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Wooden roof: evaluation of acoustic performances performed in laboratory, on an external test-cell, and on real buildings

L.Parati (1), A.Carrettini (1), C.Scrosati (2) and F.Scamoni (2)

(1) Acustica Parati & Co, Crema -CR, Italy 1
(2) ITC-CNR, Milano, Italy 2

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ABSTRACT

The study concerned the evaluation of sound insulation of light structures, such as wooden roof. A first analysis was focused on laboratory evaluations of different sequences of layers, obtained with both common and innovative materials. Based on the results obtained with the laboratory tests on the acoustic behaviour of the insulating configuration of wooden roof used, the second step of the research consisted in studying an "ad hoc" outdoor full-scale test cell on which a second set of measurements was performed. The comparison between laboratory results and those obtained from the outdoor test cell showed a remarkable difference in sound insulation between the two conditions considered. Moreover, measurements were carried out with and without roof tiles, and it emerged that the tiles heavily affect the sound insulation of the entire roof. The final step of the research involved the execution of in situ measurements of wooden roofs in real buildings, using two of the insulating configurations of wooden roof tested.

INTRODUCTION

In Italy wooden roofs are a common solution for residential buildings especially for row houses. Over the last years the people’s sensibility to noise has emphasized the sound insulation issue related to this kind of roof, in relation to the noise produced by neighbours but also by the surrounding environment. Hence the need to evaluate the acoustic behaviour of wooden roofs and the influence of their installation in layers in a real building.

Different wooden layers have been characterized by means of laboratory tests. Thickness, surface density, costs and thermal performances, in terms of thermal transmittance “U”, were also optimised. Before using the wooden roof in a real building, an intermediate step was performed: a selected number of specimens were tested in an outdoor full-scale test cell [1], and the issues related to the in-situ installation were analysed. The same sample typology was tested with different kinds of tiles and then installed in residential buildings. The acoustic behaviour measured in the laboratory has been compared to that measured in the real building.

LABORATORY SET UP

This study was carried out at ITC-CNR. The laboratory's specifications are as defined by ISO 140-1 [2]. The laboratory’s test opening size is about 10 m².

Preparation of the test

A basic wooden structure, on which the samples were assembled, was prepared. Particular attention was paid to the definition of the most suitable way to position the samples in the test opening (figure 1-2). Maximum care was taken so as to minimize the flanking transmission.

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

Figure 2. Receiving room side - basic wooden structure.

The wooden frame was composed of vertical beams inserted in the test opening and 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. The wooden frame remained unchanged throughout the whole set of tests. The other layers were added to the basic wooden structure working from the source room side (figure 3).

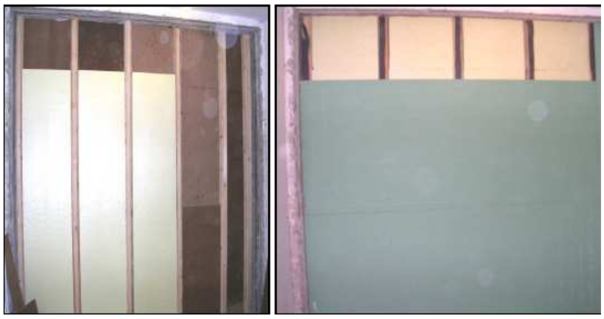


Figure 3. Test specimen - source room side

Material characteristics of the specimens

Over the last years, the most commonly used material in wooden roofs in Italy has used to be EPS (Expanded Polystyrene), which has proved to be quite effective for thermal purposes, but less useful from the acoustic insulation point of view. Beside EPS, other materials such as mineral wool have become more commonly used. Wood fibres, hemp wool and cellulose fibre as well as gypsum boards, placed in wooden roofs (since they are traditionally used in walls) can be regarded as innovative materials at least consistently with the Italian construction practice.

The different layers were arranged considering, in addition, both thickness and surface density. This solution responds to the common requirement to be fulfilled during building renovation, when the existing structure can not be further weighed down or raised, but in the meantime thermal and acoustical insulation has to be granted.

The tests specimens are described in table 1 and 2. The correspondent weighted sound reduction indexes obtained through measurements, surface density and thickness are also listed. Basically the fifteen specimens differed either in the combination of their constituent materials, internal insulation, or in the closing system. In fact, except for the first wooden boarding, the one which composed the basic wooden structure (figure 1-2), the upper locking elements were changed and their influences analysed.

