Structural reverberation time and building acoustic performance

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STRUCTURAL REVERBERATION TIME AND BUILDING ACOUSTIC PERFORMANCE

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ABSTRACT

ISO 12354 standard series describe how to evaluate building acoustic performance based on building element acoustic performance. Laboratory and in-situ structural reverberation times are necessary parameters for this evaluation. The paper presents an overview of laboratory structural reverberation time measured on several types of heavy wall and floor; and these measurement results are compared to values obtained from Annex C of ISO 12354-1 standard, the ISO 10140-5 standard limit values as well as values used in the historical CSTB Acoubat software. In-situ structural reverberation time measurements performed by CSTB have also been carried out in the past and more recently on a concrete-based building. Assumptions previously taken within the historical CSTB Acoubat software are discussed and changes proposed in order to enlarge the applicability of the calculation module. The effect of the reverberation time choice on the building acoustic performance is then evaluated.

1. INTRODUCTION

ISO 12354 standard series describe how to evaluate building acoustic performance based on building element acoustic performance. Laboratory and in-situ structural reverberation time are necessary parameters for this evaluation. The paper presents an overview of laboratory structural reverberation time measured on several types of heavy wall and floor; and these measurement results are compared to values obtained from Annex C of ISO 12354-1 standard, the ISO 10140-5 standard limit values as well as values used in the historical CSTB Acoubat software. In-situ structural reverberation time measurements performed by CSTB have also been carried out in the past and more recently on a concrete-based building. Assumptions previously taken within the historical CSTB Acoubat software are discussed and changes proposed in order to enlarge the applicability of the calculation software. The effect of the reverberation time choice on the building acoustic performance is then evaluated.

Section 2 proposes an overview of the structural reverberation time within the different ISO standards (i.e. ISO 12354 and ISO 10140-5) as well as those implemented in the historical CSTB Acoubat software.

Section 3 presents a collection of measured structural reverberation times in laboratory and in-situ for different types of structure, and a comparison with the different formulas introduced in Section 2.

Finally, Section 4 presents new reverberation time measurements carried out in a concrete based building, proposed changes in order to enlarge the applicability of the calculation module; then the effect of these changes are evaluated on the building acoustic performance. Unfortunately, measured building acoustic performance are not yet available since the building construction is not yet finished.

2. OVERVIEW OF STRUCTURAL REVERBERATION TIME

2.1 ISO 12354-1

Structural reverberation time is an important parameter when building acoustic performance has to be evaluated. The input data (in-situ) are the R and L_n indices of building elements, but also the equivalent absorption lengths a of these elements (for estimating the in-situ junction vibration level differences) and their loss factors. All these data require the knowledge of the in-situ structural reverberation times and, for the former (R and L_n), also the knowledge of the laboratory structural reverberation times, in order to transform laboratory performances into in-situ performances. Laboratory measurements of R and L_n are then corrected using the structural reverberation times T_s as follows:

$$\mathrm{R_{situ}} = \mathrm{R_{labo}} + \mathrm{C_{labo/situ}} \quad (1)$$

$$\mathrm{L_{n\ situ}} = \mathrm{L_{n\ labo}} - \mathrm{C_{labo/situ}} \quad (2)$$

with

$$\mathrm{C_{labo/situ}} = 10 \log\left(\frac{\mathrm{T_{s,situ}}}{\mathrm{T_{s,labo}}}\right) \quad (3)$$

$$\mathrm{T_s} = \frac{2.2}{f\,\eta_{total}} \quad (4)$$

where f is the band central frequency and η_{total} the total loss factor. It includes internal losses, losses due to radiation and losses at the perimeter of the element (see Annex C of ISO 12354-1)

$$\eta_{total} = \eta_{int} + \frac{2\rho_0 c_0 \sigma}{2\pi f m'} + \frac{c_0}{\pi^2 S\sqrt{f f_c}} \sum_{k=1}^{4} l_k \alpha_k \quad (5)$$

with η_{int} the internal loss factor, m' the mass per unit area, σ the radiation factor for free bending waves, f_c the critical frequency, S the surface area, α_k the absorption coefficient for bending waves at the perimeter k, l_k the length of the junction at the perimeter k, c_0 and ρ_0 the air characteristics (340 m/s and 1.21 kg/m^3 respectively).

For laboratory conditions, Annex C of ISO 12354-1 proposes the following expressions:

$$\alpha_{k,labo} = \alpha(1 - 0.9999\alpha) \quad (6)$$

with

$$\alpha = \frac{1}{3}\left[\frac{2\sqrt{\chi\psi}(1+\chi)(1+\psi)}{\chi(1+\psi)^2+2\psi(1+\chi^2)}\right]^2$$
$$\chi = \sqrt{\frac{31.1}{f_c}} \qquad \psi = 44.3\frac{f_c}{m'} \quad (7)$$

and for elements with m'≤ 800 kg/m²

$$\eta_{total,labo} \approx \eta_{int} + \frac{m'}{485\sqrt{f}} \approx 0.01 + \frac{m'}{485\sqrt{f}} \quad (8)$$

For in-situ conditions, Annex C of ISO 12354-1 proposes that the absorption coefficient α_k for a structure i can be deduced from the vibration reduction index (K_{ij}) at the junction between the considered element i and the elements j connected to it at the border k

$$\alpha_{k,in-situ} = \sum_{j=1}^{3}\sqrt{\frac{f_{c,j}}{f_{ref}}}10^{-K_{ij}/10} \quad (9)$$

with f_{ref} = 1000 Hz. The in-situ total loss factor can in general be estimated by

$$\eta_{total,in-situ} = \eta_{int} + \frac{c}{\sqrt{f}} \approx 0.01 + \frac{c}{\sqrt{f}} \quad (10)$$

with c being a constant depending on the building system.

