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On site validation of sound absorption measurements of occupied pews

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ABSTRACT

Laboratory measurements of sound absorption by audiences are known to be scarcely reliable when applied to actual rooms as a consequence of several problems, among which the different area of the "sample" and the different distribution of the reflected sound may play important roles. When dealing with worship places, characterized by a variable degree of occupation and much lower absorption due to unoccupied seats, things become more complicated as absorption seems to be proportional to the number of occupants rather than to the area they cover (as normally accepted in performing spaces). The combination of these variables has been investigated by taking advantage of laboratory measurements and analysing their application to six churches, where on site measurements of reverberation time were carried out with and without occupation. The results are discussed both in terms of simple prediction formulae (Sabine, Eyring, and Arau-Purchades) and of computer simulations, showing that laboratory measurements may be reliably used in computer simulations (at least in the frequency range from 500 Hz on). At low frequencies greater attention must be paid as the absorption coefficients need to be corrected as a function of the actual distribution of the sound field in the room.

1. Introduction

A previous paper [1] discussed the dependence of sound absorption by seated and standing audience as a function of occupation density, posture, and clothing. However, these results were obtained in a reverberant chamber and, consequently, require a further validation before they can be used in practice. In fact, many papers have demonstrated that the "edge effect" (i.e. the increased absorption obtained in the laboratory facility as a consequence of the contribution of the exposed edges) should be carefully taken into account by following one of the methods proposed by Kath and Kuhl [2] or by Bradley [3]. The first proposed putting the sample in a corner and then covering the exposed edges in order to minimize their effect and eventually obtain different absorption coefficients for all the vertical and horizontal surfaces. The second proposed measuring absorption coefficients of a number of samples varying in perimeter-to-area ratio, so that the increased absorption due to edges could be taken into account by means of simple regression equations. Both approaches proved to be satisfactory when dealing with performing spaces characterized by upholstered seats [4–6], as well as when dealing with blocks of empty pews [7,8]. However, results from laboratory measurements [1] suggest that when dealing with occupied pews, and particularly when the density of occupation is low (below about 1.7 pers/m^2), total absorbing area is better related to the number of persons rather than to the area they occupy. This is in agreement with experimental measurements by Desarnaulds et al. [9] and might be explained as a consequence of the relatively large spacing between rows of pews and by the larger amount of exposed body surface resulting from lower densities.

A further problem which generally appears when absorption coefficients measured in the lab are used in practice is a substantial discrepancy at low frequencies, due to differences in the degree of sound diffusion in actual halls and in a reverberant chamber [10]. This problem is mostly related to the dependence of the absorption coefficient on the angle of incidence so it is hard to manage and even using the approach proposed by Summers [11], in which computer simulations are involved, cannot always lead to reliable results. Care must be taken especially when the sound field is strongly lacking in diffuseness and when sound absorbing materials are disposed on opposed surfaces.

The aim of the present paper is to discuss some of the aforementioned problems taking advantage of acoustic measurements carried out in six churches both in unoccupied and occupied conditions. The six cases differ in geometry, materials used, levels of occupancy and audience clothing, providing a comprehensive picture of possible combinations.

2. Methods

2.1. Mathematical model to predict absorption coefficients by audience

Taking into account the analytical results of laboratory tests carried out in a previous study [1] it is possible to define a simple

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procedure to determine the absorption coefficient of the audience as a function of its density (d, measured in pers/m^2), its clothing resistance (I_{cl}, measured in clo [12]), and its posture. First, the absorption coefficients for a standing audience with a clothing resistance of 1.3 clo need to be calculated as a function of density using the equations given in the second column of Table 1. If actual clothing levels differ from 1.3 clo the previous values need to be corrected according to the slopes given in the third column of Table 1, which need to be multiplied by the difference between the reference value (1.3 clo) and the actual I_{cl} value. Finally, for a seated audience the resulting values need to be multiplied by the posture coefficient given in the fourth column. Such values are typical of pews with an open backrest and might be lower in the case of pews having a closed or high backrest (such as those found in Northern Europe).

Even though at the design stage the dependence on the clothing levels is likely to be neglected in most cases (assuming only average conditions at, for example, I_{cl} = 1.0 clo) and the dependence on density of occupation is likely to be practically circumscribed to a small number of standard conditions (as already happens), the availability of such formulas may nonetheless be very useful when dealing with churches and other spaces, where the audience is the only absorbing surface and such variations may result in large fluctuations in reverberation time values.

Fig. 1 shows the variations in absorption coefficients resulting from changes in density and thermal resistance of clothing. The variations between extreme conditions are quite significant, leading to almost doubling the values when moving from d = 1.0 pers/m^2 and I_{cl} = 0.7 clo to d = 1.5 pers/m^2 and I_{cl} = 1.3 clo. By differentiating the expressions as a function of density it can be observed that the largest variations take place in the high frequency range (where the gradient is about 1.0) but tend to decrease when the density grows. The variation as a function of the thermal resistance of clothing shows a peak (of 0.75) at 1 kHz and then decreases as a consequence of the significant high frequency absorption resulting from lightweight clothing.

In order to validate the above formulas a first comparison was carried out between reverberation times (T) measured in six churches with different characteristics under different conditions of occupancy, and the corresponding predicted values. The latter were determined by means of both some classical reverberation time formulas and by means of prediction software based on ray-tracing algorithms. Reverberation time measurements in empty conditions were used as a reference for both formulas and virtual models according to the procedure described in detail below. A core issue of this validation procedure, given the dependence of absorption coefficients on several variables, was the accurate (or at least reasonable) estimation of the density of occupation and of the mean clothing levels. Photographic information taken during the measurements was very helpful to identify the type of clothing, while the number of occupants was determined by counting the number of persons in the church during the measurement session (Fig. 2).

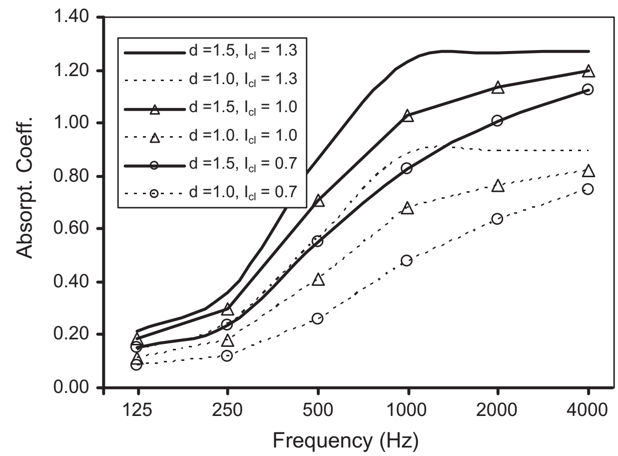

Fig. 1. Plot of absorption coefficients for a seated audience as a function of frequency, density of occupation d (persons/m^2), and thermal resistance of clothing I_{cl} (clo).

2.2. The churches surveyed

The churches surveyed were selected according to different criteria. Availability and motivation of the congregation played a major role. In addition, to increase participation, announcements were given the week before the measurements to briefly explain the scope of the research and the procedure to be followed. Relatively small churches were selected preferably, so that a smaller number of people might determine acceptable densities of occupation and induce significant changes in the reverberation times. Finally, different typologies and shapes were selected in order to test the possible influence of sound diffusion on the results (Fig. 3). A summary of the characteristics of each church is given in Table 2.

