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REMEDIAL ACOUSTICS IN A NEOCLASSICAL LECTURE THEATRE

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INTRODUCTION

One of the lecture theatres in the "Averof" building of the Tech. University of Athens was recently renovated to improve its poor acoustics. The auditorium is part of a monumental neoclassical building and though it seats only ninety six students has a relatively large volume (715 m^3) and high ceiling decorated with arches, vaults and a cross vault. This paper describes the improvements achieved by the completed remedial treatment as found in tests of physical acoustic parameters, and in subjective evaluation experiments. Results from laboratory measurements of the absorptive treatment of the theatre are also compared with the field data.

PRINCIPLES OF THE ACOUSTICAL DESIGN

Measurements made in the untreated empty theatre showed that the mid frequency reverberation time was 3.25 s (Fig. 1). The abundance of detrimental late reflections in the room was also obvious in the measured mean value of the 50 ms early energy fraction which was as low as 0.26. However the theatre could be credited for its low intruding environmental noise which was 27 PNC.

A major limitation in the choices of the remedial acoustic design was the need to preserve the view of the interesting neoclassical ceiling, the height of which imposed a value of volume per seat as high as 7.45 m^3; Fortunately the shape of the ceiling could at least ensure freedom from echoes to the audience due ot its diffusive nature. Given the above, a compromise target reverberation time at mid frequencies was adopted in the range 1.0 s to 1.2 s, which of course is higher than the value 0.75 s recommended for lecture halls of comparable volume [1].

The acoustical design was based on the introduction of a balanced absorptive treatment on the two side walls and the back wall of the room as shown in Fig. 2, and has been the object of an earlier paper [2].

DESIGN AND ACOUSTIC PERFORMANCE OF THE ABSORPTIVE TREATMENT

The absorptive treatment was designed so as to cover effectively the low as well as the mid and high frequency range. This consisted of 3 mm plywood sheets mounted over 25 mm airspace against the wall and was covered sporadically with 40 mm fibreglass. The whole treatment was finished by an open weave fabric to improve appearance (Fig. 3). The plywood was fixed on wooden battens which were arranged vertically on the wall every 0.5 m, to provide sufficient supported edge length to the panel absorber. Wooden frames of 1.25 m X 1.00 m were placed on top of the plywood to support the fibreglass plates. The plywood thickness and the airspace behind it were so chosen as to achieve peak absorption in the 250 Hz octave band i.e. where the untreated theatre exhibited maximal reverberation time. The resonance frequency of the panel absorber was estimated to

287 Hz [1].

According to data from the literature [1] the plywood was expected to absorb around 0.3 sabins/m^2 at its resonance frequency. Yet it was hoped that the fibreglass above the plywood would enhance the panel absorption, and also would absorb around 1 sabin/m^2 at and above the octave band 500 Hz.

As soon as the renovations of the lecture theatre were nearly complete reverberation chamber facilities became available of the Tech. University of Athens. A specimen made as closely as possible to the field treatment was then tested in the laboratory [3]. The measured sabine absorption coefficients (Fig. 4) show good agreement with the earlier estimation.

Given the measured reverberation time in the treated theatre it was then attempted a retrospective exercise, i.e. to predict the absorptive performance of the treatment in the field. Assuming the absorption of plywood in the field to be same as in the laboratory, the absorption coefficients were calculated of the combined treatment (i.e. of plywood covered with fibreglass) in the field.

The results are shown in Fig. 4 and suggest that the combined treatment has exhibited on average 20% higher absorption in the field than it has done in the laboratory. The most important explanation to this seems to be the fact that the ratio of "Free Edge Length"-to-"Treatment Area" (E) was higher in the field material (E_{FIELD}=2.3 m^{-1}) than it was in the laboratory specimen (E_{LAB}=1.24 m^{-1}). According to Bartel [4] "...the random incidence absorption coefficient increases approximately linearly with E for values of E ranging from 1.3 to 3.3 m^{-1}...". Also 30% of the fibreglass free edges have been unframed in the field, unlike the situation in the laboratory. The fibreglass in the field was therefore presenting to the sound some additional absorbing area which was not accounted in the calculations. This also explains why the values of the Sabine absorption coefficient of the field treatment appeared to be greater than unity.

OBJECTIVE ASSESSMENT

The following physical acoustic criteria have been used to assess the acoustics of the theatre after completion of the remedial work:

1. Classical Reverberation Time (RT),
2. 50 ms Early Energy Fraction (EEF_{50}), and
3. Signal-to-Noise ratio (S-to-N ratio).

The RT is the oldest criterion of room acoustics and despite its ambiguous subjective significance [5] continues to be used widely in practical acoustic design. The other two criteria have been compiled from Barron's work [6] in which he concludes that, the EEF_{50} together with the S-to-N ratio can be considered as sufficient criteria for speech intelligibility in theatres, and that the overall speech quality is an extention of speech intelligibility.