Especially, c=0.5 for elements with densities per unit area larger than 150 kg/m² in typical masonry or concrete buildings in Germany and France.

2.2 ISO 10140-5

The ISO 10140-5 standard concerning laboratory measurements stipulates that for structures with densities per unit area larger or equal to 150 kg/m² the loss factor of the test element is not less than

$$\eta_{min} = 0.01 + \frac{0.3}{\sqrt{f}} \quad (11)$$

leading to

$$T_{s,max} = \frac{2.2}{\eta_{min}\,f} = \frac{2.2}{\left(0.01+\frac{0.3}{\sqrt{f}}\right)f} \quad (12)$$

To check requirement, ISO 10140-5 standard mentions using as the test element a brick or block wall having a mass of (400 ± 40) kg/m² plastered on one side.

There are no special requirements to be taken into account for lighter structures (m' < 150 kg/m²).

2.3 Historical CSTB Acoubat Software

The historical CSTB Acoubat software has been used to estimate the combined acoustic performance of elements in-situ. The structural reverberation time as well as the vibration reduction index of junctions are two important parameters.

Based on CSTB experience, building elements have been separated into groups defined as follows:

- Group G1: Light elements including plasterboard with cardboard honeycomb core, 'dry' partitions and walls and masonry partitions with mass per unit area less than 200 kg/m² for which the acoustic behavior in-situ is considered to be the same as in the laboratory. Therefore, the laboratory data is used without correction (i.e. $C_{labo/situ} = 0$);
- Group G2: Cast concrete or masonry walls or floors (concrete block and brick walls) with mass per unit area larger or equal to 200 kg/m² and prefabricated floors that behave differently on site and in laboratory.

For light partitions (G1 group), the structural reverberation time in the laboratory is the same as in-situ and its value is obtained according to standard ISO 12354-1, by equaling the equivalent absorption length of the element to its surface area leading to:

$$T_{s,labo} = T_{s,situ} = \frac{2.2\,\pi^2\left(f_{ref}/f\right)^{1/2}}{c_0} \quad (13)$$

with f the one-third octave band center frequency in Hz.

For homogenous element (G2 group), the CSTB data base leads to the following empirical formula for in-situ total loss factor to use in Equation (4):

$$10\log\eta_{total,situ} = -12.0 - 3.3\log(f/100) \quad (14)$$

This expression corresponds very closely to Equation (10) using c=0.5.

For homogenous elements (G2 group) in laboratory, the following equation, has been used:

$$10\log\eta_{total,labo} = -19.6 + 10\log\left(1 + \frac{m'}{4f^{1/2}}\right) \quad (15)$$

For hollow brick walls of any thickness or density per unit area, $T_{s,labo}$=$T_{s,situ}$ using $\eta_{total,situ}$ given by Equation (14) decreased by 3 dB.

3. COLLECTION OF CSTB MEASURED STRUCTURAL REVERBERATION TIME

3.1 Laboratory

In this section results from collected laboratory measurements in terms of structral reverberation time are presented and compared to previously given expressions.

3.1.1 Concrete wall

Several concrete walls of density per unit area of 390 kg/m² were evaluated in terms of reverberation time; the results are presented in Figure 1. First of all, it should be noted that the measured reverberation times for 4 of the evaluated walls are in relative agreement with requirement from ISO 10140-5 standard starting in the mid frequency range (above one-third octave band 250 Hz). Then, the expression used in historical CSTB

Acoubat software for $T_{s,labo}$ as well as the one proposed in ISO 12354-1 standard (see Equation (8) above) give structural reverberation time well below the measured values.

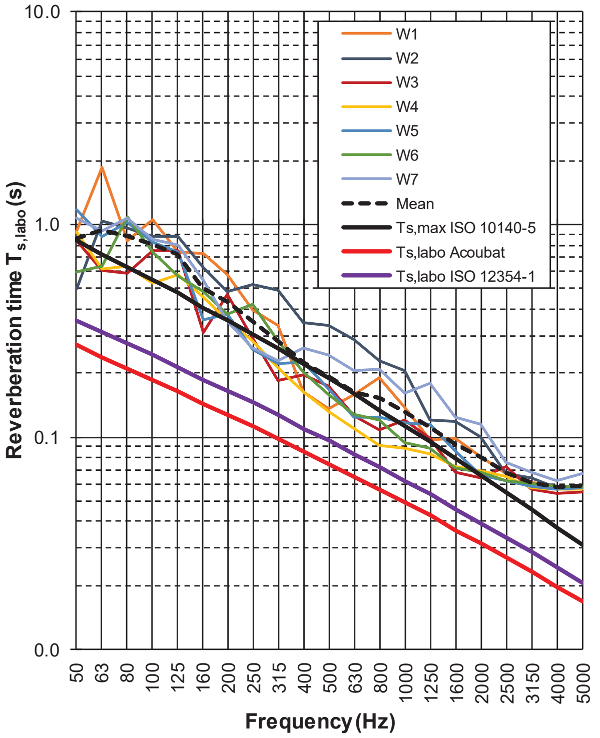

Figure 1. Laboratory structural reverberation time for concrete walls.