San Luca and Sant'Andrea (respectively church A and B) are two very similar churches located in Bari with a shoebox shape, hard reflecting walls and ceiling, and scarcely diffusing elements. The floor is mostly covered by pews so that the sound field is likely to be non-uniform as a consequence of lack of diffusion and concentration of absorbing surfaces.

The church of the Santa Famiglia in Grosseto (church C) has a hemispheric shape, with the dome made of painted concrete "slices" connected by glass windows. The marble floor is partly covered by wooden pews and partly (on the sides) by plastic seats. The church is characterized by audible echoes due to strong focusing effects.

The church of the Risurrezione (church D) is located in Bari and is characterized by an almost cubic shape, with hard reflecting walls, a moderately vibrating metal roof deck ceiling, and a floor which is mostly covered by pews and plastic seats (at the farthest rows). A strip of glass windows tops the four walls and covers the wall behind the altar.

The church of Santa Maria del Carmine (church E) is located in Bari and is characterized by an oblong, nearly elliptical shape. Vertical walls are splayed and finished in plaster with some altars which contribute to increase scattering. The church is covered with a concrete roof subdivided into eight parts, each one finished with a perforated gypsum panel on an air cavity. The sound absorption

Table 1
Summary of the equations to express absorption coefficients of a standing audience wearing winter clothing (I_{cl} = 1.3 clo) as a function of occupation density (d), of the slopes of the linear regressions as a function of clothing insulation, and of the reduction coefficient due to a seated position.

Frequency	Effect of density*	Slope (m)**	Posture coeff.
125 Hz	$\alpha = 0.142d$	0.10	1.00
250 Hz	$\alpha = 0.239d$	0.20	1.00
500 Hz	$\alpha = -0.082d^2 + 0.797d - 0.146$	0.52	1.00
1 kHz	$\alpha = -0.086d^2 + 0.986d + 0.081$	0.75	0.90
2 kHz	$\alpha = -0.115d^2 + 1.109d$	0.48	0.90
4 kHz	$\alpha = -0.114d^2 + 1.125d - 0.017$	0.27	0.90

* Strictly valid for $0.9 \leqslant d \leqslant 2.4$ pers/m^2.
** $\alpha(I_{cl}) = \alpha(1.30) - m(1.30 - I_{cl})$ Strictly valid for $0.5 \leqslant I_{cl} \leqslant 1.3$ clo, but acceptable at points close to the interval limits.

Fig. 2. Photograph of a measurement session in occupied conditions.

characteristics of this panel were extrapolated by means of an acoustic virtual model made with the CATT-Acoustics software and taking into account the empty church configuration. The absorption coefficients were obtained by means of an iterative calibration process described in Section 2.5 and were in agreement with values reported in the literature for similar materials.

The Cathedral of Sant'Eustachio in Acquaviva delle Fonti (church F) is a typical Basilica with side aisles, transept, and an apse culminating the central nave towards the chancel area. The church was completely rebuilt in the 16th century in Renaissance style. The central nave and side aisles are covered by barrel vaults finished in plaster. The walls are partly plastered (with a marble-like finish) and partly made of porous natural stone. The floor is made of marble and is mostly covered by pews. Wooden stalls in the chancel, the organ balcony, also made of richly decorated wood, many paintings on wood in the side aisles contribute to significantly absorb low frequencies.

2.3. The on site measurement procedure

In each church a detailed set of acoustic measurements was carried out in unoccupied conditions. Two sound source positions and an average of seven receiver positions were used. The equipment, complying with ISO 3382 [13], included an omni-directional sound source (Look-Line D301) with a sub-woofer to extend the frequency range down to 40 Hz, a Soundfiled Mk-V microphone, and a 24 bit/48 kHz sound card (Echo Layla 24). A 40 s constant amplitude equalized sweep [14] was used to excite the rooms and calculate impulse responses.

The occupied conditions were generally measured at the end of a pre-festive Mass, using a single source position (generally located in front of the altar) and a reduced sub-set of the receiver positions used in unoccupied conditions. Three to six positions were generally used. The equipment was the same used in unoccupied conditions, even though, when possible, in order to minimize the duration of the measurement session and avoid annoying the congregation, the number of microphones was increased to include two random incidence microphones (GRAS 40-AR), a microphone with variable polar pattern (Neumann TLM-127), and portable Soundfiled microphone (ST-350). The signal used to excite the room was the same used in empty conditions, it was only played back at a slightly reduced gain to prevent problems for the congregation. This fact, combined with the increased background noise determined a general reduction of the signal to noise ratio. However, apart from a few cases, T values could always be determined over a 30 dB interval despite the reduced dynamic range.

2.4. Reverberation time formulas

Taking into account the results of other studies [15] three reverberation time formulas were used during the validation procedure. They can all be written in the following form:

$$T = 0.161\frac{V}{Sa + 4\,mV}, \tag{1}$$

where V and S are the volume and the total surface area of the room, respectively, m is the sound attenuation constant of the air, and a is the "absorption exponent".

Different absorption exponents can be used according to the formulas to be applied, resulting in different weighting procedures involving the areas of each room surface and the corresponding absorption coefficients. The most widely used formula is that defined by Sabine, for which the absorption exponent is simply the average absorption coefficient given by:

$$a_{Sab} = \frac{1}{S}\sum_i \alpha_i S_i. \tag{2}$$

An alternative formulation was proposed by Eyring [16], according to which the reverberation time had to become zero when the absorption exponent was set to unity, consequently he obtained:

$$a_{Eyr} = -\ln(1 - a_{Sab}). \tag{3}$$

Further variations of such formulas were proposed by other researchers in the effort to better fit the actual conditions found in rooms, particularly when dealing with non-uniform distribution of sound absorption. In churches, as well as in auditoria, the absorption is mostly concentrated on the floor so the Fitzroy formula [17] might be a good choice. However, according to recent studies [15], it tends to overestimate reverberation while better accuracy may be obtained by the Arau-Purchades formula [18], which is still based on the Fitzroy approach (i.e. the calculation of directional Eyring absorption exponents) but weights them according to the following formula:

$$a_{ArP} = [-\ln(1-\alpha_x)]^{Sx/S} \cdot [-\ln(1-\alpha_y)]^{Sy/S} \cdot [-\ln(1-\alpha_z)]^{Sz/S}, \tag{4}$$

where S_x is the ceiling plus the floor surface area, S_y is the surface area of both side walls, and S_z is the surface area of both end walls.

