THE ACCURACY OF REVERBERATION TIME PREDICTIONS FOR GENERAL TEACHING SPACES

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1 INTRODUCTION

The Building Regulations Approved Document E Requirement E4 (ADE) makes it mandatory for teaching spaces within a school building to '*…be designed and constructed in such a way that it has the acoustic conditions and the insulation against disturbance by noise appropriate to its intended use*[1].' The UK Building Bulletin 93:2015 (BB93) is considered an appropriate means of compliance with Requirement E4[2].

One of the main acoustic criteria for teaching spaces is to meet the Reverberation Time (RT) targets as it is important to provide a controlled acoustic environment in which the teachers' and students' voices can be clearly heard and are intelligible. By providing a suitable RT, the build-up of sound within a classroom is also controlled, reducing the need for a teacher to raise their voice and the possible health impacts this can have.

Acoustics consultants therefore undertake design calculations to determine the amount of absorption necessary within each teaching space to meet the reverberation time targets that are listed within Table 6 of BB93[2].

Although testing of schools is not mandatory under BB93, post construction acoustic tests are often carried out. It is important to meet the design criteria as efficiently as possible. Calculations for the amount of materials required to meet targets need to be as accurate as possible, without over-engineering a solution.

The aim of this study is to critically evaluate two assessment methods for the estimation of the reverberation time in enclosed spaces (an analytical method and geometrical/ray tracing method) and to compare these results with the measured reverberation time within the completed classrooms to assess how accurate the predicted assessments are against actual in-situ measurements.

2 REVERBERATION TIME IN SCHOOLS

To assess the reverberation control in teaching spaces, studies have been undertaken on improving the room acoustic quality of such spaces. UK legislation and standards have been produced to set target reverberation time values for these spaces. In addition, studies on how to predict the acoustic behaviour of a room and how to measure this value have been undertaken and standardised.

2.1 Prediction of Reverberation Time

In order to assess room acoustics, two approaches, such as statistical calculation and geometric (ray tracing) methods, can be used; these are explained in detail below.

2.1.1 Statistical calculation

The reverberation time (RT or T60) in an enclosed space can be predicted by analytical methods. The most used analytical method is the W.C. Sabine formula for predicting reverberation time[3].

Equation 1 is stated as follows:

$$T_{60} = 0.161 \cdot \frac{V}{A} \qquad (1)$$

Where:
V is the volume of the room in cubic meters and A is the total absorption area of the room in square meters.

This equation assumes that the sound field within a room is diffuse, all room dimensions are similar (essentially cubic room shapes) and an even distribution of absorption inside the room[4].

2.1.2 Geometric or ray tracing calculation

Geometrical computer programs can predict the expected reverberation time and other acoustic parameters knowing the material finishes and the volume and geometry of the room[4]. CATT-Acoustic is a software package that can be used to obtain a detailed calculation of the room model using an image source method and ray tracing methods[5].

2.1.3 Limitations

Some limitations related to the two prediction methods for reverberation time are to be considered. The classic Sabine reverberation time formula assumes a diffuse field, similar room dimensions (cubic room shapes) and an even distribution of absorption[3]. Consequently, the predicted reverberation time calculated with this method can result in unrealistic values if the key criteria are not met. In order for the classroom to behave in accordance with the Sabine equation it will require the presence of scattering, usually in the form of furniture[6]. Consequently, measured reverberation time in an unfurnished classroom is typically higher than the reverberation time measured in a furnished classroom and thus not representative of the room in actual use[6]. CATT-Acoustic uses geometrical acoustics (GA) methods which are energy-based and do not solve the wave equation. Geometrical acoustics uses hybrid methods such as ray tracing and image source methods to calculate early and late reflections separately based on the geometric features and surface properties of the space[7]. At low frequencies, the room usually creates room modes and there will be effects such as diffraction caused by the interaction of the sound with geometric objects which are a similar size compared to the wavelength. At high frequencies such effects are fewer. Consequently, CATT-Acoustic is not generally used for small spaces. However, large spaces can be less influenced by the creation of room modes and the GA method can be used confidently[5].