3.1.2 Brick wall

Several brick masonry walls of density per unit area between 119 and 227 kg/m² were evaluated in terms of reverberation time; the results are presented in Figure 2. Some of the walls are not concerned with the requirement from the ISO 10140-5 standard ($m_s \geq 150$ kg/m²). First of all, it should be noted that the measured reverberation times are mostly above the maximum one required by the ISO 10140-5 standard (see Equation (11). Then, the expression used in historical CSTB Acoubat software for $T_{s,labo}$ does not depend on mass per unit area and gives large values than the maximum ones defined in ISO 10140-5 (Equation (12) above). Furthermore, reverberation time values obtained using expression from ISO 12354-1 standard (see Equation (8) above) are well below the measured values. Note that for a mass per unit area of 150 kg/m², Equation (12) for ISO 10140-5 and Equation (8) for ISO 12354-1 yields rather similar reverberation time values.

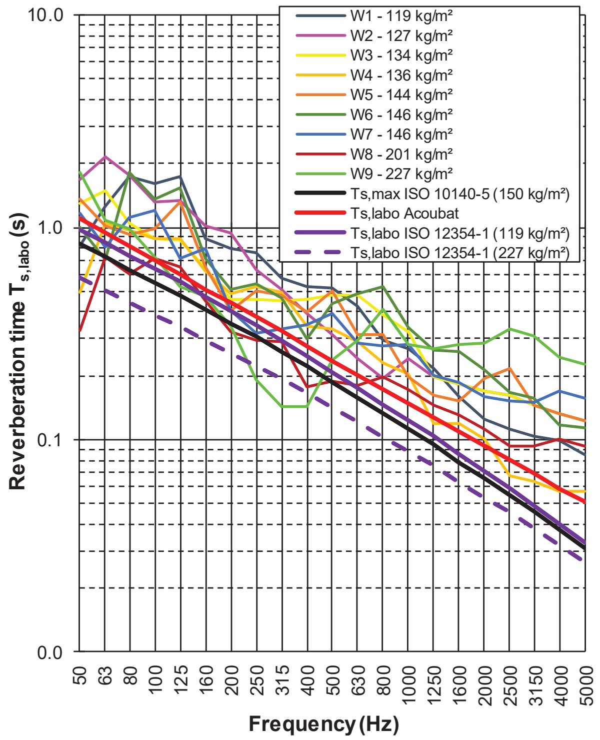

Figure 2. Laboratory structural reverberation time for brick walls.

3.1.3 Cinder block wall

Several cinder blocks masonry walls of density per unit area between 117 and 248 kg/m² were evaluated in terms of reverberation time; the results are presented in Figure 3. The measured reverberation times are generally not in agreement with requirement from ISO 10140-5 standard in the low frequency range except for the W4 wall. Then, the expression used in historical CSTB Acoubat software for $T_{s,labo}$ as well as the one from ISO 12354-1 standard give structural reverberation time below the measured values.

3.1.4 Concrete floor

Several concrete floors of density per unit area of 325 kg/m² (140 mm in thickness) were evaluated in terms of reverberation time; the results are presented in Figure 4. In this case, the different measurements are more similar. It can be noticed that the measured reverberation times are in agreement with requirement from ISO 10140-5 standard in the frequency range above the one-third octave band 200 Hz and up to 2000 Hz. Then, the expression used in historical CSTB Acoubat software for $T_{s,labo}$ as well as the one proposed in ISO 12354-1 standard give structural reverberation times below the measured values.

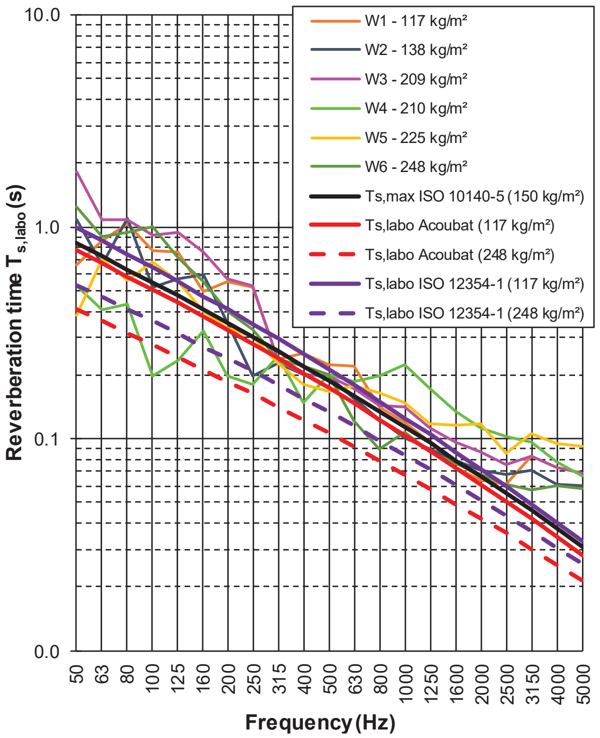

Figure 3. Laboratory structural reverberation time for cinder block walls.