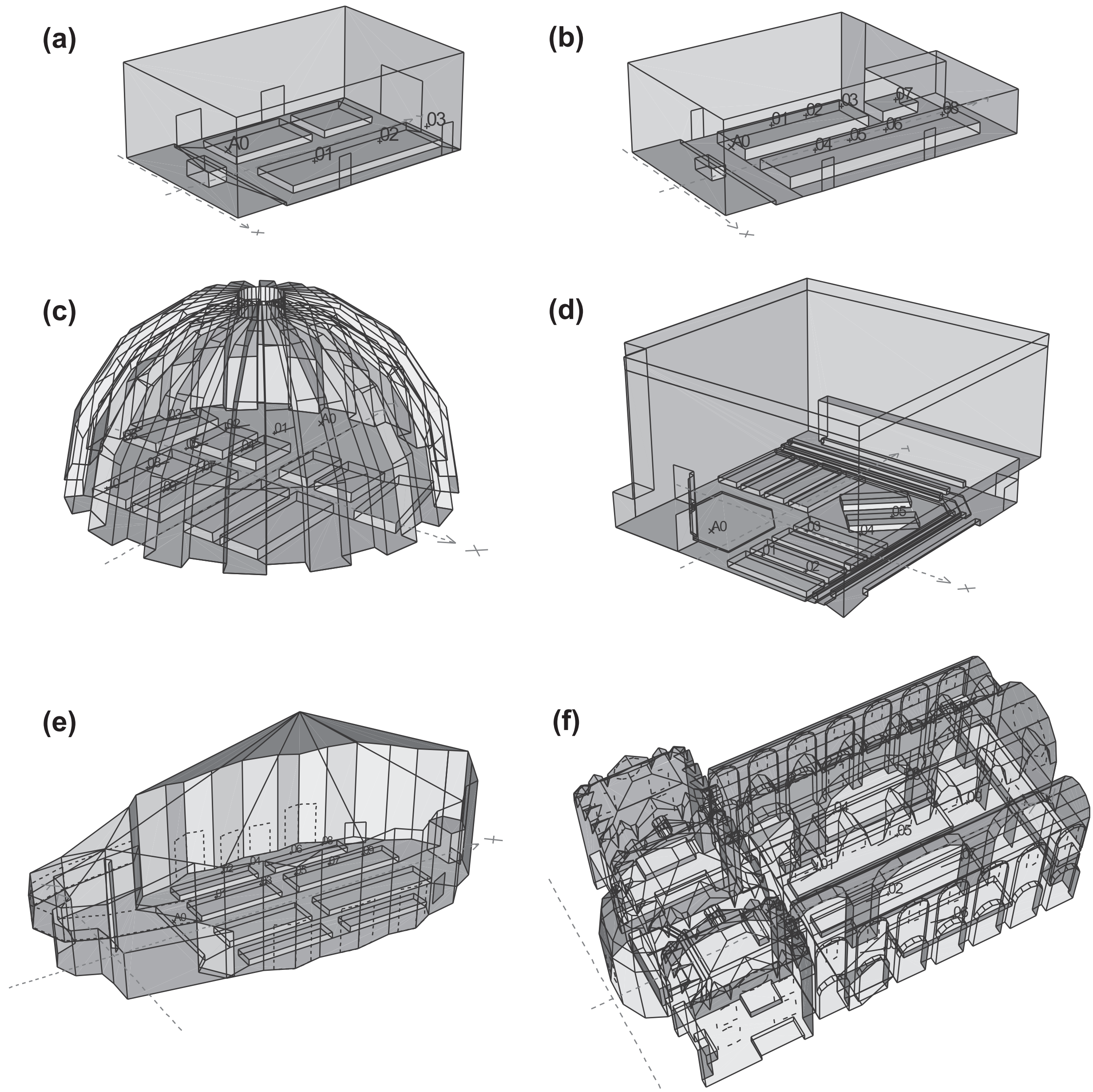

Fig. 3. 3D models of the surveyed churches. (a) church of San Luca in Bari; (b) church of Sant'Andrea in Bari; (c) church of the Santa Famiglia in Grosseto; (d) church of the Resurrezione in Bari; (e) church of Santa Maria del Carmine in Bari; and (f) Cathedral of Sant'Eustachio in Acquaviva.

In addition, α_x, α_y, and α_z are the mean absorption coefficients of the surface areas S_x, S_y and S_z.

For each church the mean absorption coefficients in empty conditions were first determined using Sabine's formula. Air absorption was estimated using ISO 9613-1 [19] and subtracted from total absorbing area so that the absorption exponent could only account for the contribution of surfaces. In all cases except for church E the resulting values were below 0.1 independent of frequency, so that no significant differences should appear when determining α using different formulas (or, conversely, when calculating the reverberation time using the same α values and different formulas). Church E differs from the others as a consequence of the perforated ceiling which determines high absorption in the low frequency range, and because of the pews with upholstered kneelers which contribute to increase the high frequency absorption (the pews correspond to type A1 and A2 in Ref. [8]). As the absorption coefficient of the pews was already available, and the absorption due to the ceiling had been determined from the calibration of the virtual acoustic model, the residual absorption was calculated only after subtracting those two important contributions to the total absorption and dividing by the corresponding residual area.

Subsequently the occupied conditions were estimated by means of a simplified approach. In all cases the absorption coefficients determined in Section 2.1 were assumed to be inclusive of pews absorption, consequently the surface originally covered by pews was assumed to be covered be a seated audience (at the corresponding conditions of density and clothing insulation). The absorbing area of the pews (obtained by multiplying the residual absorption by the pew area) was hence replaced by the absorbing area of the audience. Again, the only exception was church E, where the actual absorption coefficients of the pews were available and in addition, were significantly different from the residual absorption).

No further effort was required in order to define both the Sabine and Eyring absorption exponents. Conversely, to determine the Arau-Purchades exponent the three average absorption coeffi-

Table 2
Summary of the characteristics of the churches surveyed including mid-frequency reverberation time (T_{mid}) measured in unoccupied conditions, number of occupants (N), density, clothing levels (I_{cl}), and outside temperature (T_{ext}) observed during the measurements in occupied conditions, and date in which they were carried out.

ID		Volume (m^3)	Floor area (m^2)	Pews area (m^2)	Tmid (500–1 k) (s)	N	Dens. (pers/m^2)	I_{cl} (clo)	T_{ext} (°C)	Date
A	San Luca	1300	220	72	4.14	95	1.30	1.30	12	April 10
B	Sant'Andrea	1300	255	92	4.12	126	1.40	1.00	17	May 5
C	Grosseto	4600	530	150	5.37	80	0.53	1.30	15	November 17
D	Risurrezione	7500	544	180	7.29	174	0.97	0.80	18	June 31
E	Carmine	9500	750	199	3.64	240	1.01	1.30	10	November 12
F	Acquaviva	10,200	800	180	4.79	207	1.14	1.40	8	February 22

cients had to be calculated. In particular, in the surveyed churches only the z direction showed a substantial difference from the x and y direction, where no significant differences appeared. The resulting α_z values were hence calculated for each church by combining the absorption of the congregation (assigned to a surface area corresponding to the pews) and the residual absorption (assigned to twice the floor area minus the pew area). For the reasons already explained, in church E the α_z value was determined by taking into account the actual absorption coefficient of the ceiling. However, given the shape of the roof it was reasonable to assign to the z-axis only the fraction of the actual absorption corresponding to the projection of the roof on the horizontal plane.

Finally, for each church the resulting values of the reverberation time were calculated using the different absorption exponents and the air absorption corresponding to the actual conditions observed during the measurements.

2.5. Virtual model calibration

The computer simulation of the surveyed churches was carried out using CATT Acoustic v.8.0 h software which uses different ray-tracing algorithms which have been widely tested in different types of spaces including churches [20] and complex coupled volume arrangements [21,22].

