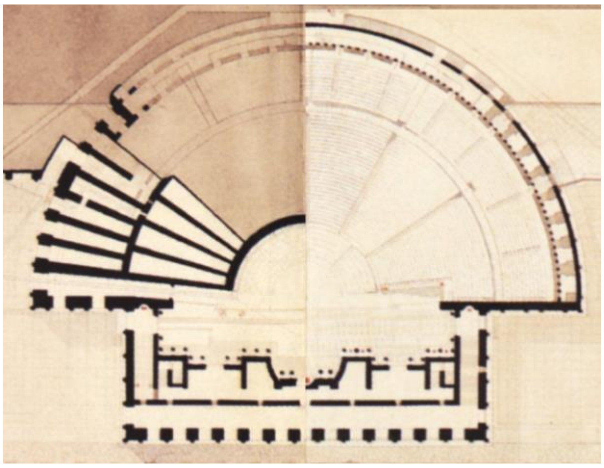

Fig. 1. Plan layout of the Roman theatre of Verona, drawn by E. Guillaume when he arrived in Verona in 1860 [7][7].

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 conditions of the ruins found at that time [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 extraneous material that was filling the cavities between the radial walls [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 were so able in adapting the architectural proposal to the difficulties of the natural sites [10][4]. The scenic building survived in few parts allowing the reconstruction to be composed of three niches: the central one (*valva regia*) is round while the two laterals (*hospitalia*) have a rectangular shape [1][3][7]. The scenic building was 6 m wide, 27 m high, and 72 m long, 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, nowadays reduced to 2000 seats in relation to the preserved conditions [2].

The *ima cavea* should have originally 25 steps, actually reduced to 23, having a height 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.

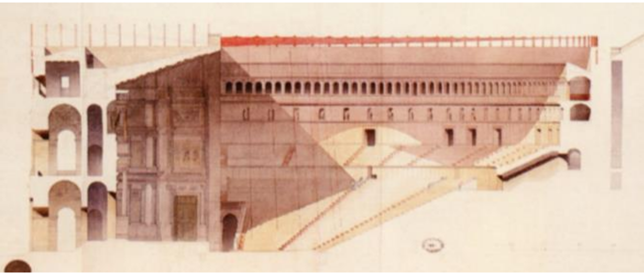

Fig. 2. Section of the Roman theatre of Verona, drawn by E. Guillaume [7].

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 arrived at the line of the 8th step of the *cavea* [3].

The structure coronating the *summa cavea* was the *ambulacrum*, a semicircular ambulatory of 2.3 m in height that had the decking level 4 m above the second horizontal corridor [3]. Such ambulatory 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 above the orchestra level, equal to the height of the scenic building 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 the 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 line with the standard requirements outlined in 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 connected to the loudspeaker and all the receivers.

The sound source was placed along the diameter of the orchestra, at the center of it and at a height of 1.4 m from the finished floor. The receivers where installed at the height of 1.2 m, in 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. shows the measurement positions of the sound source and the receivers across the *cavea*.

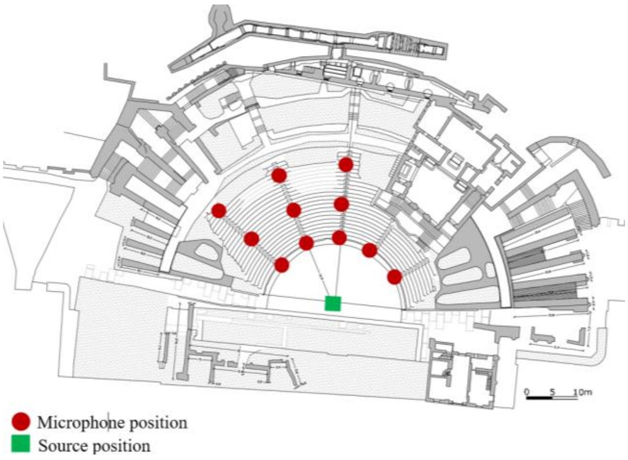

Fig. 3. Scheme of the equipment location during the acoustic measurements in Verona.

V. DIGITAL MODELS

A. Existing conditions and coefficients calibration

Before proceeding with the reconstruction of the theatre at its original shape, a model representing the existing conditions has been realized to calibrate the absorption coefficients of the materials applied to the number of 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 acoustic calibration [18]. Fig. 4 show the reconstruction of the existing conditions of the theatre.

