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THIS COMMUNICATION IS CANCELLED (PAPER IS AVAILABLE). Analysis of acoustic requirements of a small hall of a theatre according to the coupling factor with the stage tower

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In recent years in Italy, the renovation or construction of public buildings, especially auditoriums (for music) and theaters (for prose and the lyric) has become a widespread practice in urban restoration of small and medium-sized towns. The most pervasive tendency in contemporary architectural design of auditoriums and theaters is to realize one-space hall without galleries or balconies, with an accurate furniture design. In the case of theaters, the size of the stage tower is comparable to the one of the audience hall and it has an equivalent absorption area similar to the hall one, depending on the scenes equipments in the stage tower. In this paper the results of the analysis of acoustic requirements of a small theatre hall built in *San Miniato* (Tuscany region, Italy) are shown and discussed. The analysis has been conducted using the acoustic simulation software RAMSETE. In particular the influence of the stage tower on the room acoustic has been examined, focusing on the coupling factor between the two spaces.

1 Introduction

From the years after the Second World War, in Italy it has starting a complex process of restoration and reconstruction of urban centers that has a relevant importance not only for the building field but also for the social, cultural and economical one [1]. During the Second World War, the towns were deeply damaged because of the several bombings which created ruins and empty spaces in the fabric of the city. Up to the present, these areas have been restored for a mostly collective use, through buildings able to represent carriers of cultural events, such as museums, exhibition areas, cinemas, libraries, auditoria or theatres.

San Miniato (Etruscan town situated between Pisa and Florence, Fig. 1) at the end of the Second World War, during the German retreat, suffered several human losses and substantial devastations [2].

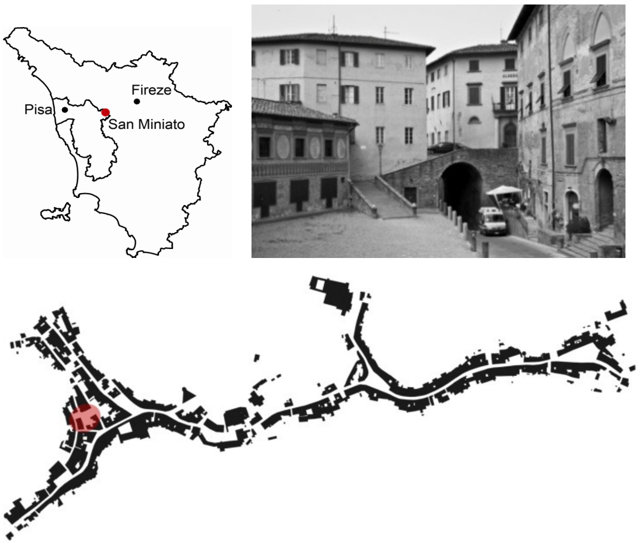

Figure 1: Site of *San Miniato* in Tuscany region (upper left). Picture of *San Miniato* (upper right) old town center. Plan of the old town center (lower).

In 1944 the Cathedral, the fortress and others monumental buildings had been seriously damaged and half of the houses was destroyed (Fig. 2). Also the nineteenth-century *Teatro Verdi* was mined and completely demolished, creating a vacuum within the fabric of the city left until today. With the passing of the time a partial suture of that wound has been possible, letting the consolidation of uses and misuses on the area of *Teatro Verdi*; today the area is exclusively used for car parking (Fig. 3). It is necessary a renewal and an improvement of this area, not only a simple infilling intervention but an effort that takes into consideration the presence of open spaces that have became an important part of the urban fabric. For this reason, technical and architectural arrangements have been adopted for the project of the new Theatre in order to maintain and to redesign the square, to establish a regular connection of the fronts of the buildings and to create a pedestrian crossing that links the square to the boundary streets [3].

Figure 2: Demolitions in the old town center of *San Miniato*, after the Second World War [2].

Figure 3: Urban void left by the demolition of *Teatro Verdi*, today used as a car parking [3].