For each church a simplified 3D model was made (Fig. 3), including all the relevant acoustic details and neglecting those which could be better simulated by a proper modification of the scattering coefficients (i.e. pews were modelled as usual using simple rectangular blocks with increasing scattering coefficients as the frequency grows). During the first step of the calibration process absorption coefficients taken from the literature were assigned to the surfaces, while the scattering coefficients were defined as a function of the actual dimension of the surface irregularities. A uniform treatment of the scattering coefficients was ensured throughout the study, trying to strictly adhere to the physical conditions found in the churches (a summary of the values used is given in Table 3). Correction for air absorption based on actual measurements of temperature and relative humidity was also provided by the software.

The resulting reverberation times were then compared with those measured on site. A conventional tolerance of 5% (corresponding to JND for reverberation time [23]) is generally accepted. However, in order to emphasize the effects due to occupation, a stricter limit of 2.5% was assumed in this phase. Absorption coefficients were consequently modified case by case in order to obtain the best possible predictions of the T values. Modifications started from surfaces with the most uncertain behaviour and covering the largest areas (so that significant variations might be obtained without altering the expected acoustic response of the material), and from those surfaces that suffered important simplifications (including the presence of pictures, panels, and small parts made of different materials). A summary of the absorption coefficients used is given in Table 4. It can be observed that the average values are in good agreement with those typically encountered in the literature, and the standard deviations are remarkably low.

After the calibration procedure the absorption coefficients of the pews were replaced by those obtained with the proposed model. It should be noted that following the results obtained in Ref. [8], absorption coefficients were only applied to horizontal surfaces, while vertical surfaces were given null values. These surfaces may be conveniently used when the absorption resulting from the model is greater than 0.99 (which is the maximum value allowed by the software, in agreement with the principle of energy conservation). In this case the exceeding absorption is uniformly distributed on the vertical surfaces. So, if α is the absorption coefficient resulting from the model, and S_H and S_V are the areas of the horizontal and vertical surfaces of the pew blocks respectively, the absorption coefficient α_V to be assigned to the vertical surface will be:

$$\alpha_V = (\alpha - 0.99)\frac{S_H}{S_V}$$

Even though this approach may appear too simplistic, it proved to be quite effective (as will be shown below) to address the problem without using more complex approaches to simulate the audience (i.e. using more detailed models of the seating areas).

Table 3
Summary of the average scattering coefficients used in the six different models.

	125	250	500	1000	2000	4000
Smooth surfaces (marble)	0.10	0.10	0.10	0.10	0.10	0.10
Flat surfaces (with irregularities)	0.15	0.16	0.17	0.18	0.19	0.20
Pews/audience	0.55	0.60	0.65	0.70	0.75	0.80

3. Results

3.1. Validation using classical formulae

The results of the reverberation time predicted according to the three classical formulas in occupied conditions are given in Fig. 4, together with the values experimentally measured on site. It can be observed that substantial differences appeared between the churches, requiring a detailed explanation.

For church A (Fig. 4a) the agreement between measured and predicted values was remarkable, with errors below 10% for both the Sabine and Arau-Purchades formulas, while the Eyring formula tended to under-predict values particularly at high frequencies (Table 5). The Arau-Purchades formula provided slightly better results, with an average error of just 4% while Sabine's formula gave an average error of 6%. The largest differences (about 10%) appeared at 125 Hz. Differences between Arau-Purchades and Sabine appeared mostly as a consequence of the high absorption of the audience at medium and high frequencies, while at low frequencies there was a substantial agreement between the two formulations. The Eyring formula performed badly, underestimating T over all the frequencies and giving an average error of 14%.

Table 4
Summary of the average absorption coefficients used in the six different models with the corresponding standard deviations.

	125	250	500	1000	2000	4000
Floor	0.01 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.01
Plaster	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.00	0.05 ± 0.00	0.05 ± 0.00
Windows	0.33 ± 0.05	0.24 ± 0.09	0.16 ± 0.06	0.10 ± 0.03	0.05 ± 0.02	0.03 ± 0.01
Wood doors	0.21 ± 0.08	0.22 ± 0.13	0.17 ± 0.12	0.11 ± 0.04	0.10 ± 0.00	0.10 ± 0.00
Pews	0.02 ± 0.01	0.05 ± 0.01	0.05 ± 0.02	0.08 ± 0.01	0.08 ± 0.01	0.08 ± 0.01
Ceiling*	0.03 ± 0.01	0.04 ± 0.01	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00	0.05 ± 0.00

* Excluding churches D and E.

