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Acoustic performances of wooden roof: a comparison between laboratory and field measurement.

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ABSTRACT

The object of this study is to analyse methods and test facilities for the evaluation of sound insulation of a wooden roof with different sequences of layers obtained with both common and innovative materials. The first part of the study focused on laboratory evaluations, and was followed by measurements performed with the help of an "ad hoc" outdoor full-scale test cell. The first results useful to understand the actual on-site behaviour of the examined structures came out from the comparison between laboratory results and those obtained from the outdoor test cell. In addition to some installation issues, what emerged was the influence of the presence of tiles by which the performance of the entire roof is affected, sometimes heavily. Such influence was then carefully analysed.

1. INTRODUCTION

The object of this study is the evaluation of wooden roofs' acoustical performances with different stratigraphies, obtained with both common and innovative materials. A measurements campaign was carried out considering the importance of stratigraphies' thickness, surface density, costs and thermal performances. The stratigraphies were characterized and optimised from the acoustical point of view both in laboratory and in an outdoor full-scale test cell [1]. Besides the problems due to the in situ installation, the effect of the tiles was analysed. The tiles seem to heavily influence the acoustical performances of a wooden roof.

2. LABORATORY TEST PROCEDURE

This study was carried out at the ITC-CNR institute. The laboratory's specifications are those defined by ISO 140-1 [2]. The laboratory is characterized by a test opening size of about 10 m².

A. Preparation of the test

The test samples have been assembled on the test opening (figure 1) taking particular care to minimize the flanking transmissions. All the tested stratigraphies were assembled on the same

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wooden frame. The wooden frame remained unchanged during the execution of the whole set of tests. The other layers were added to the basic wooden structure.

The wooden frame was composed of vertical beams inserted inside the test opening and of a wooden boarding which was fixed to the beams. In the lower part of the frame the beams were fixed by means of metal plates while in the higher part they were anchored. Figure 1 and 2 present some photos of the test set up.

Figure 1: Receiving room side - basic wooden structure, from left to right: higher part, lower part, basic wooden structure

Figure 2: test specimen - source room side.

B. Test specimens

Fifteen different typologies of wooden roof, differently composed, were analysed. Both common and innovative materials, such as hemp wool and cellulose fibre, were used. Gypsum boards were used as an alternative to the 2nd wooden boarding or in addition to the 1st wooden boarding . The stratigraphies were modified and optimised depending on the results obtained. The tests specimens are described in table 1. The correspondent weighted sound reduction indexes, obtained through measurements, are listed too.

Table 1: *Test specimens*

Test number	Stratigraphy (from inside to outside)	m' (Kg/mq)	Thickness (cm)	R_w [dB]
P1	1st wooden boarding – vapour barrier – medium density wood fibre – high density wood fibre – 2nd wooden boarding	46	16	42
P2	1st wooden boarding - vapour barrier – medium density wood fibre – high density wood fibre –gypsum board	46	16	52
P3	1st wooden boarding - vapour barrier – medium density wood fibre – high density wood fibre –gypsum board – EPS	42	19	49
P4	1st wooden boarding - vapour barrier – medium density wood fibre – high density wood fibre –gypsum board – EPS - OSB2 panels	44	20	47
P5	1st wooden boarding - vapour barrier – medium density wood fibre –gypsum board – EPS - OSB2 panels	36	16	46
P6	1st wooden boarding - vapour barrier –gypsum board - medium density wood fibre – EPS - OSB2 panels	48	17	47
P7	1st wooden boarding - vapour barrier –medium density wood fibre – cellulose fibre panels - OSB2 panels -	36	17	46
P8	1st wooden boarding - vapour barrier –medium density wood fibre – hemp wool panels – EPS -OSB2 panels	37	18	45
P9	1st wooden boarding - vapour barrier –medium density wood fibre – hemp wool panels – EPS – 2nd wooden boarding	35	18	43
P10	1st wooden boarding - vapour barrier –gypsum board – semi-rigid glass wool panels– EPS –gypsum board	42	20	49
P11	1st wooden boarding - vapour barrier –gypsum board – cellulose fibre panels– EPS –gypsum board	41	18	51
P12	1st wooden boarding - vapour barrier –gypsum board – hemp wool panels – EPS –gypsum board	43	20	52
P13	1st wooden boarding - vapour barrier –gypsum board – EPS –gypsum board	37	14.5	42
P14	1st wooden boarding - vapour barrier –gypsum board - cellulose fibre panels – EPS – OSB2 panels	31	17	45
P15	1st wooden boarding - vapour barrier –gypsum board - cellulose fibre panels – hemp wool panels – OSB2 panels	32	18	47