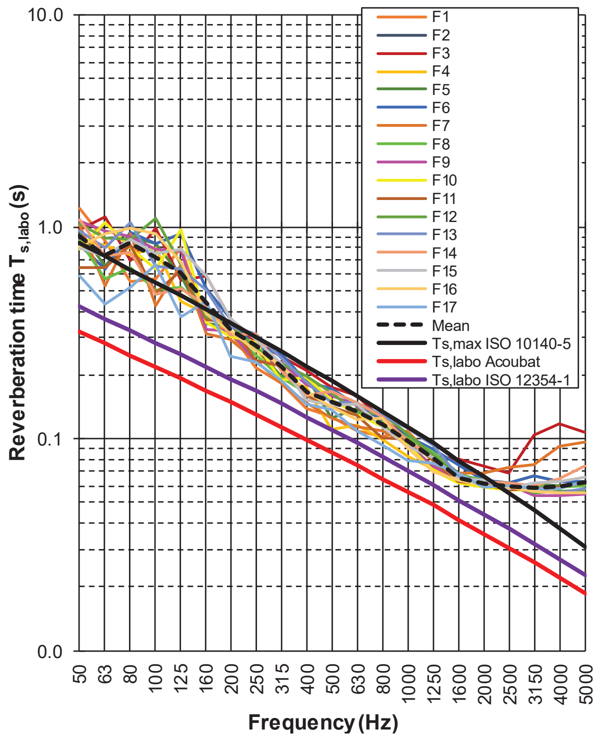

Figure 4. Laboratory structural reverberation time for concrete floor.

3.1.5 Remarks

Between the one-third octave bands 200 and 2000 Hz, the measured structural reverberation time for concrete walls and floors can be considered in relative agreement with the maximum one required by ISO 10140-5. However, those from historical CSTB Acoubat software and ISO 12354-1 are much lower than those measured.

For the masonry walls, the differences can be important between the measured structural reverberation time and the different expressions considered.

Therefore, when adding a wall or a floor in the historical CSTB Acoubat software database or just using such element in building performance evaluation care should be taken with respect to the considered laboratory structural reverberation time. For example this will lead to a difference of about 4.5 dB in average for the concrete wall and 2.5 dB for the concrete floor using the historical CSTB Acoubat software approach. For the mansonry walls considered, this difference would be around 2 dB.

Therefore it is recommended that the structural reverberation time be measured and included as input data with the element common acoustic performance (R and L_n). Without any information about the laboratory structural reverberation time for a building element the one proposed in ISO 12354-1 could be used.

3.2 In-situ

In this section results from some in-situ measurements in terms of structural reverberation time are presented and compared to previously given expressions. It should be noted that structural reverberation time measurements are not performed when building acoustic performances are verified against acoustic regulation for example; indeed structural reverberation time evaluation is rather part of in-situ junction characterization measurements. Unfortunately, it was not possible to calculate the structural reverberation time following ISO 12354-1 expression given by Equations (9) and (5) since a full description of the measurement situation was not available. However, new in-situ measurements were performed and are presented in Section 4.

3.2.1 Concrete wall

In-situ evaluated structural reverberation time is shown in Figure 5 for several concrete walls of different thicknesses. Large variation of the measured structural reverberation time can be observed and most probably dependent on the building element configuration and junctions to other building elements. Then, the expression used in historical CSTB Acoubat software for $T_{s,situ}$ independent of the element situation gives in general lower structural reverberation time than those measured in averaged.

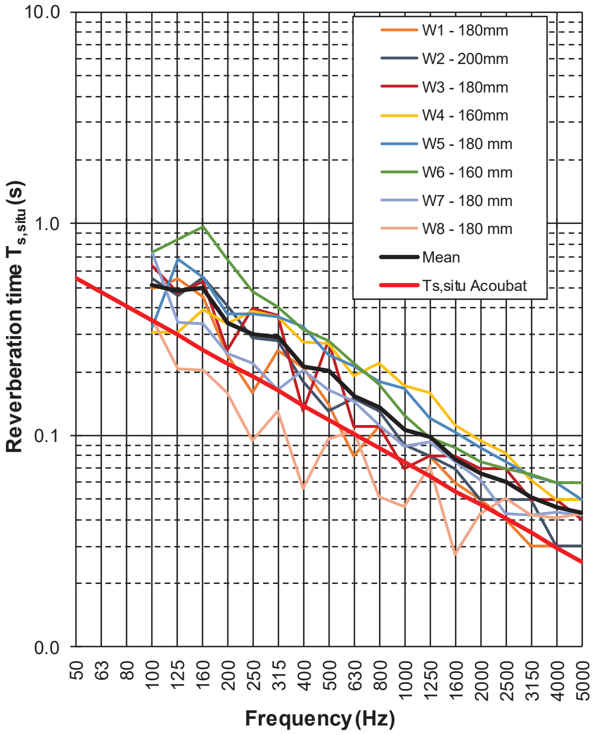

Figure 5. In-situ structural reverberation time for concrete walls.