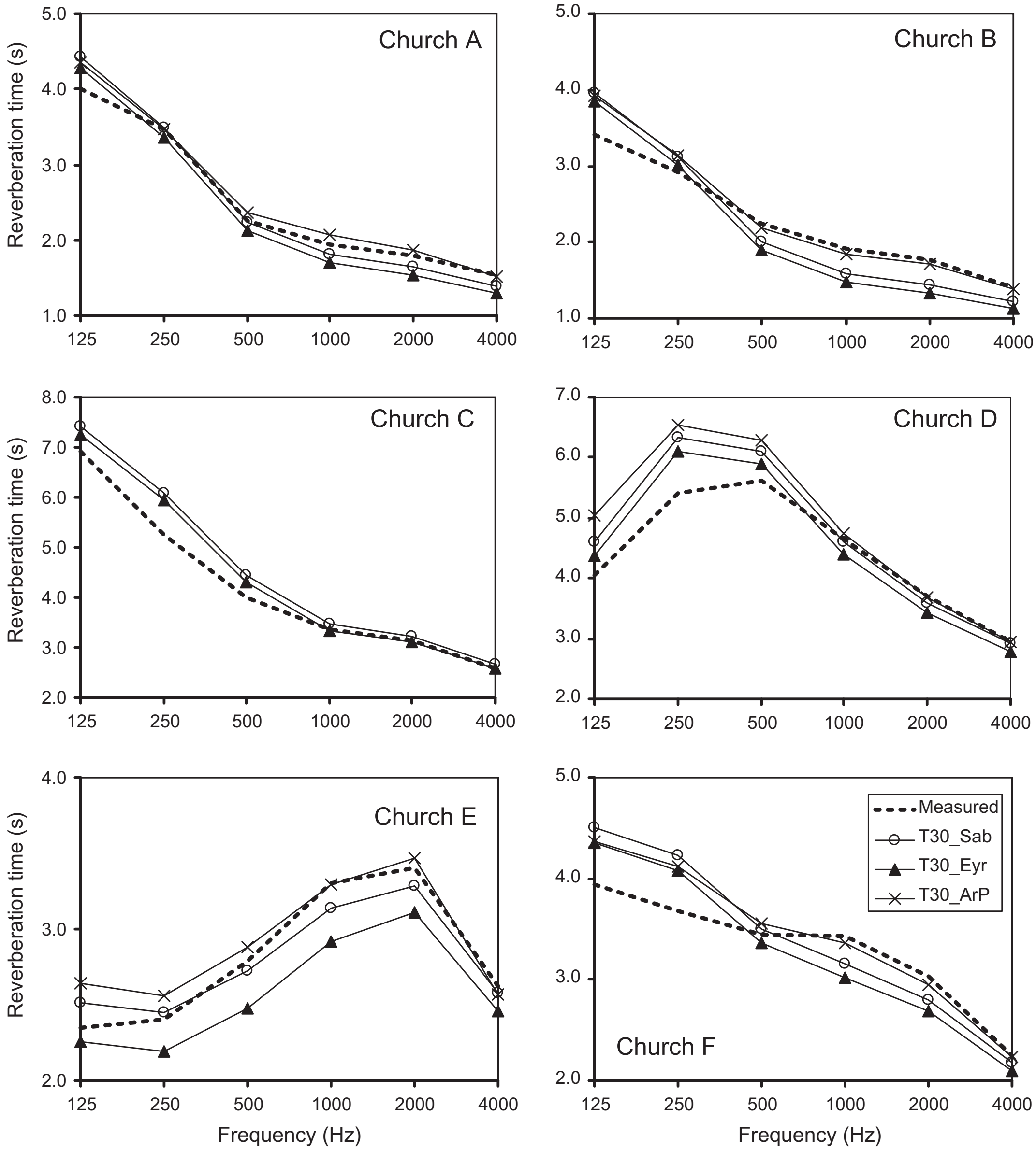

Fig. 4. Plot of measured (thick dashed line) and predicted reverberation times as a function of frequency in each of the churches surveyed. (×) predicted by Arau-Purchades formula; (○) predicted by Sabine formula; (Δ) predicted by Eyring formula.

For church B (Fig. 4b), which was very similar to church A but was characterized by a slightly higher degree of occupation, predictions by the three formulas showed the same trend, but differences between them were slightly more evident. The Arau-Purchades formula again gave longer reverberation times, which this time were in better agreement with measured values. In fact, the average error was just 6% with a peak of 15% at 125 Hz. Both the Sabine and Eyring formulas were characterized by average errors of 14% and 16% respectively, distributed almost evenly over all the frequency bands.

For church C (Fig. 4c), characterized by the hemi-spherical shape, the Arau-Purchades formula was not applicable, and the Sabine and Eyring formulas provided slightly different levels of accuracy, with an average error of 10% and 5% respectively, and largely

Table 5
Summary of the average prediction errors resulting from use of different formulas, and errors at 125 Hz and 250 Hz corresponding to the more accurate formula (typed in bold letters).

	Arau-Purch. (%)	Sabine (%)	Eyring (%)	Best at 125 Hz (%)	Best at 250 Hz (%)
Church A	**4**	6	10	9	0
Church B	**6**	14	17	15	7
Church C	n.a.	7	**5**	5	13
Church D	10	**7**	7	14	17
Church E	**4**	4	8	12	7
Church F	**5**	8	9	11	12
Average	6	8	9	11	9

due to the much larger errors appearing at the low frequencies. In fact, the largest discrepancy was at 250 Hz, where the error was 19% with the Sabine and 15% with the Eyring formula. Strangely enough, overestimation was more evident at 250 Hz than at 125 Hz (where it usually appears). A possible explanation of such behaviour might be an unusually low absorption of the pews in the low frequency range so that when they were replaced (subtracting the residual absorption which is higher) this determined a lack of sound absorption. Further elements to explain the problem could be found in the position of the windows (which are mostly responsible for the low frequency absorption in the church). The better performance of the Eyring formula even at high frequencies might be a consequence of an underestimation of the absorption coefficients by the audience, but it seems more likely to be a consequence of the shape of the church. In fact, the hemispherical vault reflects the sound towards the congregation, so that the absorbing effect is more evident. It is interesting to observe that given the particular shape, despite the scattering due to the different concrete slices, the sound was likely to be reflected towards the more absorbing audience, so that the Eyring formula (which generally underestimates reverberation time) yielded the best results.

For church D (Fig. 4d), characterized by a vibrating ceiling absorbing low frequencies and by the an audience having the lowest clothing resistance in this study (I_{cl} = 0.80 clo), it was observed that, as a consequence of the concentration of sound absorption on the two horizontal surfaces (low frequency on the ceiling and medium–high on the floor) the Arau-Purchades formula predicted longer T values compared to the Sabine and Eyring formulas over all the spectrum. In terms of accuracy the best average performance was shown by the latter formulas with a mean error of 7%, while the first gave an error of 11%. However, the largest discrepancies (greater than 15%) appeared at frequencies below 500 Hz, while in the high frequency range the accuracy was remarkably better with an average error of about 2% using both the Arau-Purchades and Sabine formulas.

For church E (Fig. 4e), characterized by a roof mostly absorbing in the low frequency range, significant differences appeared between predictions obtained with the three formulas. In terms of accuracy, Arau-Purchades and Sabine provided an average error of 4% (with the experimental curve lying in between the two predictions), while Eyring gave an average error of 8%. The Arau-Purchades formula provided the best accuracy at frequencies above 250 Hz, with a mean error of 2%, while in the low frequency range the usual overestimation appeared.

For church F (Fig. 4f), having a Basilica shape with naves and vaults, the Arau-Purchades formula again gave longer reverberation times, which were in good agreement with measured values. In fact, the average error was just 5% with a peak of 12% at 250 Hz and much better accuracy (on average 2%) at higher frequencies. Both the Sabine and Eyring formulas provided shorter reverberation times, resulting in average errors of 8% and 9% respectively with slightly different fluctuations over all the frequency bands.

In conclusion, it can be observed that apart from church D, where the discrepancy in the low frequency range significantly worsened the global performance, the best results were obtained using the Arau-Purchades formula which gave an overall mean error of 6%, followed by Sabine's formula which despite the lower accuracy gave average errors that were generally below 10%. The better accuracy of the Arau-Purchades formula was also shown by considering only medium–high frequency values. The success of the first formula was reasonably related to the uneven distribution of the absorbing surfaces and to the relatively simple geometry of the churches surveyed. In fact, in rooms having more mixing shapes (i.e. church E) the differences were less evident. Church F, despite having a clearly mixing shape shows a better agreement with the Arau-Purchades formula, possibly as a consequence of the more complex nature of the space, with high vaults, side aisles, and chapels. In particular, it should be noted that transepts and the chancel remain almost unoccupied during celebrations, while the nave and the aisles may be fully covered by occupants, resulting in the acoustic coupling of different volumes.

In terms of the reliability of the absorption coefficients predicted using the proposed model and based on reverberation chamber measurement, it can be concluded that the accuracy in the medium and high frequencies was very good, with errors generally below 5%, suggesting that (providing the density of occupation and thermal resistance of clothing are estimated with reasonable accuracy) the resulting absorption coefficients can be used "as is". At low frequencies things became slightly more complex, as the predicted reverberation times were always longer than those measured, with higher average errors (11% and 9% respectively at 125 Hz and 250 Hz), and peaks somewhat above these values. However, the observed discrepancies were in reasonable agreement (apart from some fluctuations) with the results of Nishihara et al. [10] who showed that the different distribution of the sound rays in real rooms (where sound arrives on the audience mostly at grazing incidence) was responsible for increased absorption in the low frequency range compared to the more diffuse conditions produced in a reverberant room. Further evidence of this behaviour is discussed in Section 3.4.