The measured mid frequency RT in the treated (empty) theatre was 1.15 s and was estimated to drop to 0.95 s with two-thirds audience (Fig. 1). These results show that the optimal target range 1.0 s to 1.2 s adopted for RT at the design stage is fullfilled. A significant rise of RT occurs in the octave band 125 Hz (almost 25% re mid frequencies). Nevertheless there is agreement between different authors that components in this band bear little [7] to zero [8] weight in the understanding of speech.

The measured mean 50 ms Early Energy Fraction, weighted over the octave bands 125 Hz to 4 KHz (according to the MTF weighting [7]) was 0.41. This compared with the mean EEF_{50} value 0.27 measured in the untreated room shows a definite improvement towards the optimal value 0.50 [9]. This improvement has been mainly the effect of reduction of detrimental late sound in the room. A plane surface reflector above the speaker was recommended to enhance early sound in the audience area, but this was omitted. The theoretically predicted value 0.46 of the EEF_{50} in the treated room [10] is in fairly good agreement with the measured value. This supports the notion, also implied by the smooth RT decay traces, that the sound field is nearly diffuse and decays almost exponentially.

Calculations of the Signal-to-Noise ratio in the rear most seats of the theatre (11.0 m from source) were made over the octave bands 125 Hz to 4 KHz. These were based on the measured background noise level in the room, and on the speaker sound power output [11]. The measured noise levels were subtracted at each frequency from the speaker sound pressure level, which had been calculated according to the inverse square law and the classical reverberation theory [12]. The results are tabulated below.

Octave frequency [Hz]	125	250	500	1000	2000	4000
Background noise [dB]	45.5	38.5	32.5	25.0	21.5	below 20.0
S-to-N ratio [dB]	11.0	22.0	27.0	26.1	16.5	22.0

Obviously the S-to-N ratio at all octave frequencies is well above the lower limiting value 10 dB [6]. This implies that minor to nought degradation of speech intelligibility will only occur, and also that there is no need for sound amplification in this theatre.

SUBJECTIVE QUESTIONNAIRE STUDY

In order to evaluate the acoustics of the treated lecture theatre from the listener's point of view, subjective questionnaires were used. These were distributed during a lecture in four different locations over the seating area (Fig. 2) with the aim to be filled in by self recruited subjects. A total of fifteen listeners returned their completed questionnaires, i.e. three to four listeners from each location.

The questionnaire consisted of rating scales of the sematic differential type using adjectival descriptors at the "poles" [5]. The scales were compiled from Barron's work [6] and are shown in Fig. 5.

The judgements on each scale were tested for significant differences between test locations. The results showed that no significant differences were identified (at the 5% signif. level) for each one scale. Given this, the data for each scale were pooled together and summarized in one mean scale judgement plotted in Fig. 5. The mean scale judgements from a similar subjective test, which was performed in the untreated theatre, have also been plotted on the same diagram.

An analysis of variance test performed on each scale aimed to test for significant differences between the mean scale judgements in the treated and the untreated theatre respectively.

The results from scale "speech intelligibility" showed that there was significant improvement (at 1% signif. level) of the judgements in the treated theatre compared to the judgements made before treatment (i.e. the scale judgements moved towards the "good" end of the scale). Same results were obtained from the scales "ease of listening" and "overall impression". Given that the EEF_{50} was found by Barron [6] to be highly correlated with "speech intelligibility" it can be inferred from the present results that, the significant improvement of "speech intelligibility" was the result of the increase of the 50 ms Early Energy Fraction in the treated theatre.

For each of the scales "reverberance", "intimacy" and "voice level", the mean judgements were not found to be significantly different (at the 5% signif. level) between the treated and the untreated room situation respectively. These results possibly mean that the subjective qualities described by these attributes remained virtually unchanged under the two different situations. It can also be that there was disagreement between subjects as to the meaning of the attributes. In particular this can be true of "reverberance" and "intimacy" given the relatively increased st. deviation of the mean scale judgements, and the outlook that these attributes are mostly important for music listening.

Last, there was a fairly good agreement between subjects that the qualities described by the attributes "echo disturbance" and "background noise" were not perceived in the room. This result is consistent with the low measured background noise in the theatre.

CONCLUSIONS

Remedial works were recently completed in a neoclassical lecture theatre in order to improve its originally poor acoustics. Measurements in the treated theatre have shown that the values of current room acoustic criteria have been dramatically improved to about optimal levels. These results have also been confirmed by a subjective evaluation study.