3.2.2 Brick wall

Only two in-situ measurements for brick masonry wall were found to be exploitable. In this case the measured in-situ structural reverberation and the associated one used in historical CSTB Acoubat software are in rather good agreement as seen in Figure 6.

3.2.3 Cinder block wall

Several cinder blocks masonry walls of 200 mm in thickness were evaluated in terms of structural reverberation time; the results are presented in Figure 7. For one of the walls, the measured structural reverberation time is much larger than the other ones; this is most probably related to the wall configuration and junctions to other building elements. For a couple of walls, the expression used in historical CSTB Acoubat software for $T_{s,in\text{-}situ}$ give values in line with the measured ones; however, on average it yields lower values.

3.2.4 Concrete floor

Several concrete floors of thicknesses between 180 and 200 mm were evaluated in-situ in terms of reverberation time; the results are presented in Figure 8. Comments for the cinder blocks masonry wall could apply for the concrete floors.

3.2.5 Remarks

Differences exist between in-situ evaluated structural reverberation time and values obtained using historical CSTB Acoubat software expressions, except for the brick masonry walls (but they were in rather limited numbers). Therefore care should taken. As mentioned previously the expression given by Equations (9) and (5) taken from ISO 12354-1 should be tested in order to evaluate its reliability, on in-situ measurements that should be performed in the near future.

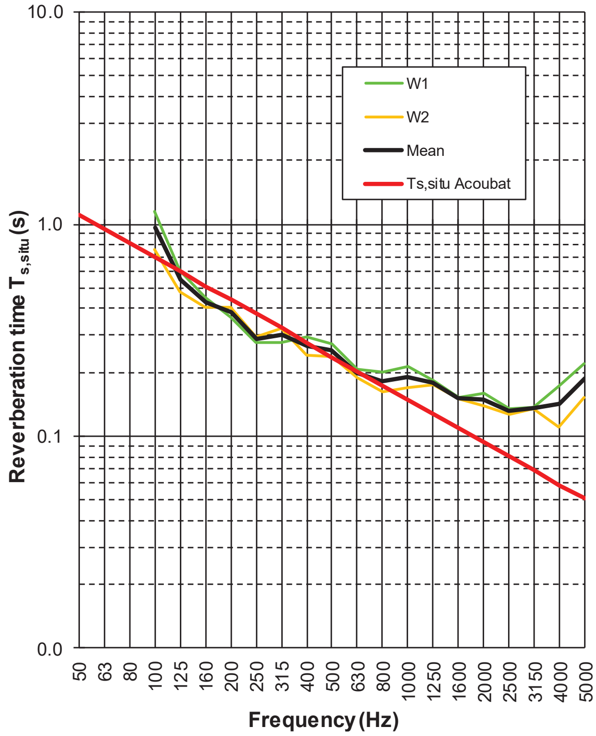

Figure 6. In-situ structural reverberation time for brick walls.

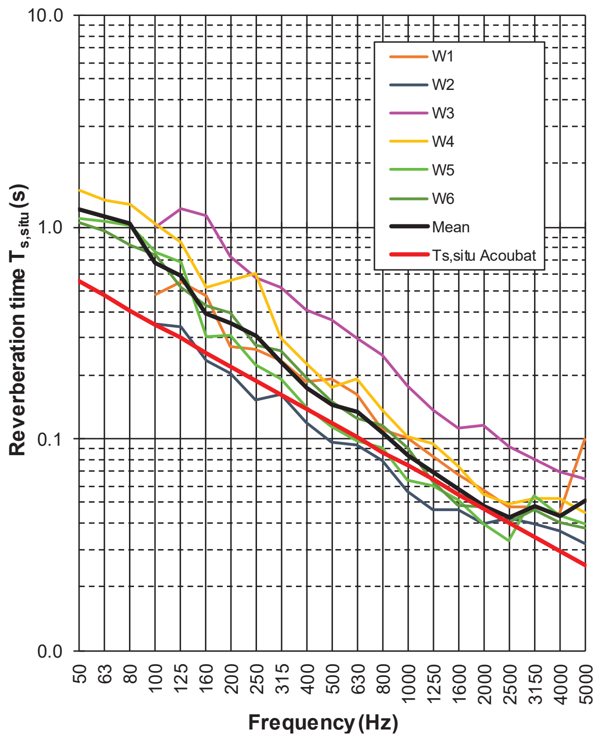

Figure 7. In-situ structural reverberation time for cinder block walls.