3.2. Validation using simulation software

The results of the reverberation time predicted according to the computer model simulation in occupied conditions are given in Fig. 5, together with the values experimentally measured on site. Given the independence of the results on particular formulas and assuming that the surface treatments were simulated as described in Section 2.4, an analysis of the possible errors deriving from incorrect estimation of thermal insulation of clothing (the most difficult parameter to estimate in the predictive model for audience absorption) was added. Variations of ±0.1 clo were applied to the values given in Table 1 and the resulting T were plotted in Fig. 5 together with the average errors given in Table 6.

Results showed some differences, with small case-by-case variations. However, the general trend observed with theoretical formulas was confirmed by the very good accuracy at medium and high frequencies (with errors well below 5%) and relatively

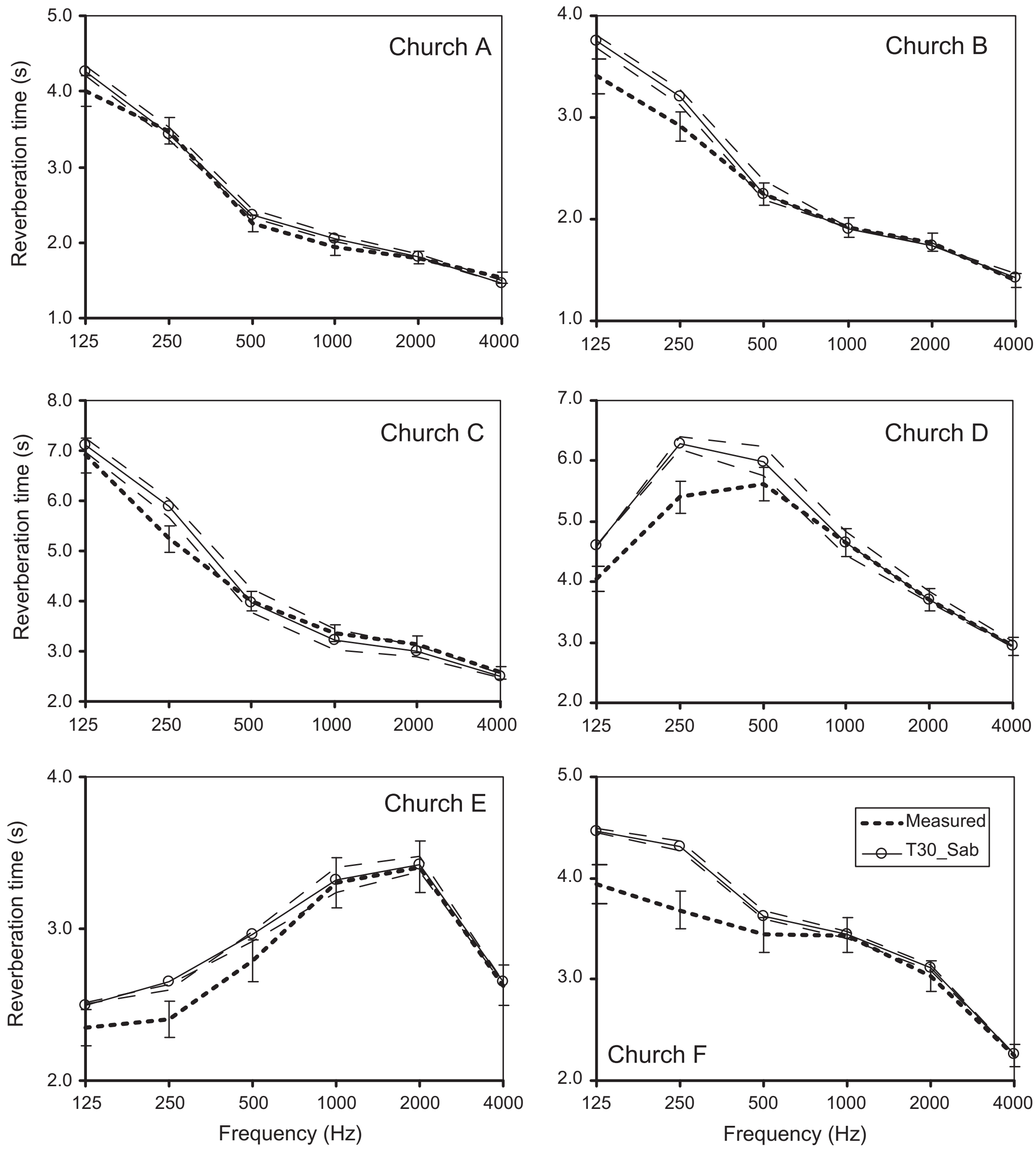

Fig. 5. Plot of measured (thick dashed line) and predicted reverberation times as a function of frequency in each of the churches surveyed. (○) predicted by CATT simulation software; (– –) predicted by CATT using absorption coefficients for an audience with thermal resistance changed by ±0.1 clo. Error bars on measured values correspond to 5% tolerance.

Table 6
Summary of the average prediction errors resulting from use of simulation software in empty and occupied condition, and errors at 125 Hz and 250 Hz and averaged over the octave bands from 500 Hz to 4 kHz.

	Empty (%)	Full (%)	125 (%)	250 (%)	500–4 k Hz (%)
Church A	2	4	7	1	4
Church B	1	4	10	10	1
Church C	1	5	10	12	3
Church D	1	6	14	16	2
Church E	2	4	6	10	2
Church F	2	7	13	17	2
Average	1	5	10	11	2

less good predictions in the lowest bands, where the average differences were of about 10% with peaks above 15% appearing in two cases.

Again, when low frequency absorption coefficients measured in the laboratory were applied to real world cases, it led to an over prediction of reverberation times.

At higher frequencies it can be observed that despite the initial "gap" represented by the small inaccuracies due to the calibration of the empty model, the simulation software managed to provide results as accurate as those given by the best theoretical formulas (and sometimes even better), without the need to choose the most suitable formula for the given case (which, in the light of the above results, is not that obvious). Such behaviour is in agreement with the observations described in Ref. [8], where α values obtained from laboratory measurements performed better in computer simulations than values derived from Sabine's formula and on site measurements.

The analysis of the errors due to the estimation of I_{cl} values pointed out that, as shown in Fig. 1, the largest variations in absorption coefficients were observed at mid-frequencies. However, the variations in T were largely dependent on the initial conditions (at the empty stage) and on the season (as the amount of absorption due to the audience changes). In all the cases the change of ±0.1 clo corresponded to a maximum relative variation of 5% in the accuracy level compared to the error due to original I_{cl} values, and to absolute errors (referred to measured T values) which, in the medium–high frequency range, remained well below 10%. This analysis confirmed that the estimation of the thermal resistance of clothing may tolerate some approximations without significantly altering the final results. In addition, it should be considered that during the design stage it might be preferable to refer to a few "reference" conditions such as those reported in Fig. 1 (i.e. 0.7 clo during summer, 1.0 clo during spring and autumn, and 1.3 clo during winter).

4. Discussion and practical implications

In order to analyse the magnitude of the variations in the estimated absorption coefficients required to match the onsite behaviour, an optimization procedure was carried out, by varying α at 125 and 250 Hz until the prediction error was minimized according to the prediction formula which performed best for that given case. Differences in the 500 Hz band were neglected as they only appear in a few cases and might result from small inaccuracies in the estimation of I_{cl} (i.e. in church D the value of 0.8 clo might be underestimated because, despite the summer season, the weather was rainy and most people wore jackets).

