Experimental measurements of flanking transmission in CLT structures

Abstract

This paper discusses the results of an experimental campaign that lead to the characterisation of flanking transmission in CLT structures with different connection systems. The vibration reduction indices $K_{ij}$ were measured in accordance with the ISO 10848-1 standard in order to provide data suitable to calculate the apparent reduction index according to the EN 12354-1 standard. The research explored several vertical and horizontal junctions on which different number and the type of screws and plates, different CLT panels, and resilient materials at the wall-floor junction were tested. The analysis of these data will hopefully provide a significant tool to improve the accuracy of the prediction methods and to help the acoustic designer of timber building.

Keywords: Building Acoustics, Cross Laminated Timber, Vibration Reduction Index, Flanking Transmission, flanksound Project
Experimental measurements of flanking transmission in CLT structures

1 Introduction

Timber buildings are recently experiencing a period of great prosperity. Frame structures, which can be counted among the most ancient construction techniques, saw a strong return on the market and an extension in areas traditionally characterised by heavy building techniques. Cross Laminated Timber (CLT) structures have been developed only from the 90’s and gained an expanding market since then.

The analysis of the acoustic performance of timber frame structures started relatively recently. It is effectively highlighted in the report of the Cost Action FP0702 [1]: it identified the criticality of poor sound insulation at low frequencies and proposed a number of technical solutions to achieve better performance. One of the problems in the acoustic design of timber buildings is the assumption of an infinite stiffness of some components in the mass-spring-mass or damped resonator modelling of structures. These assumptions fall in timber structures and return a final behaviour that can hardly be attributed to the individual elements as characterised by predictive models.

There are still few data available relative to the acoustic behaviour of CLT structures. A comprehensive study [2] explored a variety of CLT junctions through the measurement of the vibration level difference; an acoustic optimisation was carried out to select optimal construction techniques and some interesting features regarding the radiation efficiency are discussed. Vibration reduction indices and loss factor measurements have been performed for a CLT floor-wall junction as well [3] and the results are discussed for each transmission path relative to the prediction methods. CLT panels are still lighter in weight with respect to traditional structures, but have monolithic characteristics that display an intermediate behaviour between heavy buildings and lightweight buildings. Pursuant to the acoustic design, CLT falls within the category of structural elements in which the structural reverberation time depends on the constraint conditions, which is not the case for the lightweight frame buildings. The main drawback related to the acoustic properties of CLT is that the resonant transmission for thin panels might start around 800 Hz thus compromising sound insulation in a critical frequency range.

The flanksound project, promoted and funded by Rotho Blaas, is aimed at characterising the flanking transmission paths in CLT structures connected by a variety of screw, plates, hold-downs and angle brackets, with/without the use of resilient strips at the junctions. CLT panels were provided by seven different manufacturers. The vibration reduction indices $K_{ij}$ were measured for the junctions in accordance with the standard ISO 10848-1 [4] and are reported and discussed in the frequency range 100-3,150 Hz. Given the small availability of measured data, this work will hopefully contribute to the development of the acoustic design of CLT structures according to the prediction methods reported in the prEN12354-1 [5].
2 The measurement setup

The measurement campaign took place inside the Rotho Blaas warehouse in Cortaccia (Bolzano, Italy) and was conducted in accordance to the ISO 10848-1 standard [4]. CLT panels were supplied by seven different manufacturers, exploiting different production and assembly processes.

The measurement campaign involved the test of vertical and horizontal junctions. “T” and “X” vertical junctions were tested by varying the number and kind of screws (fully or partially threaded) and laying resilient material at the wall-wall interface. Not all the test configurations could be performed using all products, nevertheless some configurations were repeated for different CLT manufacturers in order to test the variability of the $K_{ij}$ which occur due to the differences among CLT panels and to the installation tolerances. 100 mm 3- or 5-ply CLT panels were provided in the dimensions of 2.30 x 3.50 m and 2.30 x 4.00 m, with the outer lamellas oriented in the vertical direction. The junctions are sketched in Figure 1 (a, b). Vertical panels are fixed to concrete blocks 100 mm thick through two hold-downs per panel.

As far as horizontal transmission is concerned, a test configuration was set partially notwithstanding the prescriptions of the standard due to installation and handling constraints. It is displayed in Figure 1 (c). The floor slab is supplied in a 160 mm 5-ply CLT panel divided into two pieces, which are assembled in order to reach the overall dimensions of 3.50 x 4.00 m. The biggest panel composing the slab has the dimensions of 4.00 x 2.50 m. The tests explored the influence of different resilient strips at the wall-floor junction and the transmission enhancement due to the increase in angle brackets and to the different screws. Figure 2 shows some of the tested configurations.