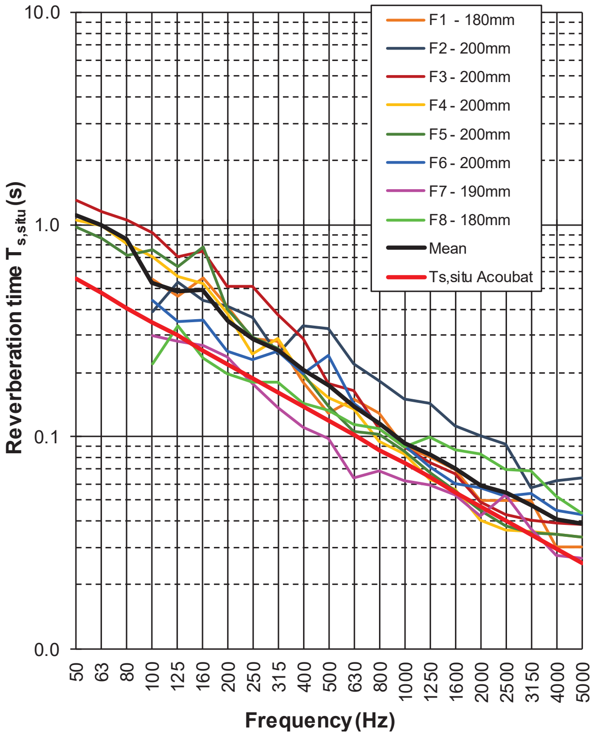

Figure 8. In-situ structural reverberation time for concrete floor.

3.3 Transformation Factor $C_{labo/situ}$

In this section the effect of the observed differences in terms of the structural reverberation time between laboratory and in-situ situation is evaluated based on averaged values for the concrete walls and floors considered. The results are shown in Figure 9; it can be noticed that from measurements the transformation factor is close to 0 dB for concrete walls and floors on average, while it is around 1.5 or 2 dB based on the expression used in historical CSTB Acoubat software. However, the acoustic performances of concrete elements in the historical CSTB Acoubat software database have been adapted to take into account the structural reverberation time based transformation factor in order to match relatively well the building acoustic performances calculated with historical CSTB Acoubat software and the one measured on site. But care has to be taken when new performance data is included in the historical CSTB Acoubat software database and used for building performance prediction.

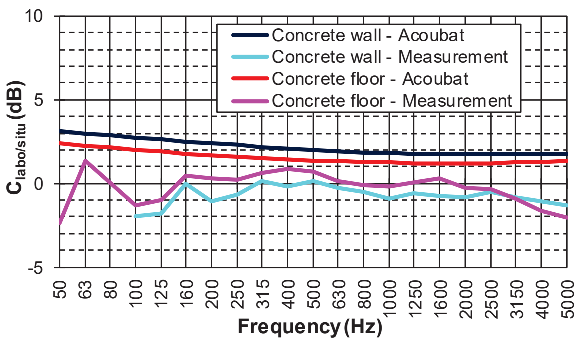

Figure 9. Transformation factor $C_{labo/situ}$ for the concrete elements considered.

4. BUILDING APPLICATION

Finally, this section presents new reverberation time measurements carried out in a concrete based building, proposed changes in order to enlarge the potential scope and applicability of the historical CSTB Acoubat software calculation module; then the effect of these changes are evaluated on the building acoustic performance. Unfortunately, since the building construction is not yet completed, only preliminary measurements are available; to complete the work, measurements in the finalized building will have to be performed and measured acoustic performance, in terms of impact sound insulation and sound transmission, compared to prediction evaluation.

4.1 Building and Measurement Description

New measurements were performed in a concrete based building corresponding to student dwellings (5 floors), with store and parking garage on the ground floor. The concrete slabs are 20 cm in thickness and the supporting and façade walls are 18 cm in thickness. Studio apartments of about 20 m² are either separated by a concrete wall or a lightweight double frame gypsum board based wall (180 mm in thickness in total). The complete concrete slab (delimited by concrete supporting walls and façade) is about 98 m². These measurements were performed without thermal lining on the façade wall and without floor covering. Acoustic measurements were no possible since the building was in a construction stage and only floor vibration was monitored. Figure 10 shows a floor plan of the measurement area. Investigation was carried out on two different levels: one with the lightweight separating wall and one without. Three accelerometers per studio apartment were implemented (i.e. 12 per floor). Three excitation positions per studio apartments were used in order to determine the structural reverberation time. Vibration level difference was also evaluated between studio apartments on the same level using a tapping machine placed at 4 different locations per lodging.

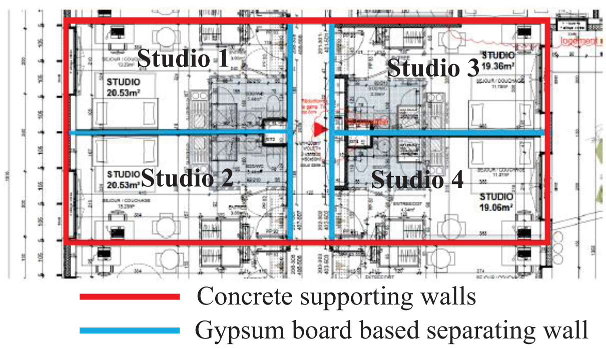

Figure 10. Floor plan of building level investigated.