The same optimization procedure was also carried out with the computer simulated models, by recursively modifying absorption coefficients until the error in the 125 Hz and 250 Hz bands was minimized (equalling the error in the medium–high frequency range).

Taking into account the ratios of optimized to predicted values, the results given in Table 7 showed two substantially different behaviours. In fact, the first group of churches, having smaller dimensions and lacking in low frequency absorption, showed ratios of 1.5 at 125 Hz and 1.3 at 250 Hz with slight variations as a function of the method used (formula or computer simulation). The second group of churches, having larger volumes (mostly due to higher ceilings) and a certain amount of low frequency absorbers (in two cases located on the ceiling) had ratios of about 3 at 125 Hz and of about 2 at 250 Hz when using formulas and slightly larger when using computer simulation. Taking into account the whole set of churches and both the methods used, the ratios became 2.3 at 125 Hz and 1.75 at 250 Hz. It is interesting to observe that the results shown by Nishihara et al. [10] comparing onsite and laboratory measurements of absorption coefficients showed a ratio of 1.7 at 125 Hz and of 1.5 at 250 Hz, in better agreement with the first group of churches the characteristics of which are more similar (also in terms of room proportions) to those observed in auditoria.

Table 7
Summary of the ratios between optimized and original (predicted) absorption coefficients at 125 Hz and 250 Hz subdivided according to the prediction method used.

	Best theoretical formula		Computer simulation model	
	125 Hz	250 Hz	125 Hz	250 Hz
Church A	1.40	1.00	1.28	1.00
Church B	1.62	1.24	1.48	1.27
Church C	1.55	1.81	1.32	1.42
Church D	3.21	2.37	2.97	2.04
Church E	3.52	1.67	3.52	2.34
Church F	2.33	1.99	2.57	2.18
Average	2.27	1.68	2.30	1.82
Average A–C	1.53	1.35	1.36	1.25
Average D–F	3.02	2.01	3.25	2.39

The larger discrepancies observed in churches D and E could be partly explained as a result of the higher ceiling which also absorbs low frequencies. Consequently, in occupied conditions sound absorption is concentrated on two parallel surfaces, resulting in a largely non uniform distribution of the sound field. Such uneven distribution of sound reflections might be responsible for the increased absorption due to the audience, in agreement with measurements in Nishihara et al. [10].

Church F represents an intermediate situation, as it is a large church with high plastered vaults and mixed geometry that is likely to have a mixing effect on sound propagation. It also shows some low frequency absorption but it is mostly distributed on the choir stalls, on the organ balcony and, partly on the side walls. So, in this case the distribution of the reflections reaching the audience should be more uniform, but the scattering effect of the vaults weakens reflections from the top in comparison with those coming from the side walls, resulting, again, in increased low frequency absorption.

In order to better understand the influence of the distribution of sound reflections on the absorption mechanism, the directional components of B-format measurements (X, Y, Z) were combined with the omni-directional component (W) to provide a 3D impulse response. Plots representing the energy content arriving from discrete directions represented by azimuthal and zenithal angles were used to make the information more easily accessible (Fig. 6). In order to make results comparable the direct sound was excluded (i.e. the first 20 ms were not considered), and a fixed 1 s interval was considered in all the cases.

Fig. 6 shows the directional distribution of the reflections in a reverberant chamber and in four selected churches. The reverberant chamber shows, as expected, the most uniform distribution with reflections coming from nearly every direction with the weakest contributions coming from the bottom (a behaviour that is systematically observed in the other examples). Church B (Fig. 6b) shows a less uniform distribution, with a dominance from the front (source direction) and, with lower levels, from the top-left quadrant and from the right side. Church C (Fig. 6c) shows even stronger non uniformities (which was expected due to the shape of the church), with a clear dominance of the front-back direction with elevation angles generally below 45°. Frontal reflections at grazing angles are also clearly visible in church E (Fig. 6d), where the strongest reflections (about 10 dB larger) come from the source direction within a ±45° interval in the horizontal plane and within 20° in the vertical plane. The presence of the sound absorbing ceiling may be noticed in the weakest reflections from the top direction among the observed churches. Church F (Fig. 6e) shows nearly the same behaviour with a front-back dominance with some lateral reflections, all arriving at grazing angles, with a slightly more uniform contribution of (weaker) diffuse reflections coming from the top.

So, combining the above results with those given in Fig. 15 of Ref. [10] may contribute to explaining the observed discrepancies and the differences between the two sets of churches. In fact Nishihara et al. suggest that the absorption coefficient of a seated audience at 125 Hz and 250 Hz is largely dependent on the angle of incidence of the impinging reflection, being relatively low for normal incidence and considerably higher (about 0.8) for a grazing incidence. Consequently, high absorption coefficients become perfectly justifiable at low frequencies if most of the reflections (or those with the larger magnitude) reach the audience at grazing incidence. However, as the determination of the actual distribution of the sound field in a room is not trivial and things may change case by case, even as a function of the seat type, only a rough estimation seems possible in those cases.

In conclusion, taking into account that the errors observed in the low frequency range when using absorption coefficients resulting from the proposed model are of about 10% and that this is