Therefore the new Theatre is partly hypogeous and the emerging buildings, although set up by simple and contemporaneous shapes, perfectly integrate with the existing buildings (Figs. 4-5). A deep symbiosis between the building and the town is what results, something that doesn't pass through direct relations between inside and outside, but rather through modeling volumes that create urban paths and architectural surroundings (Fig. 5). The new Theatre has been designed to mostly host performances of prose and occasionally musical performances. It is essentially formed by two volumes: the hall, that contains the stalls but without the balcony, and the stage tower that dominates the stage (Fig. 6).

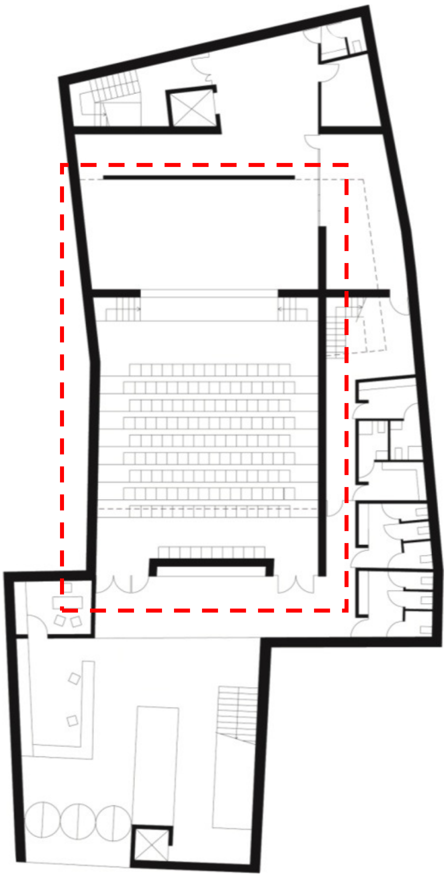

Figure 4: Plan (basement, -3.20 m, see Fig. 6) of the design of the new Theatre of *San Miniato* [3]. By a dashed line they are highlighted the hall and the stage tower.

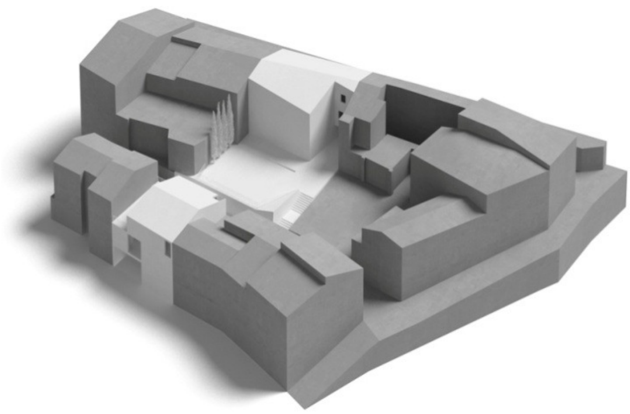

Figure 5: Architectural 3D model showing the urban infilling of the new Theatre [3].

The simple box-shaped volume strays from the nineteen-century tradition (that provides for horseshoe bat or bell-shaped plans) and follows the patterns developed at the beginning of ‘900 [4]. The hall and the stage tower are visually and acoustically connected by the proscenium. This connection determines that the acoustic characteristics of the two volumes can’t be individually treated because they depend on one another.

2 Acoustic analysis

2.1 Modeling

The definitive configuration of the covering materials of the walls and of the furniture, that determines acceptable reverberation times and acoustic comfort, has been obtained trying several possible solutions through the acoustic modeling software RAMSETE [5-6]. Immediately they have been underlined the aspects resulting from the combination of the two volumes (the hall and the stage tower) and it hasn’t been possible to determine a satisfactory configuration of the absorbing materials of the hall without considering the stage tower setting. If this volume hadn’t had an adequate equivalent absorption area, the reverberation of the hall would have been excessive, producing a duration that wouldn’t allow the accomplishment of the conditions for a good audition [7-8].