4.2 Measurement results

Figure 11 presents the measured structural reverberation time. As expected, the effect of the lightweight separating walls is rather limited on the results.

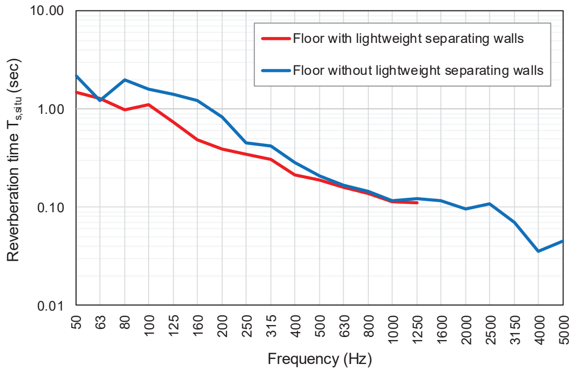

Figure 11. Measured structural reverberation time on two different floor levels.

The measured vibration level differences between the different studio apartments on the same floor level are presented in Figure 12. As observed previously on the structural reverberation time, the presence of the lightweight separating walls has little effect on the vibration propagation on the floor slab.

Furthermore, the further away the two studios, the higher the vibration level difference on the slab. This is clearly visible in the mid- and high- frequency range and shows that in that frequency range distance (ratio between the direct and reverberant field) play an important role (back flow of vibrational energy being limited). Indeed, the vibration level difference across a concrete slab through a junction with lightweight wall should be at least in the order of 3 dB.

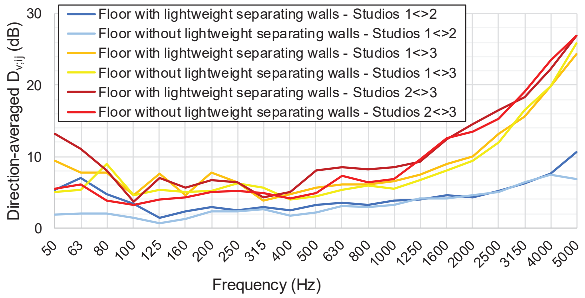

Figure 12. Measured vibration level difference between studio apartment on two different floor levels.

4.3 Proposed simplifications

The applicability of Equations (5) and (9) is dependent upon the identification of the different junctions and connected structural elements at each border of the considered wall or floor. Note that in the present case only a floor is considered. In order to simplify the calculation tabulated values for Equation (9), i.e. $\alpha_{k,in-situ}$ are proposed for the two types of junction types encountered in the investigated building, as shown in Table 1.

Figure 13 presents a comparison between in-situ absorption coefficient α_k calculated using Equation (9) or the tabulated ones. A rigid Cross- and T- homogenous junctions are considered. It can be observed that the tabulated values are acceptable when the mass per unit area ratio is not too different. The use of tabulated values will simplify the calculation procedure in avoiding a detailed calculation that could be more difficult to implement when considering a complete building.

Junction type	Description	Tabulated $\alpha_{k,in-situ}$
X	Junction with at least 4 structural elements joining	0.12
T	Junction with 3 structural elements joining	0.18

Table 1. Tabulated in-situ absorption coefficient for bending waves at the perimeter k for rigid Cross- and T-homogeneous junctions.

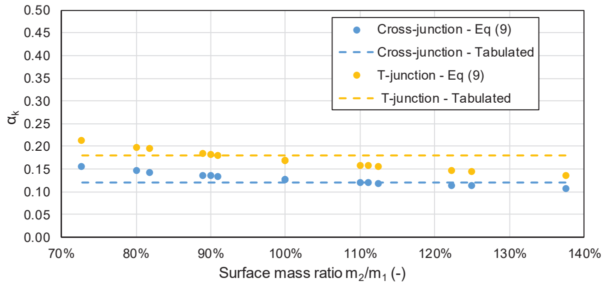

Figure 13. In-situ absorption coefficient α_k for a cross- and T-junction.

Figure 14 compares the structural reverberation time obtained with the different calculation approaches to the in-situ measured one. It can be seen that the proposed tabulated absorption coefficients lead to a quite acceptable structural reverberation compared to the measured ones since mass ratio between the vertical and horizontal concrete structural element is rather close (about 1%). However, it should be noticed that by this approach, following ISO 12354, it is an effective structural reverberation time that is calculated which is not the actual structural reverberation time, but yields the correct results for the in situ sound reduction index; the actual structural reverberation time is supposed to be larger by a factor S_{tot}/S (S_{tot} being the total surface of the slab and S the surface of the radiating element).

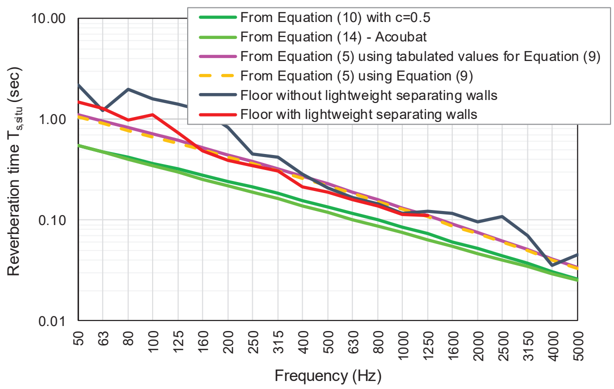

Figure 14. Comparison of in-situ reverberation time for the investigated concrete slab.