3. LABORATORY RESULTS

For the roof stratigraphies described above, the study was focused on both thermal and sound insulation performances, to find a good solution suitable for both aspects.

The surface density was taken into account as well and an effort was made to optimise the costs and the thickness of the solutions proposed.

The first step was to use those consolidated solutions whose acoustical properties were already well known. Theses solutions consisted of different layers of wood fibre, with different density, closed in the upper part by a wooden boarding.

Once the single-number values of these solutions were obtained, thickness and materials were changed and replaced step by step in order to better identify the behaviour of the different materials and combinations.

A. Single-number values comparison

The analysis of the stratigraphies, principally composed of wood fibre, shows that the weighted sound reduction index (R_w) is influenced by the upper element used for closing the stratigraphy and by the material's thickness. The values of the weighted sound reduction indexes with their spectrum adaptation terms ($C;C_{tr}$) are shown in Figure 3.

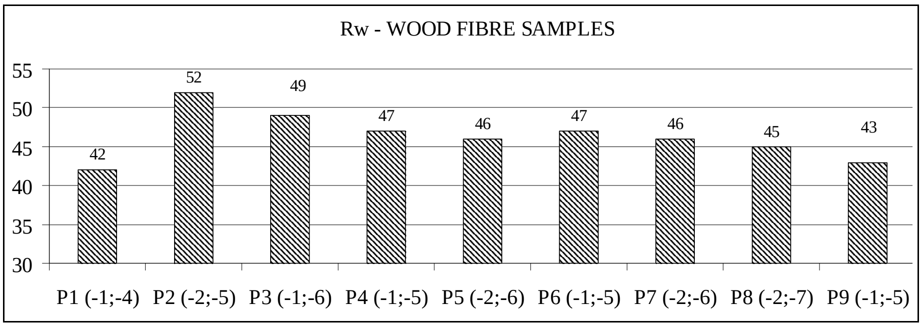

Figure 3: The comparison of R_w of different samples, composed basically of wood fibre.

Tests P1 and P2 differ just for the upper locking element: a wooden boarding for P1 and a gypsum board for P2. Simply changing the upper locking element, the weighted sound reduction index has been increased by 10 dB. Even though the acoustical performances of the two samples have proved to be good, the thermal qualities must be improved.

In solution P3 the wood fibres were reduced by one-third of the thickness previously used. So the surface density of the whole was reduced. Moreover, thanks to the introduction of materials with high thermal performances, the solution turns out to be thermally competitive maintaining, at the same time, a good value of sound reduction index.

In solution P4 only the upper locking element was replaced and OSB2 panels were used. Even in this case the upper locking element has remarkably influenced the acoustical behaviour of the whole stratigraphy.

According to the costs and to the surface density of the stratigraphy, in solution P5 an attempt to optimise the materials used was made by further reducing the thickness of the wood fibre.

In solution P6 the basic structure was changed by anchoring a gypsum board layer in direct contact with the first wooden boarding, located close to the beams, while a OSB2 panel has been used as the upper locking element. In spite of the use of the gypsum boards, neither acoustical nor thermal significant improvements were found.

At this point, after having removed the gypsum board, the wood fibre's thickness was further reduced, the thermal insulators' thickness preserved and the cellulose fibre, a natural material not yet commonly used, inserted in order to optimise the stratigraphy's performances. The acoustical behaviour of this stratigraphy (test P7) - which has a surface density of 37 kg/m² and a thickness of 17cm - is equal to that of solution P5 - which has a surface density of 36 kg/m² and thickness of 16 cm - but there is a remarkable increase of the thermal performances.