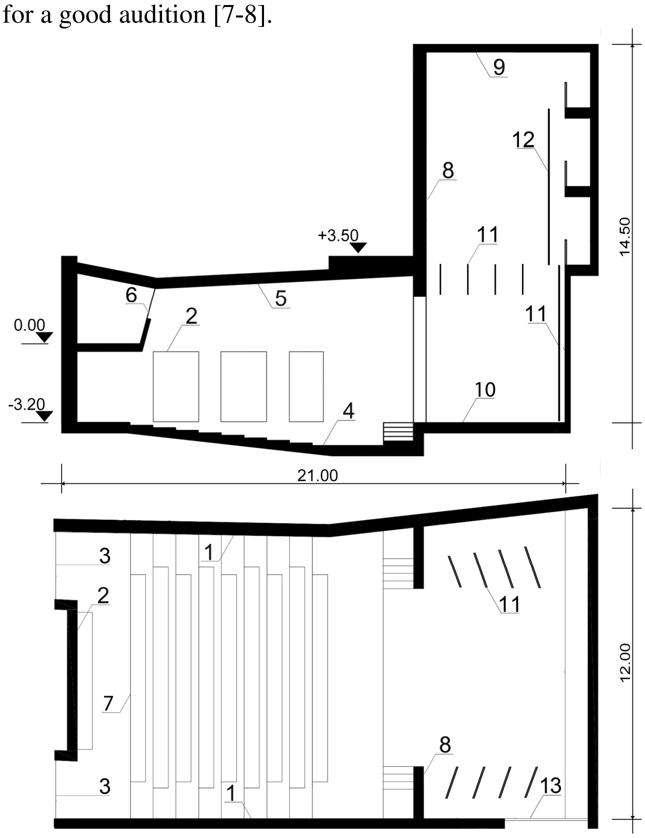

Figure 6: Plan (lower) and section (upper) of the new Theatre [3]. The numbers indicate the covering materials reported in Tab. 1.

Table 1: Sound absorption coefficients of the materials. In the second column we find the surfaces (in m^2). For the armchairs (line 7) it is indicated the total amount and the equivalent absorption area (m^2) for each one.

	Frequency (Hz)	m^2	125	250	500	1000	2000	4000
1	Plaster	187	0.02	0.02	0.03	0.04	0.04	0.03
2	RPG Panels Flutter Free D mount	68	0.76	0.40	0.23	0.16	0.18	0.22
3	Wooden Dooors	14	0.17	0.20	0.22	0.22	0.18	0.12
4	Wooden floor	156	0.03	0.04	0.06	0.12	0.10	0.17
5	Top Akustic ceiling 14/4	120	0.08	0.25	0.56	0.87	0.60	0.55
6	Glass of the control room	8	0.18	0.06	0.04	0.03	0.02	0.02
7	N° 150 Armchair (equivalent absorption area)	-	0.16	0.19	0.26	0.31	0.38	0.50
8	Acoustical plaster	394	0.16	0.28	0.63	0.74	0.66	0.71
9	Knauf Ceiling AMF Termatx Alpha HD	78	0.55	0.75	0.75	0.85	0.95	0.95
10	Wooden floor of the stage	66	0.03	0.04	0.06	0.12	0.10	0.17
11	Backdrop, wings, ceilings	160	0.05	0.12	0.35	0.45	0.38	0.36
12	Sceneries	60	0.05	0.12	0.35	0.45	0.38	0.36
13	Wooden doors	30	0.17	0.20	0.22	0.22	0.18	0.12

In Table 1 we find the sound absorption coefficients of the materials (in the definitive configuration) for the hall and for the stage tower (furniture, backdrop, wings, ceilings and sceneries). In Fig. 7 is shown an interior view (rendering realized with 3D Studio max) of the definitive solution of the audience hall.

Figure 7: Interior view of the definitive solutions of the hall.

2.2 Calculation results

In order to develop the calculations with the software 160 receivers, along a regular mesh of two meters step, have been placed as shown in Fig. 8. The sound source (not amplified male voice with strong tone, available in the data base of the software) was placed on the stage, two meters back from the proscenium as shown in Fig. 8.