In particular, subjective judgements in the renovated theatre, were tested for significant differences from judgements made earlier in the untreated theatre. The results showed that significant improvements were perceived in the renovated theatre regarding the subjective qualities "speech intelligibility", "ease of listening" and "overall impression".

Acknowledgements

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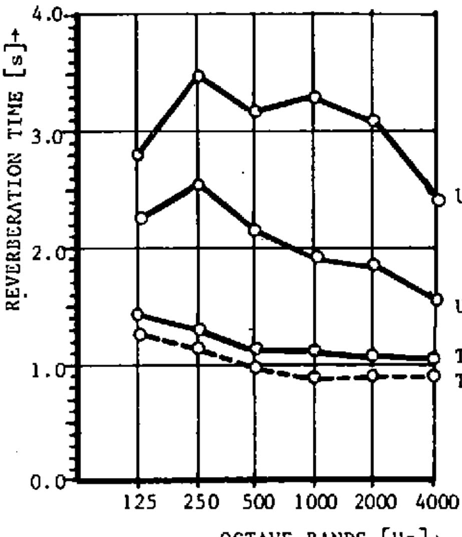

Figure 1. Reverberation time vs frequency curves.

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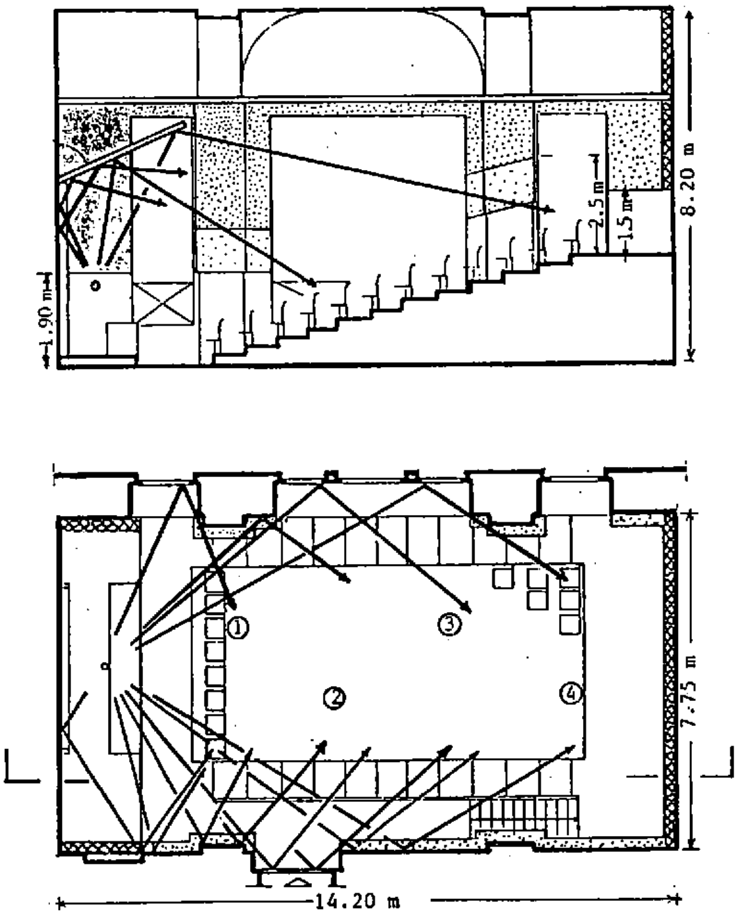


: Plywood covered with fibreglass

: Plywood covered by 20% with fibreglass strips at intervals of 1.0 m

: Plywood

1,2,3,4 : Measuring locations

Figure 2. Plan and Section of the lecture theatre.