In solutions P8 and P9 hemp wool, another natural material, was inserted instead of cellulose fibre. The upper locking element of test P8 is the same as in test P7 (OSB2 panels).

Sample P9 has the same composition as sample P8, but the upper locking element was changed: a 2nd wooden boarding was used instead of OSB2 panels.

The comparison between tests P7 and P8 has shown that the combination of wood fibre and cellulose fibre is acoustically better than that of wood fibre and hemp wool. Moreover the comparison between tests P8 and P9 highlights once again that the substitution of the upper locking element influences the acoustical stratigraphy's behaviour.

Following tests were carried out by using insulating materials which are lighter than the wood fibre (from P10 to P15).

Figure 4 presents the weighted sound reduction index values of lighter solutions with their spectrum adaptation terms (C; C_{tr}).

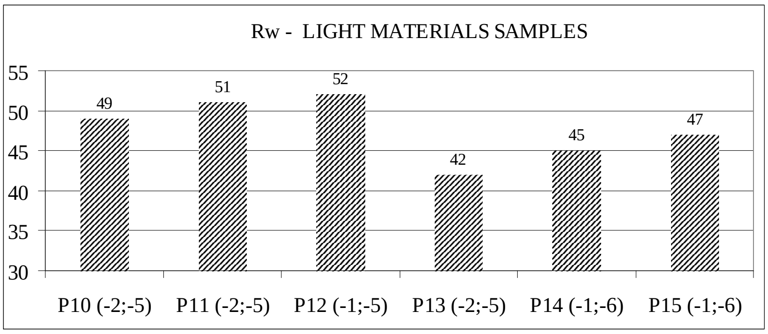

Figure 4: comparison of weighted sound reduction index of samples, composed of light materials.

In tests P10, P11, P12 and P13, where a gypsum board was anchored directly onto the 1st wooden boarding, light materials were used, and another gypsum board layer was used as upper locking element, to create a mass – spring – mass system.

Glass wool P10, cellulose fibre P11 and hemp wool P12 have shown a good acoustical behaviour and good thermal performances. The increase of the stratigraphies' surface density is due to the insertion of the second gypsum board. Only a thermal insulating material, EPS, was used in test P13. The laboratory measurements have shown that EPS, which behaves very well from the thermal point of view, does not perform as well from the acoustical point of view.

In the last two tests, P14 and P15, the entire system was modified: the gypsum board which was in contact with the 1st wooden boarding was removed and the gypsum board, which was used as upper locking element, was substituted by OSB2 panels.

The comparison between tests P11 and P14, both composed of cellulose fibre, has shown that the retaining system is of paramount importance. In test P11 the retaining system is composed of two layers of gypsum board, one anchored onto the 1st wooden boarding , the other used as upper locking element; in test P14 the first gypsum board was removed, and the upper locking element substituted with the OSB2 panel. The stratigraphies are shown in Figure 5.

Test P15, in which cellulose fibre and hemp wool are combined with OSB2 panels, highlights an improvement of the insulation properties mainly due to the materials' combination.

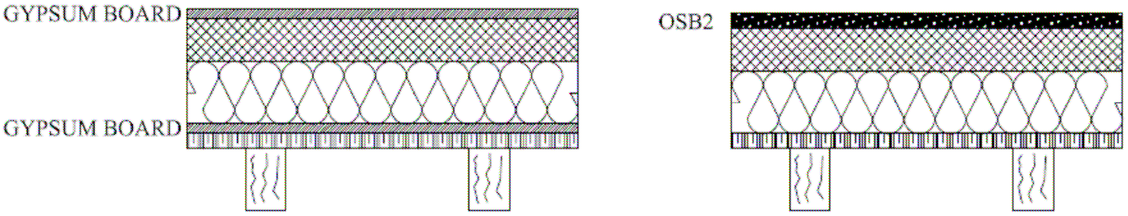

Figure 5: the retaining system: P11 two layers of gypsum board (left), P14 OSB2 panel (right)

B. Solutions with equal R_w: comparison of frequency trends

The frequency curves, of different samples, with the same R_w were compared [3].