However, for this study, only the arithmetic average of the reverberation times in the 500 Hz, 1 kHz and 2 kHz octave bands (T_{mf}) is considered. Consequently, this limitation might have less effect, and the geometrical/ray tracing model should be more accurate than the analytical method.

2.2 Building Bullettin 93 (BB93:2015)

The reverberation time requirements for teaching spaces are set out within the UK Building Bulletin 93 (BB93:2015) to provide suitable acoustic conditions within schools[2].

In terms of reverberation control, the objective of BB93 is to provide suitable acoustic conditions within schools that:

- Facilitate clear communication of speech between teacher and student, and between students;

- Do not interfere with study activities[2].

The reverberation time criteria are for rooms that are construction completed, furnished for normal use, but unoccupied. The reverberation time is quoted in terms of the mid-frequency reverberation time, T_{mf}, which is the arithmetic average of the reverberation times in the 500 Hz, 1 kHz and 2 kHz octave bands. BB93 sets out in Table 6 of the standard the maximum mid-frequency reverberation time requirements. For new-build secondary and primary school general teaching spaces, the target reverberation time is indicated below:

Type of room	**T_{mf} in seconds**
Nursery school room. Primary school: Classroom, class base, general teaching area, small group, SEN calming rooms.	≤ 0.6
Secondary school: Classroom, general teaching area, seminar room, tutorial room, language laboratory. Study room (individual study, withdrawal, remedial work, teacher preparation). Science laboratory. Design and technology: Resistant materials, CADCAM area, Electronics/control, textiles, food, graphics, design/resource area, ICT room, art	≤ 0.8

Table 1. Target reverberation time for general teaching classrooms in new-build secondary and primary schools[2]

2.3 Measurements of Reverberation Time

Reverberation time tests have been carried out in several classrooms, generally in accordance with BS EN ISO 3382: 2000[8].

According to this standard, the reverberation time can be measured using either of two methods: the interrupted noise method and the integrated impulse response method. For the purpose of this study, the interrupted noise method has been used for reverberation time measurements. In terms of excitation of the room, a loudspeaker source producing a pink noise spectrum covering a wide range of frequencies was used. The number of measurements depends on the coverage required. ANC Good Practice Guide: Acoustic Testing of Schools references BS EN ISO 16032:2004 for the minimum number of measurements necessary for a classroom when using the interrupted noise method (also called Engineering Method)[9].

3 METHODOLOGY

This assessment concentrates on the accuracy of predicted calculations in general teaching classrooms of 55 m^2 (7.3 x 7.3 m) for 30 pupils where horizontally suspended acoustic absorbers (rafts) are used for the control of reverberation, as opposed to lay-in grid ceilings. A large sample of 40 classrooms (20 secondary school classrooms and 20 primary school classrooms) in different UK schools has been tested and referenced for this assessment. A typical 55 m^2 classroom design is characterised by plasterboard lined walls, two windows (3.0 x 2.0 m high), one timber door (1.0 x 2.1 m high), a glass screen close to the main door (1.0 x 2.1 m high), a concrete soffit and a carpet/vinyl floor. Typical classrooms layouts and arrangements are shown in Figure 1 below. From left to right, it can be seen a classroom with island rafts created by ceiling tiles, proprietary suspended acoustics rafts (Ecophon Solo Square and Ecophon Master Matrix) and island raft ceiling (Rockfon Tropic) covering 70% of the area.

Figure 1. Typical 55m^2 classroom layouts and arrangements

The methodology consists of comparing the result values of the reverberation time in a typical 55 m^2 general teaching classroom in schools using the three approaches below.

3.1 Statistical approach

For the first approach, the dimensions and material characteristics of the teaching classroom are inserted into an Excel spreadsheet for a Sabine calculation of the reverberation time.

3.2 Geometric/ray tracing approach

For the second approach, considering only the inner surfaces and materials of the room, the teaching classroom is modelled using SketchUp 8 software, to create a 3D model. The acoustic simulation of the space is studied using the software CATT-Acoustic in which it is necessary to set source-receiver positions, materials, and room properties in order to obtain parameter result values. For the purpose of this study, the following consideration has been taken into account in the software:

- When the room was not furnished during the in-situ acoustics measurements, a minimum of 10%-20% of scattering has been considered for all the surfaces;
- When the room was furnished during the in-situ acoustics measurements, a 40%-50% of scattering has been considered on the walls (simulating cupboards and wardrobes) and on the floor (simulating the tables and the chairs).