The software provides the impulse response and all the parameters of acoustic quality in the rooms (e.g.: T_{30}, EDT, D_{50}, …) for each selected receiver, allowing local and average analysis of the hall. By means of tracing a sequence of mappings it is possible to verify the distribution of the sound field.

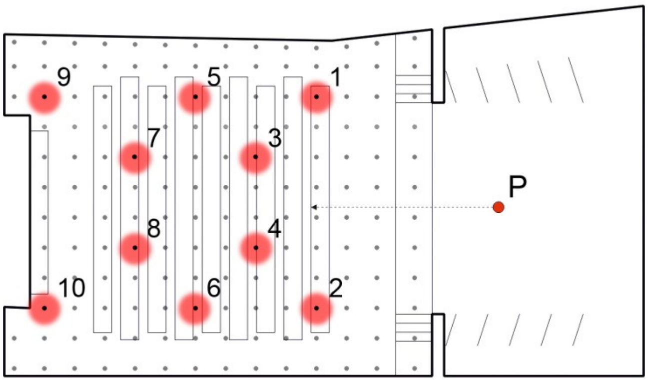

Figure 8: Position of the examined receivers. The dot P on the stage indicates the position of the sound source (human voice).

In Tab. 2, for the reverberation time of the hall (T_{30}), the results obtained in average conditions (ROOM) and for 10 relevant positions (Fig. 8) have been indicated, for the frequencies between 125 and 4000 Hz. The results evidence how local T_{30} is close to the average one for every examined position, showing a good uniformity of the hall. To note that the medium values (ROOM) in Tab. 2, regarding all the 160 receivers, are very close to the average values derived from the results obtained for the 10 receivers analyzed in this paper.

In Tab. 3 we find the average values of the hall of the Early Decay Time (EDT), of the Definition index (D_{50}) and of the Clarity index (C_{50}) for the frequencies interval between 125 and 4000 Hz.

Comparing the T_{30} and the EDT, relevant changes are not noticed (Tabs. 2-3 and Fig 9), hence the hall can be considered as *"Sabinian"* room [5].

Table 2: Calculation results regarding the average values (ROOM) and the local ones (receivers, see Fig. 8) of the reverberation time (T_{30}) of the hall.

T_{30} (s)	Frequency (Hz)					
	125	250	500	1000	2000	4000
ROOM	1.30	1.09	0.83	0.71	0.76	0.72
1	1.31	1.10	0.84	0.71	0.76	0.72
2	1.29	1.09	0.84	0.71	0.77	0.72
3	1.30	1.10	0.84	0.70	0.76	0.71
4	1.29	1.09	0.83	0.70	0.76	0.72
5	1.30	1.10	0.84	0.71	0.76	0.72
6	1.28	1.09	0.84	0.71	0.77	0.73
7	1.29	1.10	0.84	0.72	0.76	0.72
8	1.29	1.10	0.84	0.71	0.76	0.72
9	1.31	1.09	0.82	0.70	0.74	0.69
10	1.29	1.08	0.82	0.70	0.75	0.72

Table 3: Calculation results of average values (ROOM) in the hall for EDT, D_{50} and C_{50} indexes.

ROOM	Frequency (Hz)					
	125	250	500	1000	2000	4000
T_{30} (s)	1.30	1.04	0.74	0.62	0.66	0.65
D_{50} (%)	50	60	72	77	74	76
C_{50} (dB)	0.06	1.7	4.0	5.3	4.6	5.1