The weighted sound reduction index of stratigraphy P1 is 42 dB, and that of P3 and P9 is 43 dB. The comparison between the frequency trend of the different stratigraphies, shows that at high frequencies, the acoustical performances are improved once the wooden fibre is partially substituted with hemp wool.

The R_w of stratigraphies P5 and P7 is 46 dB; while stratigraphies P8 and P14 have R_w equal to 45 dB. The comparison between the frequency trend in each third-octave band of the different stratigraphies has shown that at middle frequencies (315 Hz – 1250 Hz), the acoustical performances are improved by means of wood fibre and cellulose fibre (P7); at high frequencies the combination of wood fibre and hemp fibre (P8) has shown the best acoustical performance, to the detriment of low frequencies.

The R_w of stratigraphies P4, P6 and P15 is 47 dB. Even though these stratigraphies have the same weighted sound reduction index, comparing the different stratigraphies, extremely different values, up to 5 dB, in each third-octave bands were found out.

The stratigraphies P4 and P6, composed of wood fibre, have shown better acoustical performances at low frequencies, up to 250 Hz; in the frequencies range between 315-630 Hz the three stratigraphies, with R_w equal to 47 dB, have shown a frequencies trend very close to one another. Up to 800 Hz, the stratigraphies' frequency curves tend to be very different, and solution P15, composed of hemp wool and cellulose fibre, is better than the other two.

Comparing stratigraphies P3 and P10, whose R_w is equal to 49 dB, an extremely different frequency trend was found. In each third-octave band the gap among the solutions can be 2 dB up to 6 dB. In the frequencies range between 100 Hz and 315 Hz, stratigraphy P10, composed of gypsum board and glass wool, has shown a better acoustical performance compared to solution P3. Solution P3, composed of wood fibre, is much better than solution P10 in the frequencies range between 400 Hz and 2500 Hz. Beyond the frequency of 2500 Hz the two stratigraphies have shown the same acoustical performances.

The best $R_{w,}$ equal to 51 dB and 52 dB, was obtained with stratigraphies P2, P11 and P12, but they greatly differ in third-octave bands. Up to the 630 Hz frequency, solution P2, composed of gypsum board and wood fibre, has shown the best behaviour. Beyond 800 Hz, solution P12, composed of gypsum board and hemp wool, has proved to be the best.

C. Third-octave bands comparison based on the closing system

The results obtained, from different stratigraphies, have shown that the upper layer - used for closing the wooden roof, before the tiles were positioned - affects the acoustical insulation of the full stratigraphy in a different way based on the combination of the other materials. Comparisons are shown in Figure 6 and 7.