3.3 In-situ measurements approach

For the third approach, acoustic testing is undertaken in different teaching classrooms of numerous UK schools using the acoustic testing Good Practice Guide of the Association of Noise Consultants (ANC) and BS EN ISO 3382:2000[8,10]. Reverberation time measurements are made using the interrupted noise method, as described in ISO 3382-2, with twelve measurements made (at six positions in the room), using two loudspeaker positions, in order to reduce the measurement uncertainty[8]. Results are numerically averaged to give a single set of figures of the 500 Hz, 1 kHz and 2 kHz octave bands[1] as explained in the ANC Good Practice Guide: Acoustic Testing of Schools[10]. When it has been possible the classroom has been measured furnished as BB93 states[2].

4 DISCUSSION OF RESULTS AND COMPARISON

[1] BB93 also allows for measured reverberation times to be the arithmetic average of 1/3 octave bands 400 to 2500 Hz.

4.1 Secondary Schools results and discussion

The following graphs indicate the results of the reverberation time for each assessed secondary school classroom calculated with the Sabine formula, simulated with the CATT-Acoustics software and in-situ test results post-construction.

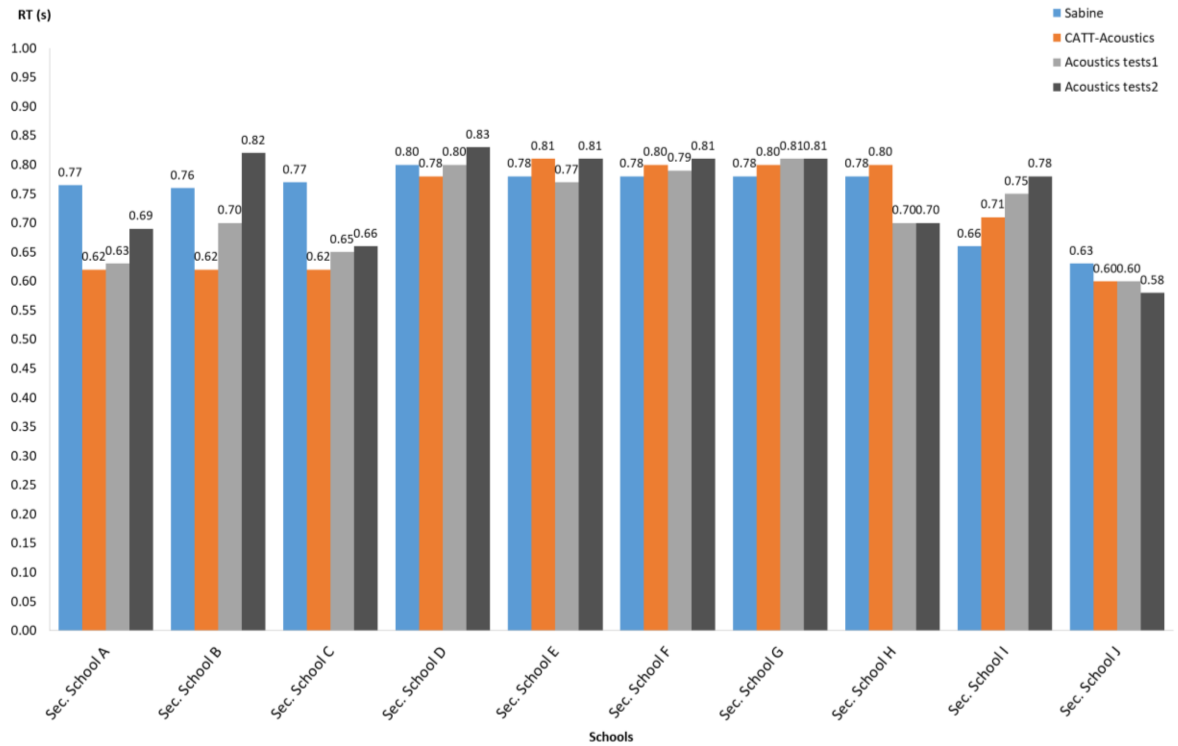

Figure 2. Reverberation time results for secondary schools

As can be seen in Figure 2, the majority of the in-situ measured reverberation times are lower than the Sabine predictions or effectively the same (with the notable exception of Secondary School I). The Sabine calculation typically overpredicted the reverberation time in most of the cases.