The excitation and measurement points were chosen according to the EN ISO 10848-1 standard [4]. For each panel, three source positions and four measurement points were used. The source consisted of a shaker with sinusoidal peak force of 200 N, which was mounted on a heavy-weight base and screwed to the panels using a plate. The accelerometers were fixed to the panels using magnets. Eyelets are screwed to the panels with screws whose length was...
at least half of the thickness of the panels, in order to reach the innermost layer of lamellas. During the measurements, temperature and humidity of the environment were monitored: the average temperature varied between 14 °C and 15 °C and the relative humidity varied between 40% and 50%. The humidity of the panels ranged around 9%. For the acquisition of the vibration velocity levels, a pink noise filtered at 30 Hz was fed to the shaker and the velocity levels were acquired using four accelerometers at a time. Structural reverberation times have been extracted from impulse responses that were acquired in the same excitation and measurement points used for the velocity levels. ESS signals were used, which were found more performing than MLS signals. The structural reverberation time $T_{15}$ was then extracted using the pre-processed energy detection method [6, 7] implementing a reverse filter. For one test configuration, the measurements were repeated using an instrumented hammer as impact source; details are reported in the dedicated section 3.1 which follows.

3 Experimental results

The results presented in this work partially complement some previously published results [8] and are presented grouped in order to allow comparisons between configurations. First, a comparison is made between two measurements procedures applied to the same configuration. Then, four test configurations are compared which were mounted in the same way but with CLT panels provided by four different manufacturers. The analysis aims at pointing out differences among the CLT panels related either to the mechanical properties of the panels themselves or to the tolerances relative to the assembly process. Then, horizontal junctions are investigated: in particular, the floor slab was firstly fixed using screws and hold-downs; then angle brackets were added and the measurements were repeated in order to point out the increase in sound transmission. Finally, wall-floor junctions were investigated changing the resilient interlayer. Three resilient strips were used having different dynamic stiffness and one of them was tested under an additional static load.
3.1 The measurement technique: hammer vs shaker

A horizontal junction, similar to the one displayed in Figure 2 (c), was chosen to perform measurements with two distinct techniques. The transmission paths investigated, relative to Figure 1 (c) are between panels 1-2 (wall-wall) and between panels 1-5 (wall-floor). Both vertical walls (100 mm) and floor slab (160 mm) consist of 5-ply CLT panels; the lamellas of the vertical panels are oriented parallel to the vertical direction and the lamellas of the floor slab are parallel to the junction tested. The test configuration has been tested using the measurement equipment mentioned earlier (shaker, pink noise/ESS); measurements were repeated afterward with an instrumented impact hammer, used both to determine the velocity level difference and as impact source to record impulse responses. The measurements with the instrumented hammer were performed using three different tips: rubber, teflon and steel and were compared to the results obtained using the shaker in Figure 3. Though the different tips should be related to distinct frequency ranges, in the following the results are reported in the whole frequency range for each tip, in order to spot a peculiarity of the excitation of this kind of structures.

First, the structural reverberation times $T_{15}$ are plotted vs frequency in Figure 3 (a, b), together with their standard deviations, for panels 2 and 5. The results show no sensitive difference between the measurement techniques. As anticipated, the use of different tips returns the same results in the whole frequency range. This might be due to the fact that each hit on the panels actually causes a deformation on the surface whose entity depend on the mechanical...
characteristics of the CLT and on the distance of the cut from the heartwood for each wooden batten. In the same graphs, the standard deviation relative to each set of data is reported as a thin black line on the top of each column of the histogram. In the 1/3 octave bands centred at 100 and 200 Hz there is a significant increase in the variance of the data. This is very clear for panels 2 and 5, while less evident for panel 1. This behaviour spots resonances of the panel at mid-low frequencies and calls for a deeper investigation relative to the modal behaviour of the vibrational field inside the panel and for a re-definition of the total loss factor derived from the modal reverberation time [9].

In Figure 3 (c, d) the $K_{ij}$ values are reported in terms of difference with respect to the measurements performed with the shaker. The difference among the measurement techniques always range around 2 dB, thus it can be considered negligible with respect to the measurement tolerances. For the wall-wall connection the differences between the two techniques does not display a peculiar trend in frequency while the wall-floor connection does display a specific decreasing trend vs frequency. Measurements performed with the shaker provide higher $K_{ij}$ values up to 800 Hz with respect to the values measured with the hammer. At higher frequencies, the $K_{ij}$ measured using the shaker return values smaller than those measured with the hammer. However, this specific trend, related to the different surface masses of the panels, is to be considered carefully since, as pointed out above, the differences range within the measurement tolerances.