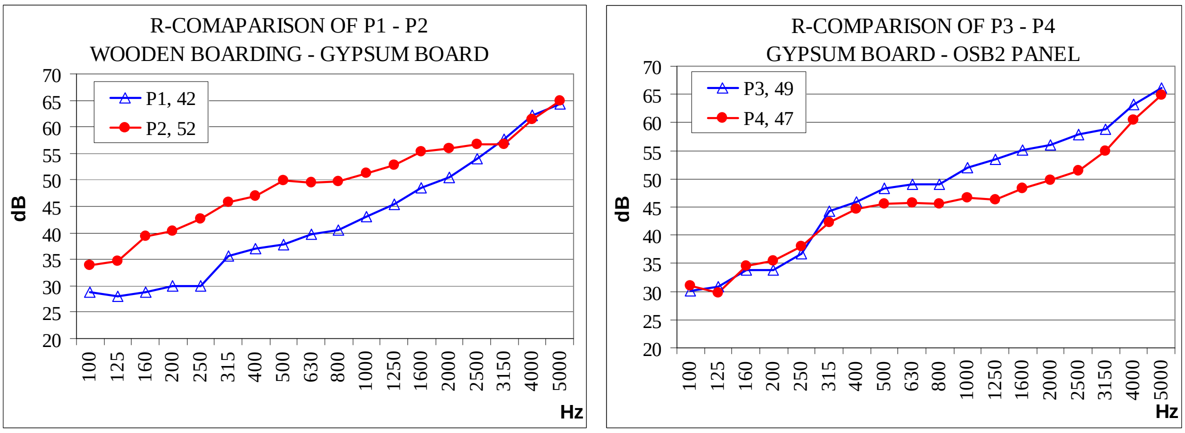

Figure 6: One-third octave bands comparison between P1 – P2 and P3-P4

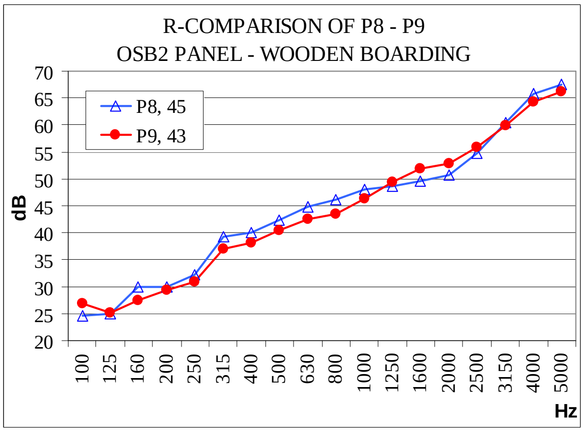

Figure 7: One-third octave bands comparison between P8 – P9

D. Comparison between the different analysed parameters

The different solutions were analysed and optimised considering many different building needs such as thermal insulation, thickness, weight and costs (based on the Italian market). By comparing all the properties considered, five stratigraphies were chosen as the most competitive. The comparison is shown in Figure 8.

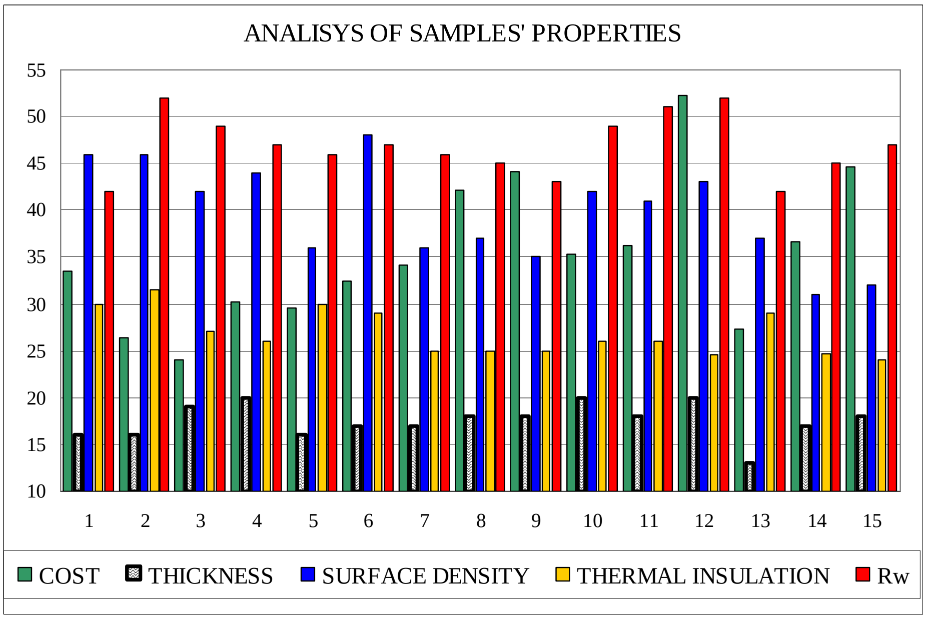

Figure 8: comparison of R_w, thermal insulation, thickness, weight and cost

4. OUTDOOR FULL-SCALE TEST CELL TESTING PROCEDURE

The main purpose of this work was the evaluation of the in situ acoustical behaviour of wooden roofs with tiles, so the five selected stratigraphies were reproduced in the external full-scale test cell located at ITC-CNR. The tests have been carried out following standard ISO 140 - 5 [4]. The test set-up is shown In figure 9. The in situ test set up, and the set up used for optimising the flanking transmission were defined ad hoc. Figures 9 and 10 show some steps of the implementation of the system. The source was placed on a mobile support, and sloped in order to obtain an angle of (45±5)°, as to the roof.