Secondary School A, B and C classrooms are characteris
ed by island rafts created by ceiling tiles and, at the time of the in-situ testing, were fully furnished. For each of these, the predicted reverberation time is over-estimated by the Sabine formula. This might be explained by the fact that, in practice, the presence of the furniture considerably influences the directions and energy of the reflections inside a room.

Indeed, the Sabine formula does not specifically take into account at which overall system depth from the soffit the rafts are positioned inside the room.
CATT-Acoustics software considers the furniture in the model since the scattering coefficient is increased. In addition, CATT-Acoustics software considers the absorption that the rear side of the rafts can provide to the room. The Sabine formula considers only one side of the rafts as opposed to both. Consequently, the CATT-Acoustics results are more similar to the measurement results than the Sabine results.

In addition, it can be seen that the second classroom tested in Secondary School B has a reverberation time of 0.82s. This can be explained by the fact that the room was unfurnished during the test. The difference between the two classrooms tested is about 0.1s. The measurement result of the second classroom correlates more accurately with the Sabine reverberation time result confirming again that the Sabine formula considers a diffuse field which is not exemplified in the real classroom.

Secondary School D, E, F and G classrooms are characterised by suspended acoustics rafts (Ecophon Solo Square and Ecophon Master Matrix). At the time of testing, the classrooms were not fully furnished, except for Secondary School D. The difference in the results from the predictions and the in-situ measurements is not noticeable. The sound seems to be well diffused even though the amount of absorption is concentrated on the ceiling. The differences are about +/- 0.01 s and this can be considered acceptable as an uncertainty in the calculation, simulation, or in-situ measurement.

It is noticeable though that the CATT-Acoustics model result for Secondary School D predicts a lower reverberation time compared to the other schools since in the model the furniture has been considered in terms of scattering coefficient.

As can be seen in the figure above, even though Secondary School H classrooms are characterised by the same ceiling/wall treatments as the above and were fully unfurnished at the time of the in-situ measurement, the reverberation time measured is lower compared to that predicted with the Sabine formula and CATT-Acoustics software by 0.1 s. This can be explained by the fact that, during the measurements, three MVHR units were installed on the soffit. The grid and the void behind them allow the sound to be ‘trapped’ and not able to be reflected anymore.

Secondary School I and J classrooms are characterised by an island raft ceiling (Rockfon Tropic) covering 70% of the area. Secondary School I classrooms were unfurnished, and Secondary School J classrooms were fully furnished. For Secondary School I, the prediction methods under-estimate the reverberation time compared to that measured. Since the coverage area of rafts is a large percentage of the ceiling area, the Sabine formula predicted a shorter reverberation time considering the amount of absorption equally distributed into the space. The measured reverberation time is higher compared to the Sabine value.

The island ceiling tile raft in Secondary School J classrooms almost covered the overall area of the soffit. The Sabine prediction of the reverberation time is quite low as per Secondary School I classrooms, however this time the measured reverberation time is within 0.05 s the Sabine prediction. The furniture, in this case, has considerably impacted the results when compared to the results from Secondary School I. The CATT-Acoustics software results are similar to the measured value since the furniture has been considered in terms of the scattering coefficient.

4.2 Primary Schools results and discussion

Figure 3 shows the results of the reverberation time for each primary school classroom calculated with the Sabine formula, simulated with the CATT-Acoustics software and in-situ test results post-construction. At the time of testing, the primary classrooms were all furnished.