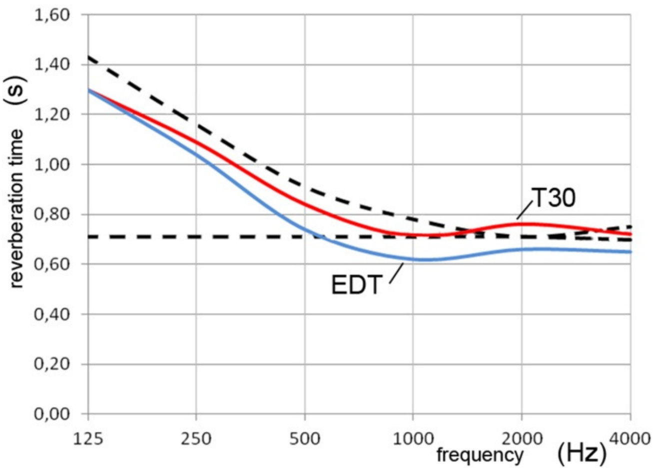

Figure 9: Trend of T_{30} and of EDT depending on the frequencies. The dashed lines indicate the acceptability range for the reverberation time in the halls destined to prose performances, with a volume comparable to the one examined.

The analysis of the calculation results obtained with the software allows the description of a room where the reverberation time (T_{30}) is consistent with its acoustic use: the sound field is uniform and the reverberation has a sufficiently linear decay without echoes.

The Definition index (D_{50}) is higher than 50% and the Clarity index (C_{50}) is higher than 3 dB (for frequencies over 250 Hz), this guarantees a good speech intelligibility [9].
In Figs 10 some of the graphic outputs obtained with the software RAMSETE have been shown, they are concerning the following indexes: T_{30}, EDT, D_{50} and C_{50} at the 500 Hz frequency.