Table 1. Test specimens

Test number	Layers configuration (from inside to outside)	m' (Kg/mq)	Thickness (cm)	R_w [dB]
P1	1st wb–vb–mdwf–hdwf–2nd wb	46	16	42
P2	1st wb–vb–mdwf–hdwf–gb	46	16	52
P3	1stwb–vb–mdwf–hdwf–EPS-gb	42	19	49
P4	1stwb-vb–mdwf–hdwf–EPS-OSB2	44	20	47
P5	1stwb-vb–mdwf–EPS-OSB2	36	16	46
P6	1stwb-vb–gb-mdwf–EPS-OSB2	48	17	47
P7	1stwb-vb–mdwf–cf–EPS-OSB2	36	17	46
P8	1stwb-vb–mdwf–hw–EPS-OSB2	37	18	45
P9	1stwb-vb–mdwf–hw–EPS–2ndwb	35	18	43
P10	1stwb-vb–gb–srgw–EPS–gb	42	20	49
P11	1stwb–vb–gb–cf–EPS–gb	41	18	51
P12	1stwb-vb–gb–hw–EPS–gb	43	20	52
P13	1stwb-vb–gb–EPS–gb	37	14.5	42
P14	1stwb-vb–cf–EPS–OSB2	31	17	45
P15	1stwb-vb–cf–hw–OSB2	32	18	47

Table 2. Legend of contents

wb	wooden boarding
vb	vapour barrier
mdwf	medium density wood fibre
hdwf	high density wood fibre
EPS	*Expanded Polystyrene*
gb	gypsum board
OSB2	*Oriented Strand Board*
cf	cellulose fibre panels
hw	hemp wool panels
srgw	semirigid glass wool panels

LABORATORY RESULTS

Fifteen different typologies of wooden roof, differently composed as described above, were analysed. The layers configurations were modified and optimised depending on the results obtained.

The results were analysed focusing on four different goals:

- Comparison of the weighted sound reduction indexes (R_w),
- Comparison of the frequency trends;
- Comparison of the closing systems;
- Comparison of the different analysed parameters.

Comparison of the weighted sound reduction indexes

The samples were divided in two categories: those based on wood fibre, combined with other materials, basically working by mass, and light solutions.

The analysis of the configuration of layers, principally composed of wood fibres, shows that the weighted sound reduction index (R_w) is influenced by the upper element used for closing the layers configuration and by the material's thickness. The values of the weighted sound reduction indexes together with their spectrum adaptation terms ($C;C_{tr}$) are shown in Figure 4.

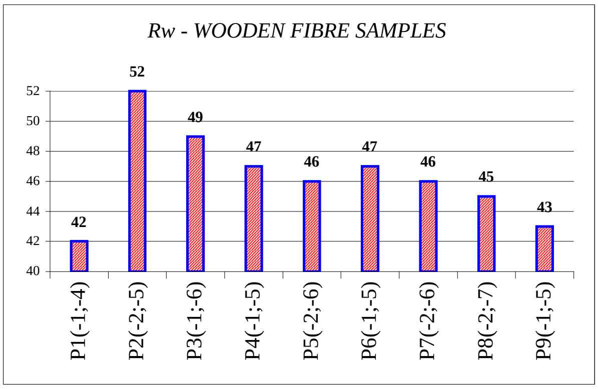


Figure 4. The comparison of R_w of different samples, composed basically of wood fibre

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

In solution P3 the thickness of wood fibres was reduced by one-third as to the previous value. The surface density of the whole was therefore 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.

Solutions P4, P5, P6, P7, P8 and P9 are modifications of the previous samples; they were changed in order to analyse and optimise the different parameters (thickness, surface density, costs and thermal transmittance) taken into consideration. P7, P8 and P9 proved to have very good thermal transmittance among all the laboratory tested wood fibre samples.

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

Figure 5 presents the weighted sound reduction index values of lighter solutions with their respective spectrum adaptation terms (C; C_{tr}).

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

Glass wool P10, cellulose fibre P11 and hemp wool P12 have shown a good acoustic behaviour and good thermal performances. Sample P12, whose sound reduction index, together with that of P2 is the best of all specimens tested, has one of the best thermal transmittance values among the different combinations especially compared to that of P2. The increase of the layers configuration's surface density is due to the insertion of the second gypsum board. Only one 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 acoustic point of view.