Figure 9: full-scale cell set up: source's position (left, centre); reverberation time measurements (right)

Figure 10: construction of the first wooden boarding; detail wall - roof connection

5. COMPARISON BETWEEN LABORATORY AND TEST CELL MEASUREMENTS

Due to the size of test opening of the laboratory and the size of test area S of the external cell, which are both about 10 m^2, and due to the geometry of both rooms (laboratory and test-cell), the sound reduction index R can be compared to R'_{45} measured in situ (the comparison between in situ and laboratory measurements should be made only when the coupling surface is about 10 m^2 [5]).

A Comparison between the frequency trend of laboratory and test-cell

In addition to the five stratigraphies chosen to be tested on the outside full-scale test cell, another stratigraphy (P16) was tested in laboratory and afterwards also in the outside cell. Stratigraphy P16 is composed only of wood fibre inserted between two wooden boardings. In the external cell, another type of tile T2 (70-80 Kg/m^2) was used, whose surface mass is twice that of type T1 (30-40 Kg/m^2), used for the other 5 stratigraphies.

The measurements campaign carried out in the external cell has shown that the acoustical behaviour of samples is extremely different compared to that of the laboratory, once the wooden roof is built. On the external cell the wooden roof has a 10° slope, while in the laboratory the test is mounted vertical. In particular, it is interesting to note that the stratigraphies with the OSB2 panels as retaining element show a big loss in sound insulation, principally between 160 and 315 Hz, as shown in figure 11.

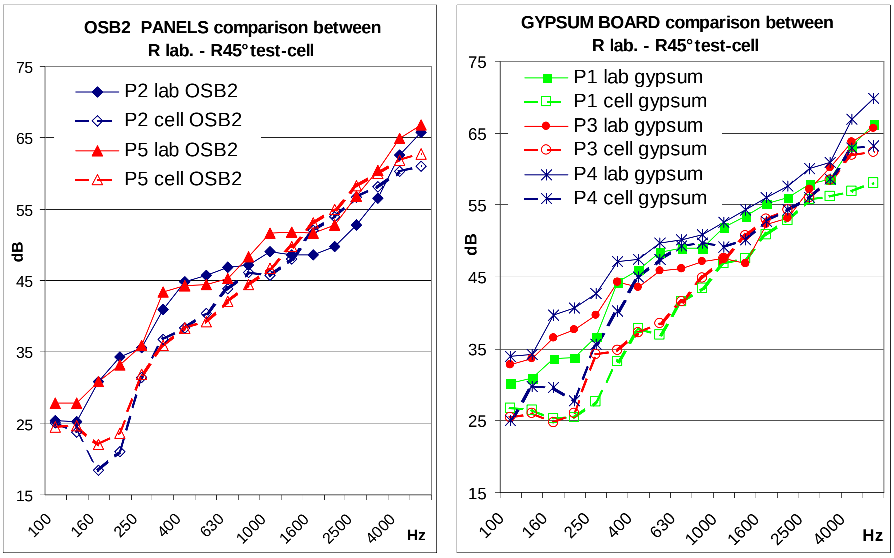

Figure 11 Comparison between laboratory R and test cell R'45. OSB2 (left), and Gypsum board (right).

B Tiles influence

The first series of tests of samples without tiles, was followed by a second series of tests, which consisted in the completion of the roof by placing the laths and then the tiles, type T1 or T2. Table 2 reports, for all tests, the single-number values related to the laboratory and to the test-cell with and without tiles. At first glance P16 test seems the only test without a loss of R from the laboratory to the external cell. It must be taken into account that in laboratory, unlike other tests, P16 was tested without laths just before the second wooden boarding, and this is why it has a lower laboratory R_w.