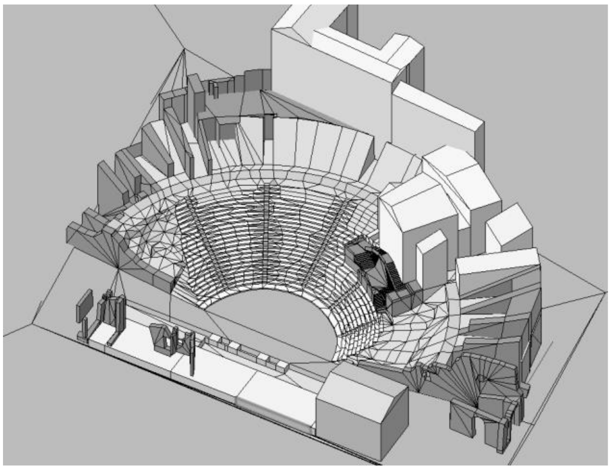

Fig. 4. Digital reproduction of the existing conditions of the Roman theatre of Verona.

The absorption and scattering coefficients considered for the calibrations are summarized in TABLE II. The scattering coefficients were obtained from literature [16][19], while the absorption coefficients are the results of the calibration process other than based on experience on similar Roman theaters.

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 direction and the presence of buildings away from 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. Original shape

Based on 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.

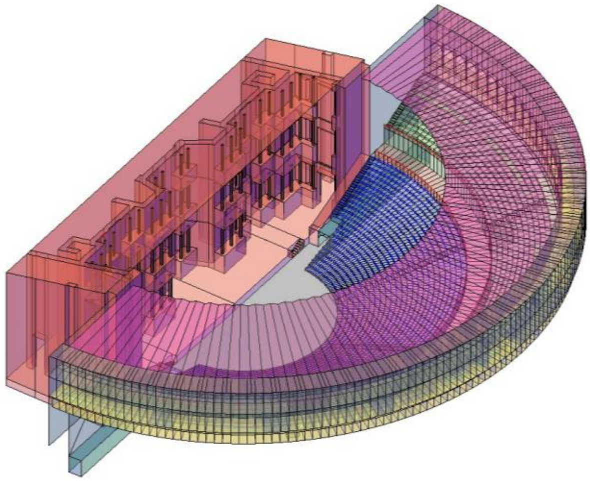

Fig. 5. Digital reconstruction of the original shape of the Roman theatre of Verona.

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 from the finish floor, while the receivers were placed at a 1.3 m height from the relative finish floor. 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 (m^2)	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.

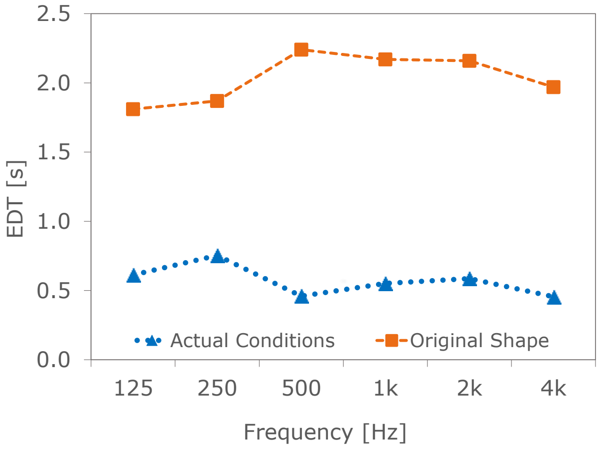

Fig. 6. Compared values of early decay time (EDT).

Fig. 6 shows that the results of EDT related to the open-air theatre of Verona at its original shape are found to be very close to the optimal values of an enclosed space, ranging between 1.8 s and 2.6 s as defined by Jordan [20]. This noticeable difference is mainly due to the absence 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].

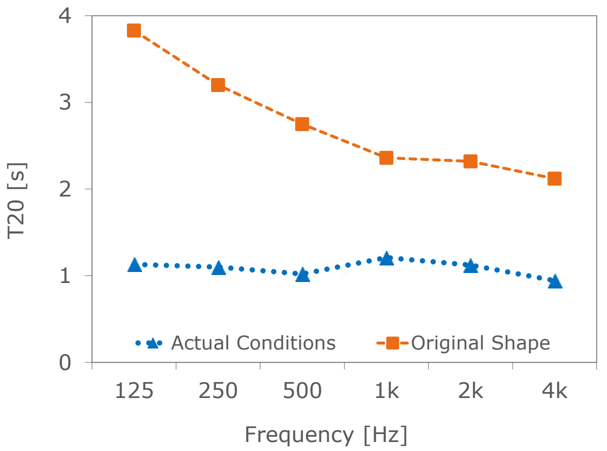

Fig. 7. Compared values of reverberation time (T_{20}).