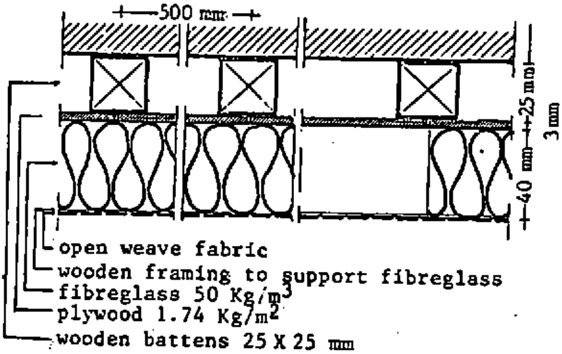
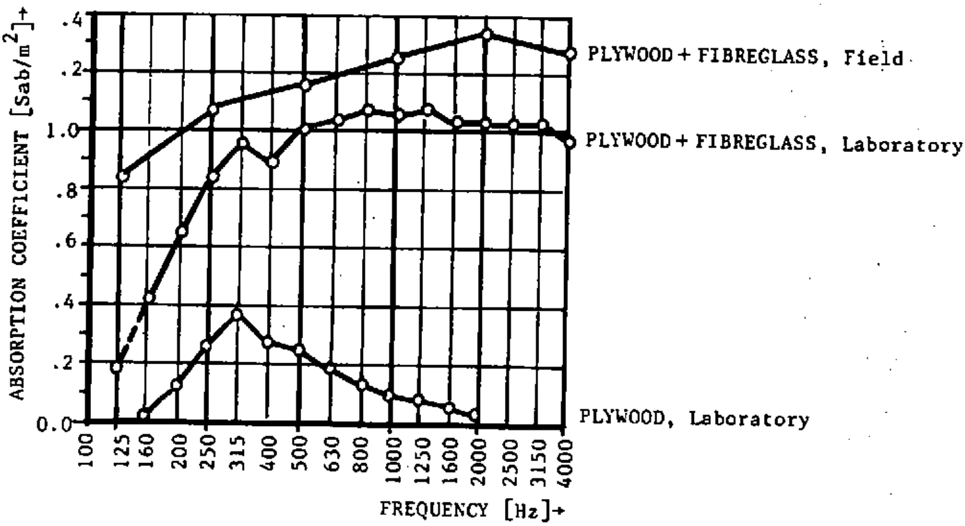


Figure 3. Detail of absorptive treatment.



Specifications
Volume of Reverberation Chamber: 242 m^3
Specimen size: 3.0 m X 3.5 m
Fifty four measurements per frequency

Figure 4. Measured absorption coefficients of the absorptive treatment.

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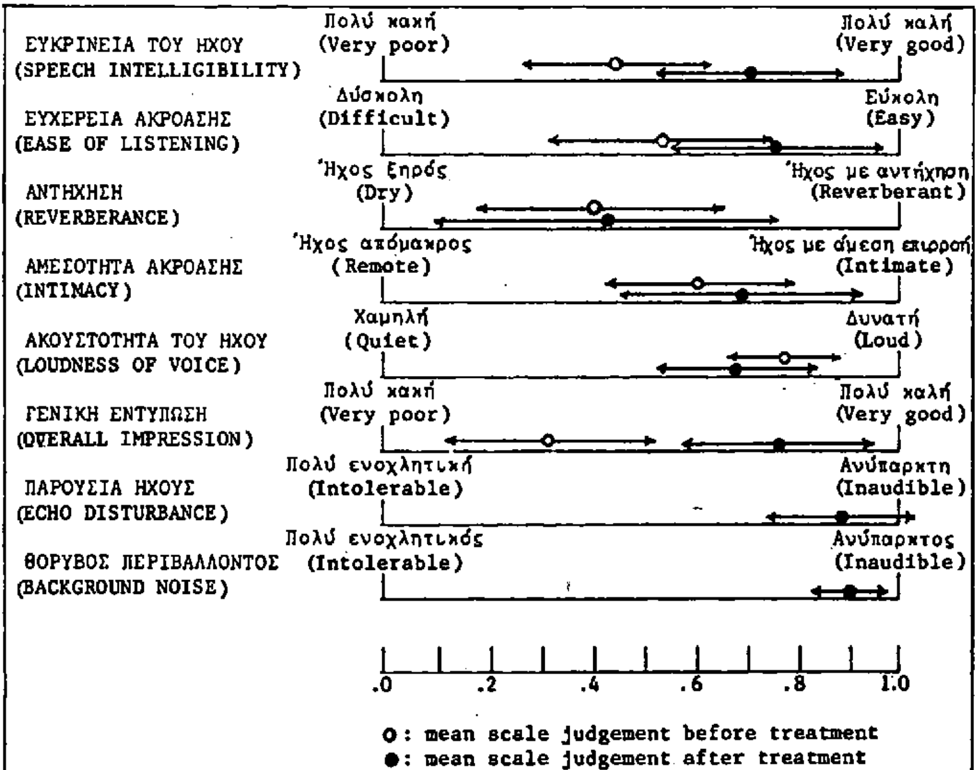

RATING SCALE	MEAN SCALE JUDGEMENT		SIGNIFICANT DIFFERENCE	*Signif. Level*
	Theatre untreated	Theatre treated		
SPEECH INTELLIGIBILITY	.45	.71	YES	*1%*
EASE OF LISTENING	.55	.75	YES	*5%*
REVERBERANCE	.42	.43	NO	*5%*
INTIMACY	.61	.69	NO	*5%*
LOUDNESS OF VOICE	.77	.67	NO	*1%*
OVERALL IMPRESSION	.35	.76	YES	*1%*
ECHO DISTURBANCE	-	.89	-	-
BACKGROUND NOISE	-	.90	-	-

Figure 5. Rating scales and mean scale judgements from the subjective tests.