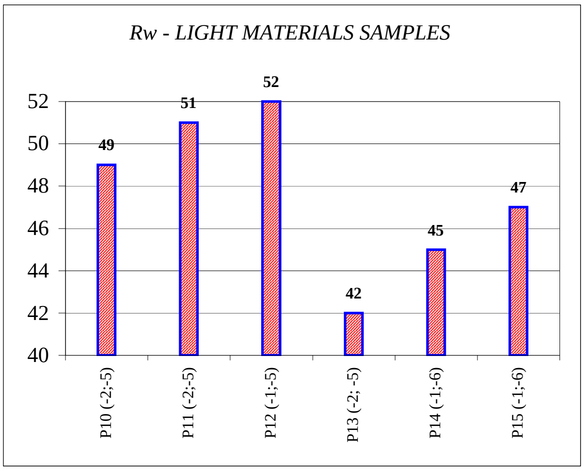


Figure 5. Comparison of weighted sound reduction indexes of samples made of light materials

In the last two tests, P14 and P15, the entire system was modified: the gypsum board anchored to the basic structure was removed and OSB2 (Oriented Strand Board) panels substituted the upper locking element.

The comparison between tests P11 and P14, where specimens are made of the same internal materials but the closing systems are different, has shown that the retaining system is of paramount importance. A drawing of the two specimens is shown in figure 6.

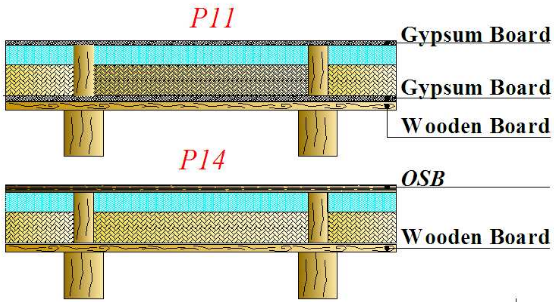


Figure 6. The retaining system: P14 OSB2 panel, P11 two gypsum board layers

The last sample, P15, has shown that insulation properties are improved by the combination of cellulose fibre and hemp wool.

Comparison of frequency trends

The frequency curves of different samples with similar R_w values were compared [3].

The frequency trends of P7 and P8 (R_w 46 dB) are compared in figure 7. The comparison between the frequency trend in each third-octave band of the different layers configurations has shown that at middle frequencies (160 Hz – 1250 Hz) the acoustic 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 acoustic performance, to the detriment of low frequencies.

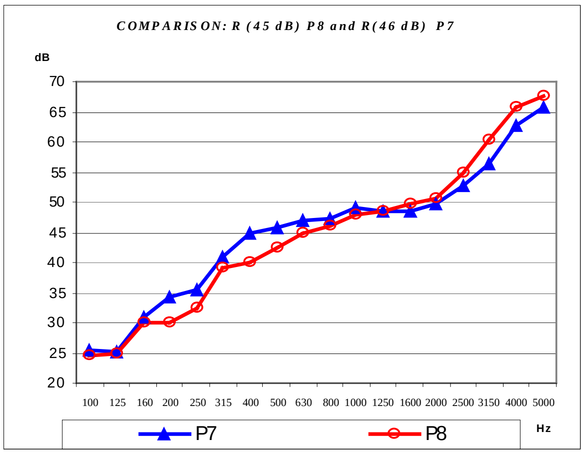


Figure 7. Comparison between P7 and P8

The R_w of layers configurations P4, P6 and P15 is 47 dB. Even though these layers configurations have the same weighted sound reduction index, extremely different values, up to 5 dB in each third-octave bands have resulted from the comparison of the different layers configurations. The layers configurations P4 and P6, composed of wood fibre, have shown better acoustic performances at low frequencies, up to 250 Hz; in the frequencies range between 315-630 Hz the three layers configurations, with R_w equal to 47 dB, have shown a frequency trend very close to one another. Up to 800 Hz, the layers configurations' frequency curves tend to be very different, and solution P15, composed of hemp wool and cellulose fibre, is better than the other two. Results are shown in figure 8.

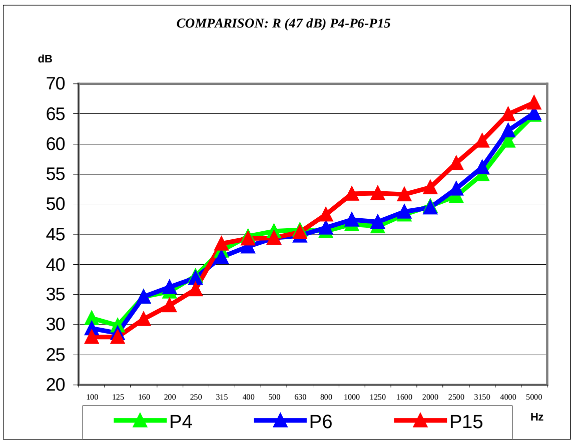


Figure 8. Comparison between P4-P6 and P15

The best R_w, 52 dB, shown in figure 9, was obtained with layers configurations P2, and P12, but they greatly differ in third-octave bands. Especially beyond 800 Hz, where solution P12, composed of gypsum board and hemp wool, has proved to be the best. As already shown in the single number analysis, solution P12 is also one of the best from the thermal point of view.