Table 2: *Single-number quantities: laboratory R_w; test-cell $D_{2m,nTw}$ with and without tiles*

Test number	R_w (dB) laboratory	$D_{2mn,T,w}$ WITHOUT tiles	$D_{2mn,T,w}$ WITH tiles
P3	49(-1;-6)	42(-2;-6)	40(-4;-8)
P7	46(-2;-6)	42(-4;-9)	38(-5;-10)
P10	49(-2;-5)	43(-2;-6)	42(-2;-7)
P12	52(-1;-5)	47(-2;-7)	45(-4;-9)
P15	47(-1;-6)	42(-2;-7)	39(-4;-9)
P16	40(-1;-6)	44(-1;-4)	39(-2;-6)

Figure 12 shows that for all tests performed in the outdoor cell, the contribution due to tiles T1 is positive, because of the added mass, from 315/400 Hz up, while tiles T2 start to give a positive contribution from 1250/1600 Hz up.

At low frequencies, the presence of tiles causes a loss of sound reduction index. Tiles T2 accentuate the R loss between 100 Hz and 500 Hz, while tiles T1 accentuate it only from 100 to 315/400 Hz. As already stated, the surface mass of tiles T2 is twice that of tiles T1, and their influence is greater. Furthermore, the positive contribution due to the mass, at medium-high frequencies, for tiles T2 is lower than that of tiles T1, because it starts at a higher frequency, 1600 Hz instead of 400 Hz, which takes place for T1 tiles.

The analysis of one-third octave curves of laboratory tests is essential. Knowing that the loss of sound reduction index of tiles T1 is between 100 and 400 Hz, to have a better acoustical behaviour, R_w being equal, the stratigraphies with a better laboratory value in that frequency range have to be chosen. This fact is confirmed by the comparison between P3 and P10 samples, that have a laboratory R_w equal to 49 dB, but their $D_{2m,nTw}$ value (with tiles) in the external cell is 40 dB and 42 dB respectively. In fact P10 stratigraphy shows a greater sound reduction index R, between 100 Hz and 315 Hz, which are the frequencies affected by the negative contribution of tiles.

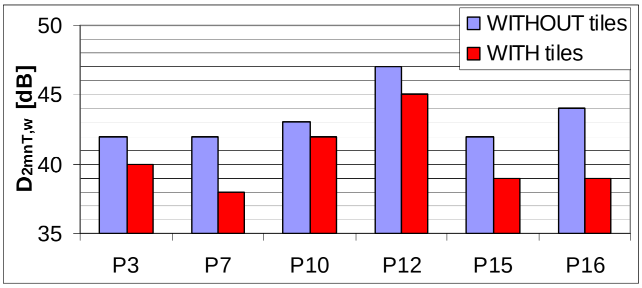

Figure 12: comparison of single-numbers values between the all tested stratigraphies WITH (red) and WITHOUT (light blue) tiles.

6. CONCLUSIONS

By using the results of this study it is possible to choose the most suitable solution for a wooden roof. The analysis shows that the sound insulation is due to the combination and order of the different elements and not only to the behaviour of each single material.

In order to guarantee a good acoustical comfort inside the building against the environmental noise, the suitable stratigraphy solution has to be chosen by considering not only the R_w but also the frequency trends.

When the samples are tested in the outside test-cell, there is a loss of sound insulation with respect to the laboratory values, principally due to the layout of the wooden roof: on the external cell the wooden roof has a slope of 10°, while in the laboratory the test sample is mounted vertical. Moreover, all stratigraphies tested show that the performance of the entire roof is affected, sometimes heavily, by tiles, in particular at low-middle frequencies. The tiles affect every kind of roof stratigraphy, whether it is a massive or light stratigraphy. If the tiles are heavy the loss of sound insulation is even more evident. Indeed, the weight of tiles is inversely proportional to sound insulation: tiles T2 - whose average surface density is twice that of tiles T1 - further affect the acoustical performances of roof.

Therefore, the final choice of the wooden roof stratigraphy to be used will be determined by all of the priorities of the project, such as energy-saving or structural requirements (in particular for ~~the~~ restructuring), or issues relating to costs (such as the thickness of the package that has an impact on the thickness of the gutter thus increasing the costs), and so forth.

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