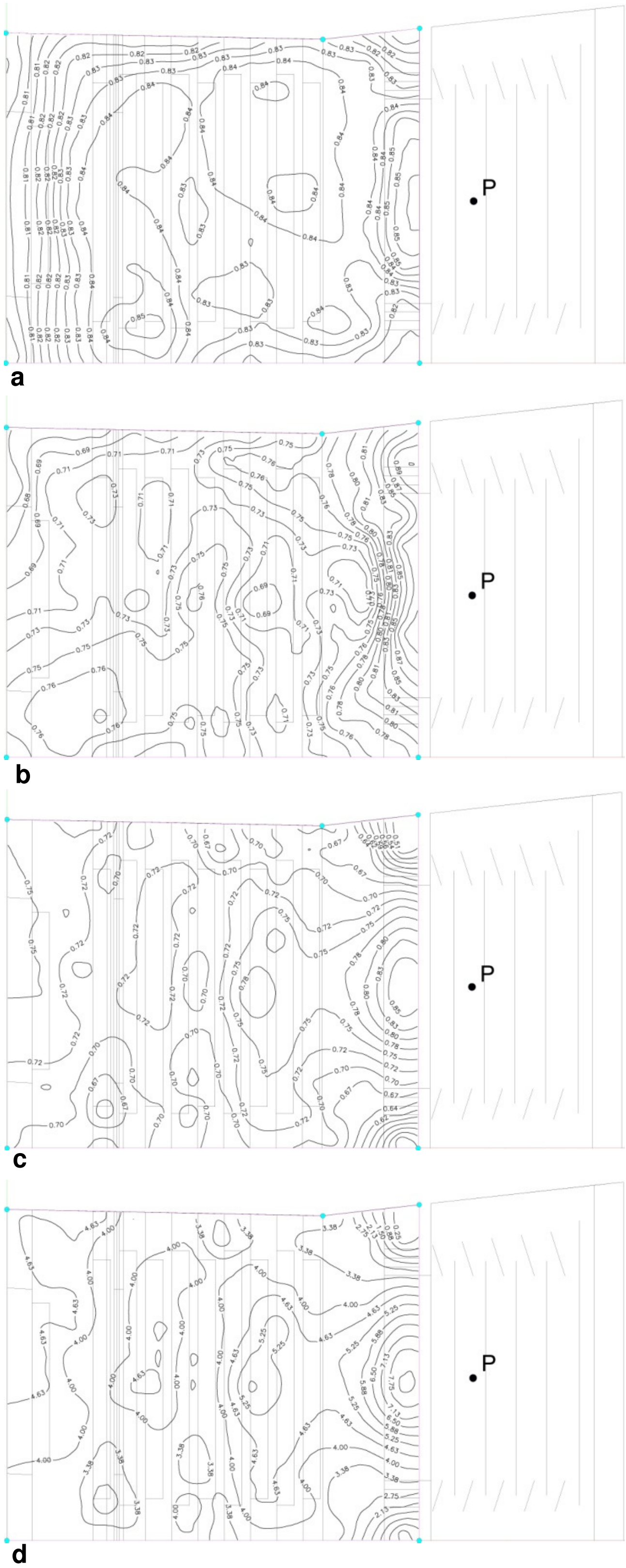

Figure 10: Graphic outputs concerning indexes T_{30} (a), EDT (b), D_{50} (c), C_{50} (d) at the 500 Hz frequency.

2.3 Stage tower without sceneries

The performances of contemporary theatre, the cabaret, the entertainments and the conventions, are events that generally do not require the presence of the sceneries but they usually take place in municipal theatres. For this reason it has been conducted an acoustic analysis considering the stage tower without sceneries. Particularly to determine the absorbing power of the stage tower the 60 m^2 surface of the sceneries (Tab. 1, line 12) hasn't been considered, on the contrary it was considered in the previous paragraph 2.2. Some results of this analysis are shown in Tab. 4, where the values obtained for the reverberation time T_{30} and for the D_{50} and C_{50} indexes have been indicated.

Table 4: Calculation results regarding the medium values (ROOM) of the T_{30}, D_{50}, C_{50} indexes for the hall with a stage tower without sceneries, in the frequencies range considered.

ROOM	Frequency (Hz)					
	125	250	500	1000	2000	4000
T_{30} (s)	1.35	1.11	0.82	0.69	0.75	0.71
D_{50} (%)	50	60	72	77	74	76
C_{50} (dB)	0.01	1.7	4.0	5.3	4.6	5.0

It is possible to observe how the absence of the sceneries in the stage tower doesn't cause relevant changes of the parameters of the hall acoustic quality. This happens because the walls of the stage tower are characterized by a high acoustic absorption due to the acoustic plaster (Tab. 1, line 8).

3 Coupling rooms effect

In the previous paragraphs it has been underlined how the acoustic absorption of the stage tower affects on the reverberation time of the hall. This phenomenon is referable to the theory of the coupled rooms [8] and can be described determining an appropriate coupling factor (K):

$$K = S \cdot \left(\frac{1}{S + A_1} \cdot \frac{1}{S + A_2} \right)^{1/2}$$

The K factor depends on the equivalent absorption area of the two contiguous rooms (A_1 for the hall and A_2 for the stage tower) and on the coupling surface (in this case the opening of the proscenium, S). The K factor obviously takes values between 0 and 1. For small values of K, the coupling of the two rooms produces negligible effects and the two volumes may be acoustically analyzed as separate rooms. For high values of K, the two contiguous rooms may be analyzed as an unique volume.

For this case study the values of K have been estimated for three relevant configurations (Tab. 5):

- Definitive solution (see paragraph 2), DS;
- Reverberant stage tower, RST;
- Deaf stage tower, DST.

In the case of reverberant stage tower (RST), the acoustic plaster and all the absorbing coverings (see Tab. 1, lines 8, 9 and 10) have been changed with surfaces covered by plaster having the same acoustical properties of the ones in line 1 of Tab. 1.

In the case of deaf stage tower (DST) all the surfaces previously covered by plaster have been considered completely absorbing (we admit an unitary sound absorption coefficient for all frequencies).

Obviously the equivalent absorption area of the hall (A_1) remains the same for all examined configurations (Tab. 5).

From the analysis of Tab. 5 it can be observed how the values of K coupling factors are small for the DST and DS configurations; on the contrary they are higher for RST configuration, underling a great mutual influence between the two rooms (hall and stage tower). These conclusions have been confirmed by the results obtained with the use of RAMSETE. They are shown in Tab. 6 and Fig. 11, concerning the reverberation time (T_{30}) in the three configurations.