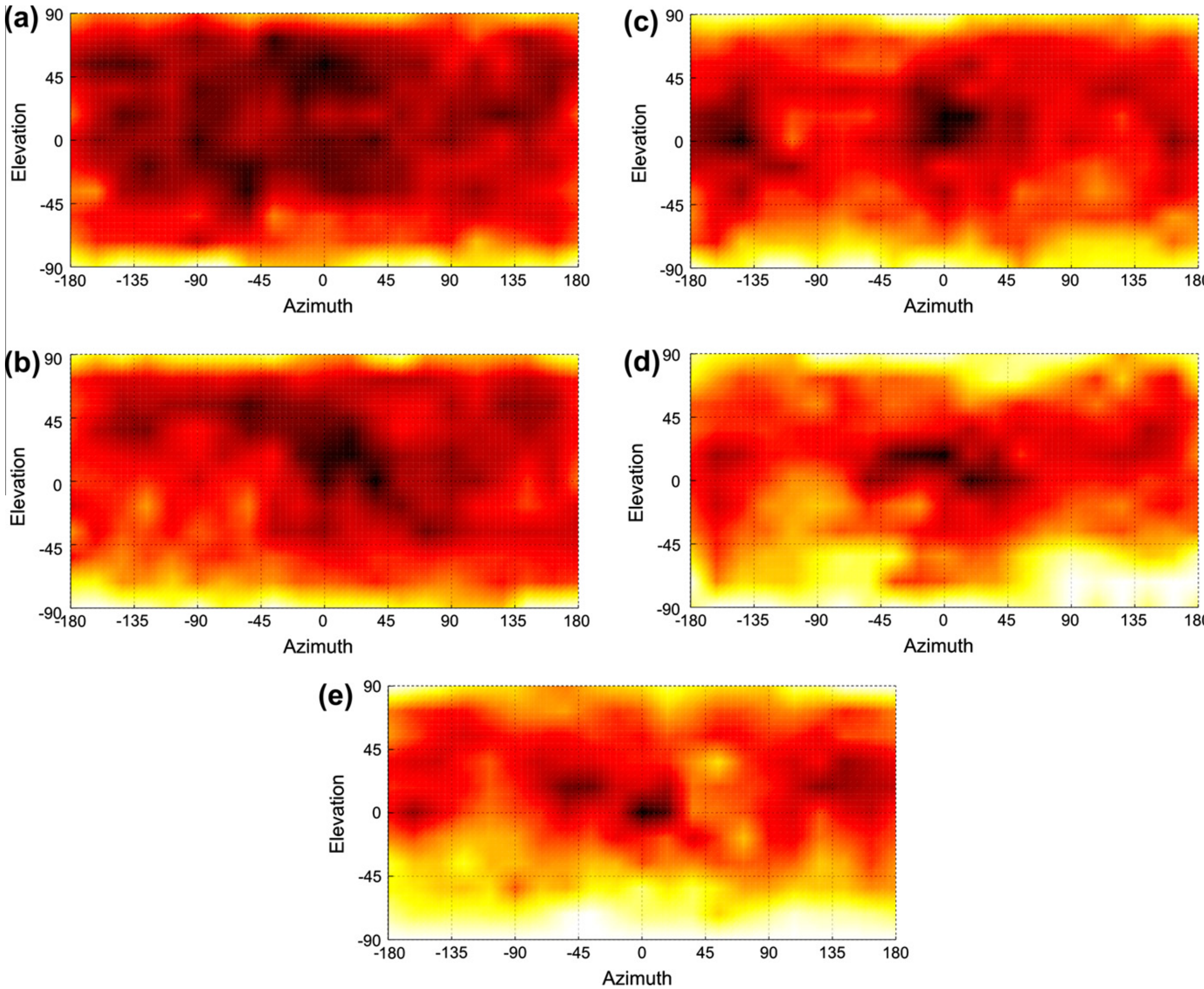

Fig. 6. Plot of the directional distribution of the energy content of the reflections in the 125 Hz frequency band as a function of azimuth and elevation angles (assuming as a reference the source-receiver direction). Reflection levels were normalized with reference to the maximum energy content within a 30 dB range and computed over the first 1.0 s interval of the selected IRs excluding the very first 20 ms corresponding to direct sound. (a) reverberant chamber, (b) church B, (c) church C, (d) church E, and (e) church F.

Table 8
Summary of the average prediction errors resulting from corrected absorption coefficients according to their use in prediction formulas or in simulation software at different frequencies. Results for prediction formulas are subdivided into six-octave-bands average (with best result typed in bold letters), low frequency error for the most accurate formula, and low frequency average error for Sabine's formula.

	Theoretical formulas (125–4 k)			Most accurate formula		Sabine	Computer simulation	
	ArP	Sab	Eyr	125	250	125–250	125	250
Church A	**4**	6	11	2	6	5	6	8
Church B	**2**	11	15	3	0	2	2	2
Church C	n.a.	5	**3**	1	8	6	6	5
Church D	4	3	5	2	1	1	7	1
Church E	**2**	4	12	5	1	5	3	4
Church F	3	5	8	4	5	5	3	0
Average	3	5	9	3	4	4	5	3

generally assumed as an "engineering" level of accuracy for reverberation time predictions [15,24], a possible choice could be simply to accept this level of uncertainty and use the values "as is". However, all the results found in the surveyed rooms support the arguments proposed by Nishihara et al. [10] and suggest adopting at least a minimum correction to account for the different distribution of the reflections in a reverberant chamber and in actual rooms. Such a correction should consist of increasing the absorption coefficients obtained from the model by an amount depending on the use of either a theoretical formula or a computer simulation program. However, given the required level of accuracy and the approximations made, it seems a more practical approach to only propose a frequency dependent correction factor of 1.50 and 1.25, respectively at 125 Hz and at 250 Hz. In the case of rooms with significant low frequency absorption or where the strongest reflections are expected at grazing angles, the absorption coefficients obtained from the model could be corrected by simply doubling the previous factors. However, greater inaccuracies should be expected in this case.

Taking into account the proposed corrections, the resulting residual errors in the prediction of reverberation times using both formulas and simulation software were finally analysed. The results showed (Table 8) that using the same formula which originally minimized the error in the medium–high frequency range, generally led to errors below 5%. Larger discrepancies appeared in church A and church C at 250 Hz because in the first case there was almost no need for corrections and in the second because of the already discussed problems. Supposing that, for the sake of simplicity, only the Sabine formula was used, the average errors would have been about 5% over all the frequencies and about 4% at low frequencies, showing an improved agreement which could have been even better had the differences for church B been smaller.

Using the same corrections in a simulation program led to considerably reduced errors in the low frequency range, with an average of about 4% and a maximum of 8% appearing again at 250 Hz for church A.

In conclusion, the proposed corrections to account for the on site distribution of sound reflections and the consequently increased absorption coefficients at low frequencies proved to be quite effective, keeping the average errors below (or slightly above) 5%. Taking into account the whole frequency range the proposed model appears to predict the absorption coefficients with good accuracy provided that both the density of occupation and the thermal resistance of the clothing are estimated with reasonable accuracy. However, as the larger variations due to clothing appear in the mid frequency range, where the amount of total absorption in generally not negligible, an incorrect estimation of I_{cl} by ±0.1 clo would lead to a maximum additional error of 5%.

5. Conclusions

The results of a previous set of laboratory measurements of sound absorption by a seated audience were validated by means of on site measurements. The laboratory results showed a dependence on density of occupation, posture and thermal resistance of clothing, leading to the definition of a series of equations to predict absorption coefficients as a function of frequency. On site measurements carried out in occupied churches of different shapes and dimensions and with different levels of occupancy and clothing insulation were used to validate the lab model. Comparisons were made both using classical theoretical formulas and simulation software. In both cases, results showed a good level of accuracy (with errors below 5%) at medium and high frequencies, even though in the first case a dependence on the formula used to make the calculations was observed. In all the cases greater discrepancies appeared at low frequencies, where the predicted reverberation times were longer than those measured, with average errors of about 10% and peaks above 15%. The subsequent attempt to increase the absorption coefficients in order to match the measured reverberation times led to observing two different behaviours which were explained following the observations of Nishihara et al. [10] about the variation of the low frequency absorption coefficient as a function of the angle of incidence of the impinging reflections. In particular, rooms with uniform treatment of surfaces and proportionate shapes required absorption coefficients to be increased by a factor of 1.5 at 125 Hz and of 1.25 at 250 Hz in order to match the measurements. Conversely, the rooms with high (scattering) ceilings and low frequency absorption required an increase in the absorption coefficients by a factor which was approximately doubled (3.0 at 125 Hz and 2.5 at 250 Hz). Such strange behaviour appeared to be related to the considerably non uniform distribution of the reflections in such spaces. Diagrams showing the arrival direction of the reflections proved that the ceiling absorbed or scattered the incident sound which consequently arrived at the audience from walls and with a grazing incidence which corresponded to a significantly higher absorption. The adoption of the proposed corrections allowed reduction of the prediction errors in the low frequency range, keeping them around 5%. In conclusion, the model derived from laboratory measurements proved to be reliable at medium and high frequencies. At low frequencies a correction was required depending on the way the room influences the sound propagation. Further studies are needed to consider the effect of different room shapes and different distribution of sound absorbing materials in order to better understand the influence of these parameters on the final results and on the degree of diffusion of the sound field.

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