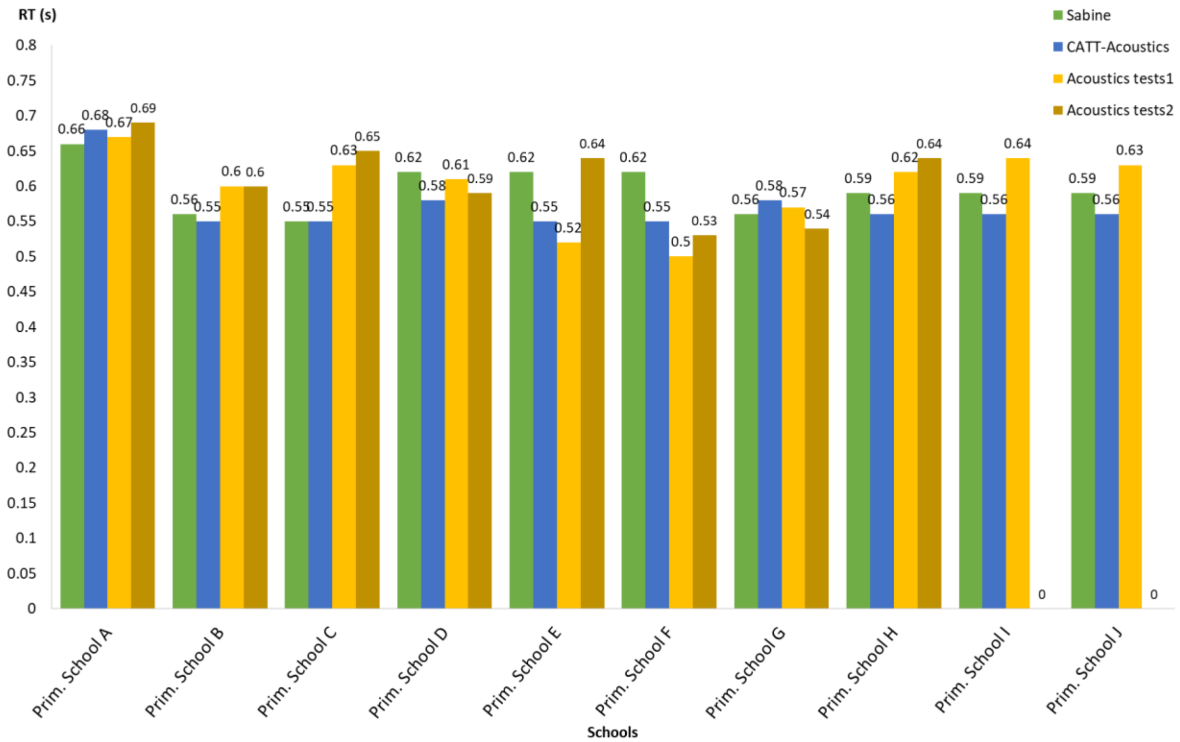

Figure 3. Reverberation time results for primary schools

As can be seen in Figure 3, the in-situ measured reverberation time is higher than the predictions for 50% of the rooms studied. The Sabine and CATT-Acoustics calculations underpredicted the reverberation time in the other cases.

Primary School A is characterised by island rafts created by ceiling tiles. The absorption is equally distributed across the walls and the ceiling. However, the floor is completely reflective as it is vinyl or linoleum. On site, the island rafts were different types and manufacturer compared to the one specified by designers and used in the calculation and consequently the reverberation time is higher than the target reverberation time for a primary classroom. In terms of the difference between the prediction methods and the measurement results, however, this is very little (± 0.03 s). It confirms that the field is diffuse.

All the rest of the schools are characterised by 100% carpet floor finish or 80% carpet and 20% vinyl to the 'wet area'. This difference does not affect the results of Sabine and CATT-Acoustics considerably, consequently it has not been considered. In addition, during the in-situ measurements, the vinyl floor was covered by furniture which has influenced the results in terms of diffusion/scattering of the sound.

Primary School B and C classrooms are both characterised by proprietary acoustic suspended rafts. The classroom is not furnished apart from some shelves on one wall. In this case, the Sabine formula has under-predicted the reverberation time compared to the measured value. In reality, the diffusion is not equally spread in the area and this can cause an increase in reverberation time. In addition, the wall panels are mounted in close proximity to the ceiling resulting in them being less effective in the reduction of reverberation time.