Table 5: Calculation results for K factor in the three examined configurations. In the Table equivalent absorption area A_1 (hall) and A_2 (stage tower) have shown for each case.

Cases		Frequency (Hz)					
		125	250	500	1000	2000	4000
DS	A_1	101	102	145	197	175	202
	A_2	121	197	373	444	407	426
	K	0.24	0.20	0.13	0.10	0.11	0.11
RST	A_2	12.6	12.6	18.8	25.1	25.1	18.8
	K	0.44	0.43	0.36	0.30	0.31	0.31
DST	A_2	628					
	K	0.12	0.12	0.10	0.09	0.09	0.09

Table 6: Calculation results of average values of the reverberation time (T_{30}) for the hall in the definitive solution (DS), reverberant stage tower (RST) and deaf stage tower (DST).

T_{30} (s)	Frequency (Hz)					
	125	250	500	1000	2000	4000
DS	1.30	1.09	0.84	0.71	0.76	0.72
RST	5.23	5.05	3.91	3.26	3.19	3.34
DST	0.81	0.79	0.66	0.57	0.62	0.56

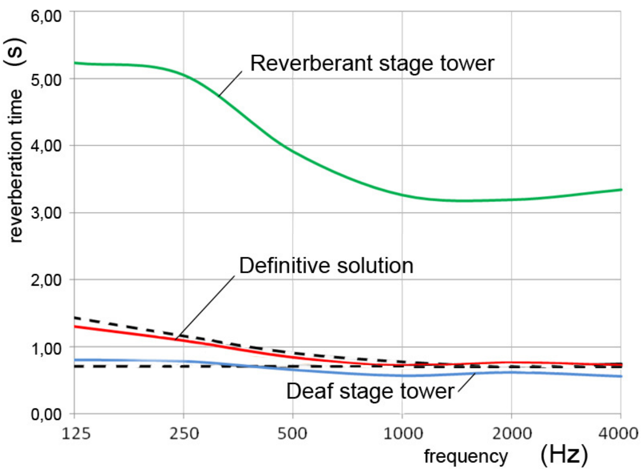

Figure 11: Trend of T_{30}, for the hall in the definitive solution (DS) and the other two. The dashed lines indicate the acceptability range for the reverberation time in the halls destined to prose performances, with a volume comparable to the one examined.

Analyzing the curves in Fig. 11 it can be noticed that the stage tower treated with sound reflective material (reverberant stage tower, RST) has a negative influence on the reverberation times of the hall that tend to markedly increase. On the contrary, the stage tower treated with absorbing materials (deaf stage tower, DST), doesn't significantly influence the reverberation of the hall. In Fig. 11 it can be also noticed that the definitive solution (DS) curve keep between the acceptability range (dashed line) for the reverberation time in the halls destined to prose performances, with a volume comparable to the one examined.

It's interesting to observe that: modeling the hall by substitution of absorbing surface (unitary sound absorption coefficient for all frequencies) to the proscenium, it can be obtained a trend of reverberation time (T_{30}) coincident with the one of DST configuration, in accordance with the coupled room theory [7-8].

5 Conclusions

Recently, for the realization of new theater buildings in small and medium towns, the single hall solution is frequently preferred. In these cases the size of the stage tower is comparable to the one of the audience hall and it has an equivalent absorption area similar to the hall one, depending on the scenes equipments in the stage tower. For this reason, the acoustic of the hall may be influenced by the opening of the proscenium that links the hall to the stage tower through a suitable coupling factor.

In this paper it has been described the acoustic analysis of the new Theatre of *San Miniato* (Tuscany region, Italy), essentially dedicated to prose performances. The new building presents a box-shaped hall connected to a stage tower with a similar volume. The choices of the absorbing material to cover the walls (both for the hall and the for the stage tower) and the furniture, allow to realize an hall capable of guaranteeing a good speech intelligibility.

The study of the coupling factor between the audience hall and the stage tower has underlined the influence of the equivalent absorption area of the stage tower on the reverberation of the hall, in accordance with the coupling rooms theory.

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