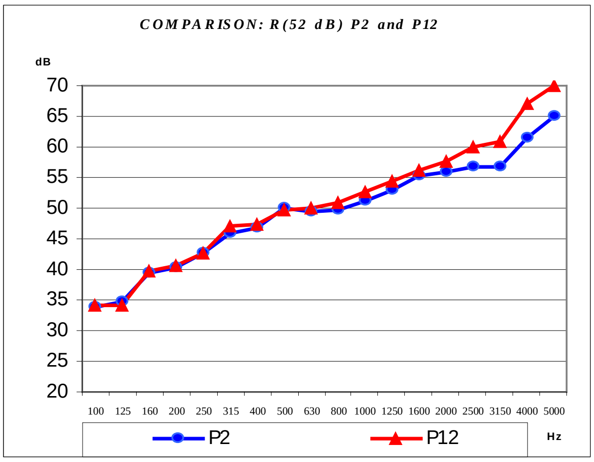


Figure 9. Comparison between P2 and P12

Third-octave bands comparison based on the closing system

The results obtained, from different layers configurations, have shown that the upper locking element affects the acoustic insulation of the full layers configuration in a different way based on the combination of the inner materials; but in the meantime, once the closing system has been chosen, it is possible to concentrate on the frequency insulation using different inner materials, with a reduced effect on the Rw. Comparisons are shown in Figure 10 and 11.

Tests P1 (wooden boarding) and P2 (gypsum board) showed differences up to 10 dB not only in single numbers but also in their frequency trend, in particular at low – medium frequency range (first graph in Figure 10).

Although the differences between gypsum board and OSB2, in terms of single numbers did not show a great gap, just 2 dB, they showed great differences in frequencies between 1000 and 2500 Hz greater than 5 dB, as shown by samples P3 and P4 in the second graph of Figure 10.

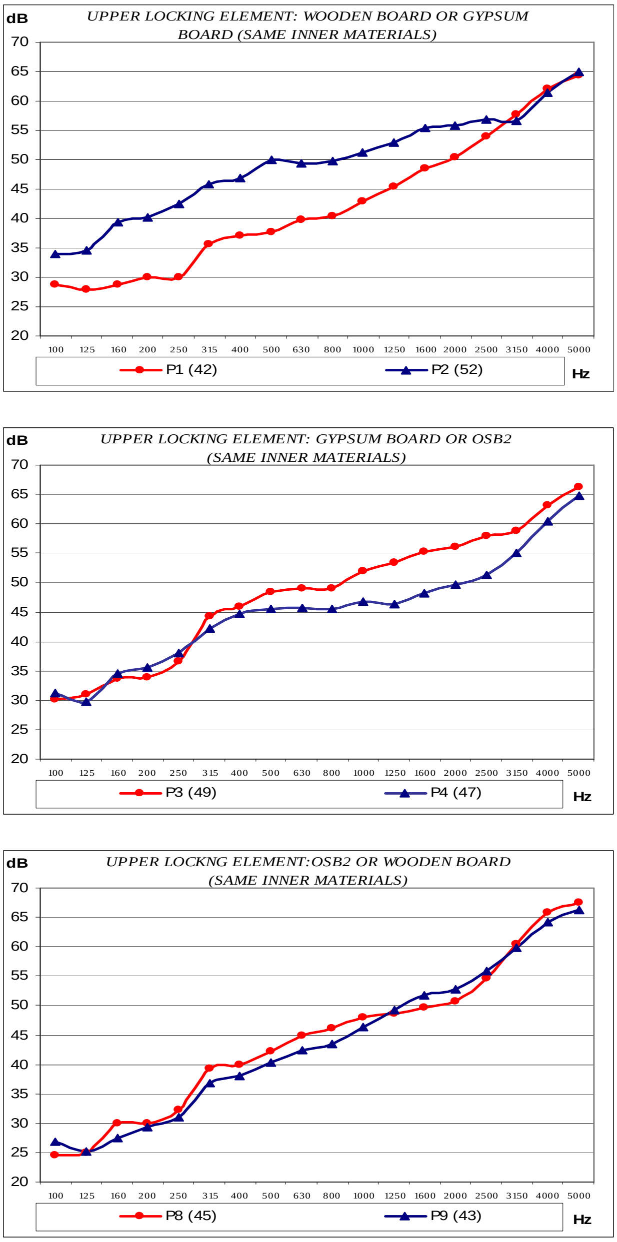


Figure 10. Influence of the upper locking element on the same inner materials

The third graph of figure 10 shows the frequency trend of sample P8 and P9, which differ only for the upper locking element: OSB2 sample P8, and wooden board sample P9. The obtained difference was much less than the one expected based on the two previous results, not only in singles numbers but also in frequencies.