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 existing conditions of the theatre. In fact, the difference between the two configurations are mainly due to the marble material (applied to almost the whole surface area of the digital model, 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].

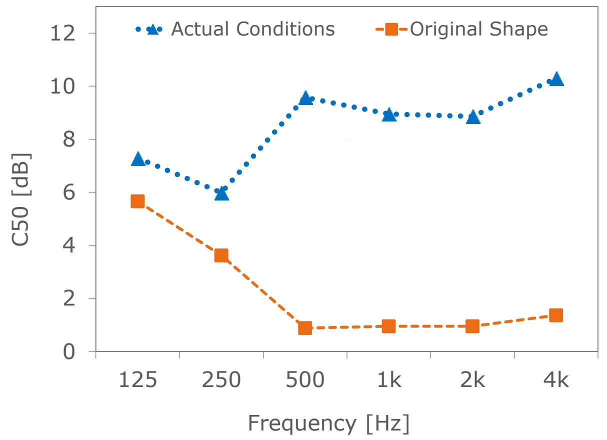

Fig. 8. Compared values of speech clarity index (C_{50}).

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 some difficulties in speech understanding might be existing for the actual configuration, due to the lack of any vertical reflecting surface such that would be contributing to support the voice energy [23].

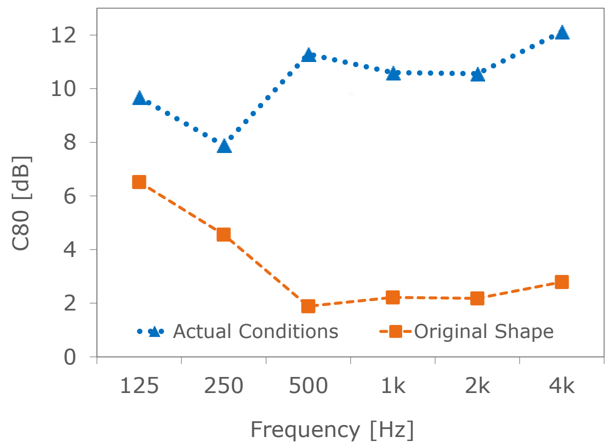

Fig. 9. Compared values of musical clarity index (C_{80}).

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 for the frequency bands comprised 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 by listening to music in the existing theatre, compared to the values obtained by simulations.

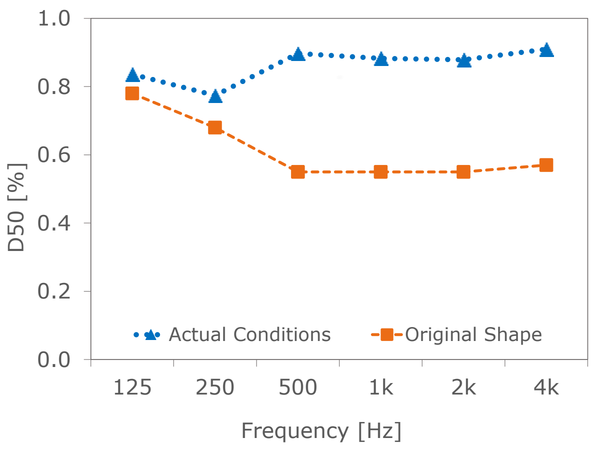

Fig. 10. Compared values of definition (D_{50}).

Fig. 10 indicates that the existing conditions of the theatre are more suitable for speech performances, while the values of D_{50} to be around 0.5 (i.e. 50%) for the mid-high frequencies show that the acoustics of the theatre at its original shape would be suitable for both speech and musical performance [24].

VII. Conclusions

This paper deals with the reconstruction 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 reflect 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, mainly due to the absence of the entire scenic building, that would be representing a strong reflecting surface for the early reflections, and of the coronating constructions (i.e. *summa cavea*, ambulatory, and upper gallery) that would be contributing to making this performing arts space suitable for both speech and music shows.

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To have non-visible rules on your frame, use the MSWord "Format" pull-down menu, select Text Box > Colors and Lines to choose No Fill and No Line.

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