4.4 Acoustic performance prediction

In this section, the different approaches are compared in terms of building acoustic performance. The historical CSTB Acoubat software was used first and then modifications related to the in-situ structural reverberation time applied. The building acoustic performance is evaluated in a "bare" configuration (not thermal insulation on façade wall and no floor covering) and in a "completed" configuration (so the building fulfills French acoustic regulation). The vertical transmission and horizontal transmission (between studios 1 and 2 as depicted in Figure 10) are considered.

Figure 15 presents the predicted vertical impact sound level for the different cases investigated. The single number ratings are given in Table 2 for the vertical and horizontal impact sound transmission. Differences are rather limited in this case. The historical CSTB Acoubat software is slightly more conservative (1 dB for the "completed" configuration).

The single number ratings are given in Table 3 for the vertical and horizontal airborne sound insulation. For vertical transmission, differences are rather limited; the historical CSTB Acoubat software being again slightly more conservative. However, the horizontal transmission, a 3 dB difference is obtained but rather problematic is that the modified calculation yields a problematic performance, i.e. 2 dB below regulation level (53 dB).

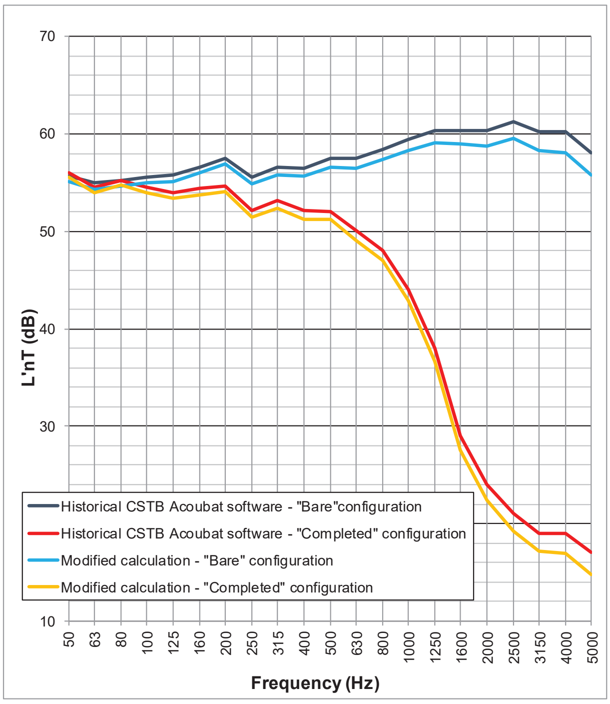

Figure 15. Predicted vertical impact sound insulation.

4.5 Remarks

Structural reverberation time has an impact on the evaluated acoustic performance. The historic CSTB Acoubat software uses specific laboratory and in-situ structural reverberation time that might not be representative any longer of the encountered situations. However, it has been recognized that building acoustic performance for French heavy constructions is relatively well predicted with the historic CSTB Acoubat software. More work is needed in order to evaluate the proposed changes in terms of in-situ structural reverberation time. Detailed acoustic measurements in the considered building should be performed.

Vertical transmission	$L'_{nT,w}$ (C_I,$C_{I50-2500}$)
Historical CSTB Acoubat software – "Bare" configuration	67(-12,-11) dB
Historical CSTB Acoubat software – "Completed" configuration	49(-1,1) dB
Modified calculation – "Bare" configuration	65(-11,-11) dB
Modified calculation – "Completed" configuration	48(-1,1) dB
Horizontal transmission	$L'_{nT,w}$ (C_I,$C_{I50-2500}$)
Historical CSTB Acoubat software – "Bare" configuration	66(-12,-11) dB
Historical CSTB Acoubat software – "Completed" configuration	48(-1,1) dB
Modified calculation – "Bare" configuration	64(-11,-10) dB
Modified calculation – "Completed" configuration	47(-1,1) dB

Table 2. Building performance – Impact sound level single number rating.

Vertical transmission	$D_{nT,w}$ + C
Historical CSTB Acoubat software – "Bare" configuration	57 dB
Historical CSTB Acoubat software – "Completed" configuration	56 dB
Modified calculation – "Bare" configuration	58 dB
Modified calculation – "Completed" configuration	58 dB
Horizontal transmission	$D_{nT,w}$ + C
Historical CSTB Acoubat software – "Bare" configuration	54 dB
Historical CSTB Acoubat software – "Completed" configuration	54 dB
Modified calculation – "Bare" configuration	51 dB
Modified calculation – "Completed" configuration	51 dB

Table 3. Building performance – Air-borne sound insulation single number rating.

5. ACKNOWLEDGEMENTS

This work was funded by CSTB Research and Development Department.