The inner materials composing the samples are respectively: P2 12 cm medium and high-density wood fibre, P3 8 cm medium density wood fibre and EPS, both with gypsum boarding as upper locking element. The analysis performed has showed (see Figure 11) that at low frequencies, wood fibre has a relevant influence on sound insulation.

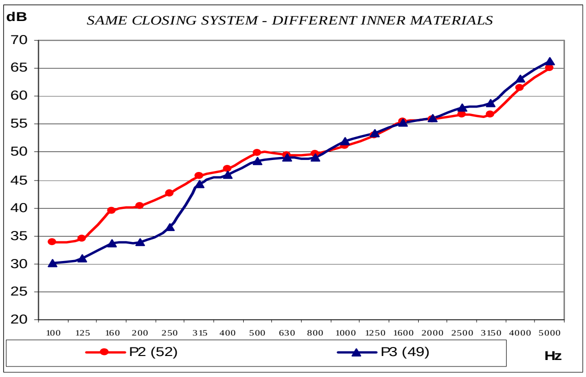


Figure 11. Comparison between P2 and P3 – closing system: wooden boarding – gypsum board

Comparison of the different analysed parameters

The different solutions were analysed and optimised considering many different building needs such as thermal transmittance, thickness, weight and costs (based on the Italian market). By comparing all the properties considered, six layers configurations were chosen as the most competitive. The comparison is shown in Figure 12.

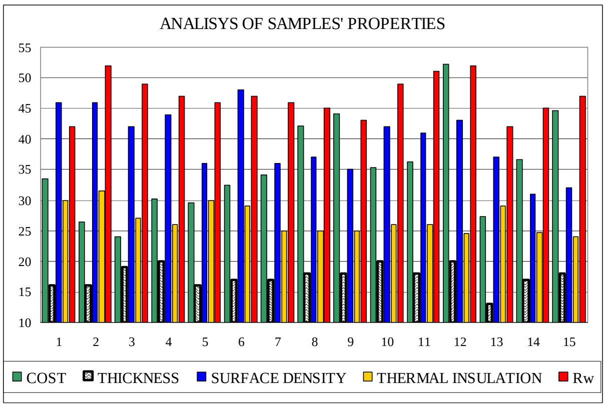


Figure 12: Comparison of R_w, thermal insulation, thickness, weight and cost

Solution P1, composed of wood fibre, was chosen because only one single material was used as inner element. This solution was deemed to be closer to the traditional construction practice, compared to the others. In addition to that the thickness of this solution is quite small (16 cm).

Solution P3 is the most cost-effective solution, (prices based on the materials' cost), acoustically and thermally well performing, but still quite heavy.

Solution P7 is one of the most competitive specimens: it is cost-effective, its thickness is 17 cm, it has high thermal characteristics and good acoustic qualities (R_w 46 dB) and a surface density of 36 Kg/sqm.

Solution P10 showed characteristics close to that of sample P3, even though it is more expensive. This configuration was chosen because it is starting to be used in real buildings.

Sample P12 proved to be acoustically and thermally the best solution with a 20-cm thickness. Cost is the uncompetitive aspect of this solution. The high price is due to hemp wool which is actually an uncommon material, therefore still quite expensive. All the samples containing hemp wool turned out to be the most expensive.

Sample P15 showed very high thermal performances. At the same time, it is one of the lightest solutions, its thickness being small, and it has good acoustic qualities. Its high price is still due to hemp wool.

INTERMEDIATE STEP: OUTDOOR FULL-SCALE TEST CELL

The main purpose of using the outdoor full-scale test cell was to evaluate the acoustic behaviour of the specimens, in a configuration close to a real building.

Six selected layers configurations were reproduced in the external full-scale test cell located at ITC-CNR. The tests were carried out in accordance with standard ISO 140 - 5 [4]. The test set-up is shown in figure 14. The in-situ test set-up, and the set-up used for minimizing the flanking transmission were defined ad hoc. Particular attention was given to the lateral wood retaining beams since, in real buildings, those elements are generally made of wood: a drawing and an image are shown in figure 13. Figures 15 shows some steps of the implementation of the system.