Primary Schools D, E, F classrooms are also characterised by proprietary acoustics suspended rafts. Similarly, in this case, the furniture is positioned only on one wall and no desks or chairs are included in the room. However, in most of the classrooms tested, different equipment and materials left by workers on site provide some additional diffusion. For Primary School D, the correlation between the three methods seems to be stable. For Primary Schools E and F classrooms, the reverberation time calculated by the Sabine formula is higher than that measured. The Sabine formula, in fact, does not consider in the calculation the absorption that the back of the rafts can provide in the room. CATT-Acoustics software result values, in this case, are more correlated to the measured value as it considers all the reflections that can travel around and above the suspended rafts. One apparent peculiarity is the second test for Primary School E. In this case, the second classroom was unfurnished and consequently the reverberation time is higher than the first acoustics test by 0.1 s.

Primary School G is characterised by acoustic suspended rafts created by ceiling tiles. The Sabine equation is very close to the measured value of reverberation time since the room was fully furnished during the testing. In addition, different equipment and objects were placed in the middle of the classrooms providing additional sound diffusion. CATT-Acoustics results do correlate with the two other methods well.

Primary School H, I, J classrooms are characterised by island rafts for 50% of the ceiling area, and a metal ceiling grid providing Class D absorption for 30% of the area. The prediction methods underestimate the reverberation time compared to the measurements. Since the coverage area of rafts is a large percentage of the area, the Sabine formula predicted a shorter reverberation time as it considers the amount of absorption equally distributed in the space.

5 CONCLUSIONS

The aim of this project is to assess how accurate the two assessment methods for the estimation of the reverberation time in enclosed spaces (analytical method and geometrical/ray tracing method) are against actual in situ-measurements.

It has been demonstrated that the two prediction methods (Sabine formula and CATT-Acoustics software) are valid for the calculation of the reverberation time in enclosed spaces such as school classrooms. In fact, the room dimensions are very similar to each other; this is one of the three assumption of the Sabine formula[3]. In addition, CATT-Acoustics is a powerful software for this application since, even though the room is small and it might result in unrealistic values of the reverberation time at low frequencies, only the T_{mf} frequencies are considered for the purpose of this study.

For both secondary and primary schools, the Sabine formula has given different result values depending on the ceiling treatment chosen for the specific classroom.

- When the ceiling treatment consists of ceiling tile-island rafts, the Sabine reverberation time is higher compared to the measured value. The Sabine formula considers only one side of the absorption area of the rafts and considers the rafts evenly distributed in the volume. In reality, the rafts are positioned at 0.4/0.5 m from the soffit and both sides of the surfaces absorb the sound that travels above and around the rafts.
- When the ceiling treatment consists of island rafts for 70% of the soffit (wider area than the case above), the Sabine reverberation time is lower compared to the measured one. The back of the rafts is not considered anymore, and the absorption area is concentrated only on the soffit. The sound travels more effectively parallel to the walls rather than in the z direction.

For both secondary and primary schools, the CATT-Acoustics software has given different result values compared to the measured and Sabine reverberation time depending on the installation of furniture.

- If the CATT-Acoustics model considers the presence of furniture in the room (increasing the scattering coefficient), the results are similar to the in-situ measurement results.
- If the CATT-Acoustics model does not consider the furniture, the result value is not equal to the Sabine value and differs by around 0.05s. This is because the CATT-Acoustics software considers a more realistic situation of the model.

For the secondary schools, the presence of wall panels seems to not significantly affect the result conclusions of this assessment since the quantity is not sufficient to give an appreciable difference. In addition, these are positioned at a very high level on the wall, consequently their effect is limited. Their presence is important only to reduce the reverberation time and meet the target criteria of BB93.

It has been demonstrated also that furniture influences the measured reverberation time in a room by almost 0.1 s.

The study demonstrated that the CATT-Acoustics reverberation time prediction is more accurate than the Sabine reverberation time calculation for most of the cases when the model is well built. However, extra effort is needed in the preparation and creation of the model. A possible solution would be to use the Sabine formula considering a marginal tolerance in the results.

In conclusion, the study demonstrated that both prediction methods are useful for the room acoustics assessment of teaching classrooms and correlate well with the in-situ measurements, where rooms are furnished.

6 REFERENCES

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