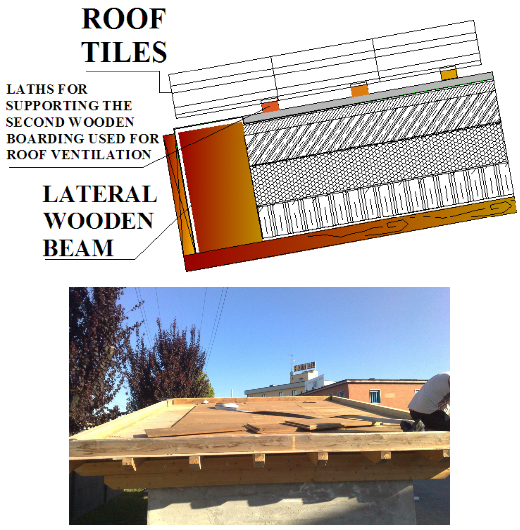


Figure 13. Lateral wood retaining beams

The source was placed on a mobile support, and sloped in order to obtain an angle of (45±5)° as to the roof.

Figure 14. Test set-up

Figure 15: Construction of the sample

COMPARISON BETWEEN LABORATORY AND TEST CELL MEASUREMENTS

Due to the size of the test opening of the laboratory and that of test area S of the external cell, which are both about 10 sqm, and on account of the geometry of both rooms (laboratory and test-cell), 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]).

Comparison between laboratory and test-cell frequency trends

The measurements carried out on the external cell have shown that the acoustic behaviour of samples is extremely different compared to that of the laboratory, once the wood roof is built. On the external cell the wooden roof has a 10° slope, while in the laboratory the test element is mounted vertical. In particular, it is interesting to note that the layers configurations with the OSB2 panels as retaining element show a big loss in sound insulation, principally between 160 and 315 Hz. Two of the samples tested are shown in figure 16.

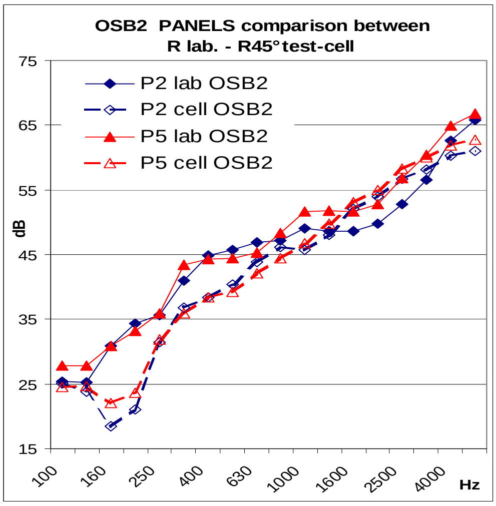
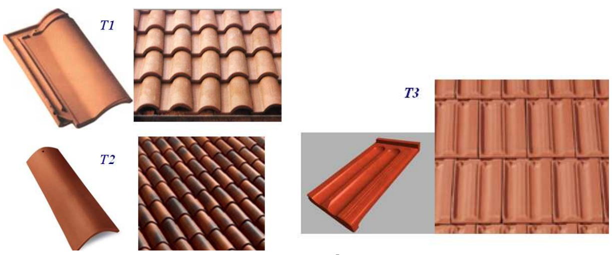


Figure 16. The difference between laboratory and out door cell – without tiles

Tiles influence

The first set of tests including samples without tiles, was followed by a second set of tests, which consisted in the completion of the roof by placing the laths and then the tiles. The specimens were tested with three different types of roof tiles: T1 called "Tegola", T2 called "Coppo" and T3 called "Marsigliese". Basically the three types of tiles differ in shape, weight or both: T1 has a surface mass of 30/40 Kg/m2, T2 70/80 Kg/m2 and T3 40/50 Kg/m2. The roof tiles are shown in figure 17.



Source: Web

Figure 17. The roof tiles

Table 3 reports, for all tests, the single-number values related to the laboratory and to the test-cell with and without tiles.

Table 3: Single-number quantities: laboratory Rw; test-cell D2m,nTw with and without tiles

Test number	*R_w (dB) laboratory*	*$D_{2mn,T,w}$ WITHOUT tiles*	*$D_{2mn,T,w}$ WITH tiles*
P1	*42(-1;-4)*	*36(-2;-5)*	*38(-3;-8)*
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)*

Results contained in table 3 show that the roof tiles placement cause a variation in sound reduction index. Contributions observed with the tiles were both positive and negative: a loss of sound reduction index was observed with roof tiles T1 and T2; an increase in the sound reduction index was observed with roof tiles T3 (sample P1 in Table 3).

IN SITU MEASUREMENTS

The layers configuration based on wood fibre was tested firstly in laboratory, secondly in the outdoor cell, and finally in the real building.

Comparison between laboratory, outdoor test cell and real building

The frequency trend of the different configurations tested (laboratory, outdoor test-cell and real building) is compared, as shown in figure 18. In the real building, the type of tiles used was T2 "Coppo".

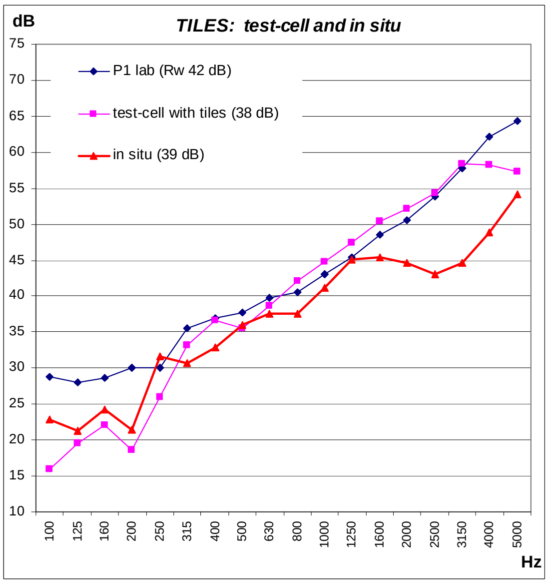


Figure 18. The comparison between laboratory, test cell and the real building

The results obtained on sample P1 have shown that the main difference between the values obtained in laboratory and those obtained both in the outdoor cell and the real building is the insulation decreasing at low frequencies. The frequency trend analysis, shown in figure 18, has outlined that both outdoor cell and real building show loss in sound insulation below the frequency of 250 Hz. In the frequency range between 250 and 1250 Hz the three curves proved to be very similar. Above the frequency of 1250 Hz the in-situ measurements have shown a different trend compared to the other two curves. In fact in the real building there are many factors that influence sound insulation mainly due to the installation. Thus this comparison has underlined that useful information on the acoustic behaviour in the real building can be obtained using the external cell.

The insulation decreasing at low frequencies is observed also in other measurements, carried out in the outdoor cell and in the real building. Figure 19 shows the comparison between two outdoor cell samples and one in-situ measurement, differing in material and closing system. Irrespective of the layers configuration, at low frequency, in both conditions, the decrease of sound insulation at low frequencies due to the tiles is evident.

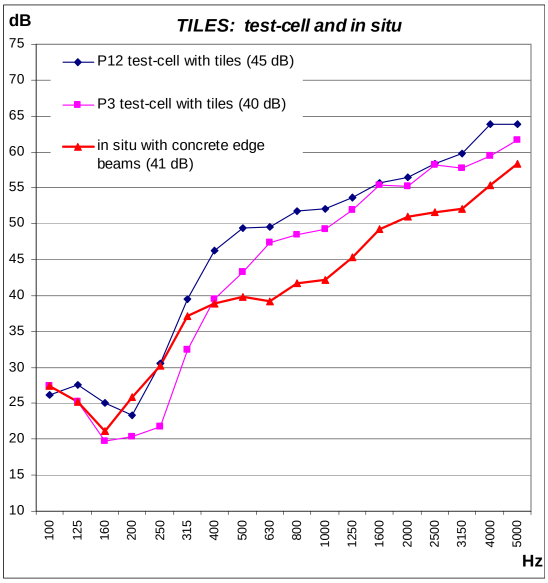


Figure 19. Tiles: outdoor cell and real building

CONSTRUCTION SYSTEM IMPROVEMENT

The research conducted in the laboratory and in the outdoor full-scale cell was aimed at offering easy, cost-effective, acoustically and thermally effective technical solutions suitable for different needs, with regard to the Italian building tradition.

The final part of the project, which is still under way, has been carried out in synergy with construction companies, public and private clients and consists in the application of the samples previously analysed in the outdoor cell to real buildings.

The common multi-layer solution for wooden roofs, shown in figure 20, is composed of wooden beams, wooden board, steam barrier, EPS the thickness of which depends on the thermal needs, roof ventilation realized by laths, a second wooden board on which tiles are anchored, lateral wooden retaining beams, like those shown in figure 15.

In situ measurements were carried out on this kind of wooden roofs, and the standardized sound insulation index of façade D_{2mntw} obtained was between 29 and 31 dB.

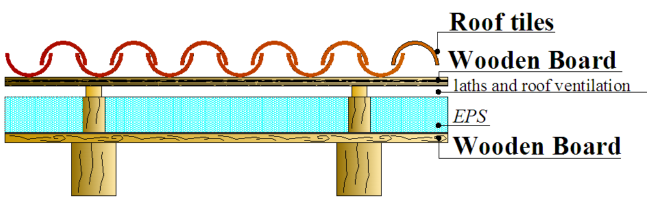


Figure 19. Drawing of the wooden roof layers

Based on the results obtained on the existing wooden roof, clients were aware that changes needed to be made, but they were concerned about the workers and their ability to change their habits. Because of this, it was suggested to preserve the construction system and just change the inner materials. The first configuration tested was composed of: wooden beams, wooden board, steam barrier, 10 cm of wood fibre of medium-high density (only one density was used), roof ventilation realized by laths, a second wooden board on which tiles are anchored, lateral wooden retaining beams and tiles; layers are shown in figure 20.

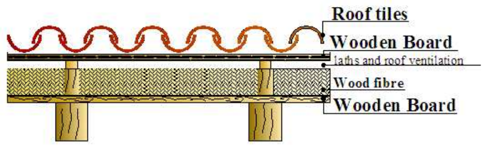


Figure 20. The wooden roof realized

In-situ measurements were carried out on this kind of wooden roof, and the standardized sound insulation index of façade D_{2mntw} obtained was 37 dB.

In the second tested configuration the wood fibre was still 10 cm, but two different alternated densities were used. The construction system was kept the same. The standardized sound insulation index of façade D_{2mntw} obtained was 39 dB.

Change in the construction system

In some of the tested specimens the upper closing element, wooden boarding, was located directly on the inner materials, and the laths positioned on top just to anchor the tiles.

Based on this, in synergy with builders and workers, a different construction system was defined, taking into account both the upper closing element and the lateral retaining beams. As a first step the roof ventilation was shifted above the upper locking element, as shown in figure 21.

The second step consisted in interrupting the contours of the roof façade in order to reinforce the containing system.

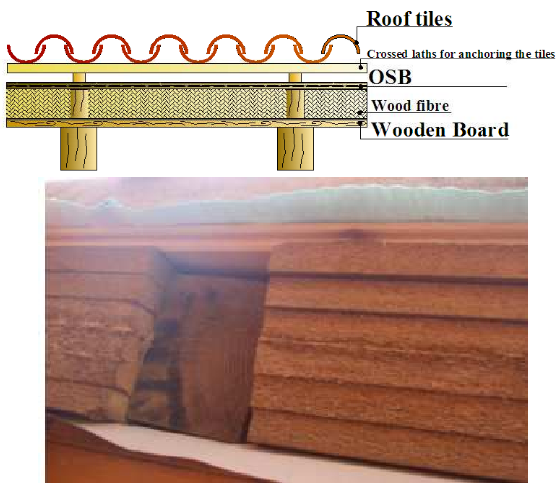


Figure 21. The development system

The retaining edge beams have been built in reinforced concrete, instead of wood; the secondary beams built passing through the concrete edge beams, the inner materials and the upper locking element contained in the height of the concrete edge beams. Details are shown in figure 22.

Figure 22. Secondary beams built passing through the edge beam

The changes in construction systems were applied in two buildings. In both situations, the wooden roof was composed of OSB2 as upper locking element, located directly on 12 cm of wood fibre, and the laths positioned on top of the OSB2 just for anchoring the tiles. The main difference is that in the first case the tiles positioned were T2 "Coppo", there was no edge beam and the inner materials went on till the eaves; in the second case the tiles were T1 "Tegole" and the inner material was interrupted with a concrete edge beam before the eaves.

The two tested rooms differ in size: the first one with tiles T1 is a bedroom in a residential building, the roof surface is 19 m^2, and the volume is 47 m^3; the second is a reading-meeting room in a school for people affected by down syndrome, the roof surface is 109 m^2 and the volume is 521 m^3.

The standardized sound insulation index of façade D_{2mntw} obtained was 39 dB for the smaller and 41 dB for the other.

CONCLUSIONS

The results of this study can be used 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 acoustic comfort inside the building against the environmental noise, the suitable multilayer solution has to be chosen by considering not only the R_w but also the frequency trend.

When the samples are tested in the outdoor 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 layers configurations tested show that tiles affect the performance of the entire roof, sometimes heavily, in particular at low frequencies. The tiles affect every kind of roof layers configurations, whether it is a heavy or light configuration. The real building measurements confirmed the insulation decrease at low frequencies, because of the tiles contribution.

In addition, the acoustic insulation improvement can require the variation of the building construction system.

All these considerations lead to further investigate both the influence of tiles and the improvement of the construction system.

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

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