3.2 Four different CLT manufacturers

A comparative analysis was performed on four “X” vertical junctions characterised by the same nominal fastening system but with CLT panels provided by four different manufacturers. A scheme of the assembly of the panels is reported in Figure 4 (a); the panels are fixed with 4x3 partially threaded $\phi$ 8 x 240 mm screws, spaced apart of about 40 cm. The vibration reduction index $K_{ij}$ was measured for each transmission path and the results are reported in Figure 4 (b-g). Each transmission path has its specific trend in frequency which is coherently spot by all of the four test configurations. Nevertheless, though the slope of the $K_{ij}$ is roughly the same, discrepancies among the different manufacturers reach up to 10 dB. This might be related to two factors: (i) the mechanical characteristics of the panels; (ii) the assembly tolerances. As remarked above, the same fastening system was used and the configurations were mounted by the same people with the same power tools providing the same tightening torque (clutch controlled). If all the differences were due to the mounting tolerances, one could draw the conclusion that in situ realisations will provide a more uniform behaviour among the panels due to the greater number of constraints. On the other side, further work will be carried out in order to detect the different characteristics of the CLT panels in terms of propagation velocity, radiation efficiency, and through the analysis of the total loss factor in the resonant regions which were spot in the section above. With reference to Figure 4 (f) and (g), the discrepancies found for manufacturer C might be related to a slightly different mounting condition: in this case the floor slab was mounted on panels 3 and 4, which have a different connection with respect to panels named 1 and 2.
Figure 4: $K_{ij}$ values measured in a X vertical configuration (a) for the transmission paths 1-3 (b), 1-4 (c), 2-4 (d), 1-2 (e), 1-2 with the floor mounted over the two panels (f) and 1-5, i.e. wall-floor junction. The four test configurations (indicated as B, C, D, H) have the same nominal fastening system (number of screws, kind of screws, relative position of the panels) but the CLT panels are supplied by four different manufacturers.
3.3 Hold-downs and angle brackets

The influence of the addition of angle brackets in the vibration transmission has been investigated on horizontal test junctions. First, the floor slab was connected with screws and hold-downs (two per panel); then three angle brackets were added on each side of the wall-ceiling junction and measurements were repeated. Two different configurations were tested: in the first one, labelled E, the screws used in the wall-wall and wall-floor connection were fully threaded; in the second one, labelled H, all screws were partially threaded. The different screws affect significantly the vibration transmission between panels, effect which is magnified in this kind of weak junctions. The results are reported in Figure 5 for a wall-wall junction and for a wall-floor junction. The results show that the decrease in $K_{ij}$ with the addition of angle brackets is negligible. There is a greater increase in attenuation at the wall-wall junction, especially with reference to the fully threaded screws. Fully threaded screws tend not to bring in contact the walls notwithstanding the use of tensioners, while partially threaded screws bring panels to a closer contact. Anyway, these effects might be considered negligible when the whole structure is set and the junctions are less weak than the tested ones.

3.4 Resilient profiles: a comparison of the performance of strips with different dynamic stiffness

This section relates to the use of resilient interlayers placed at the wall-ceiling junction. Figure 6 reports the influence of resilient strips in different materials both at the wall-ceiling junction and at the wall-wall junction, which is indirectly affected by the change in sound energy distribution. The static load provided by the bare floor was about 10 kN/m$^2$. Three materials were tested with different values of dynamic stiffness and thickness, which are reported in the caption of Figure 6. Configuration H4 was tested with the same resilient profile used in configuration H3 but with a static load increased by 1,500 kg - resulting thus in a static load of about 23 kN/m$^2$. Before the application of the additional load, angle brackets and hold-downs were unscrewed, while the screws that fastened the floor to the vertical walls were not, in order to replicate the
on-site installation practice. All measurements described here were performed using the same CLT panels provided by one manufacturer and assembled in the same way.

As far as it concerns the analysis of the wall-ceiling junction, resilient layers produce a significant increase in sound attenuation starting from 800 Hz on. At lower frequencies, only one material provides a higher performance. Of course, given the limited load provided by the bare floor, materials with a higher dynamic stiffness could not work properly as mass-spring-mass resonators. Nevertheless it is interesting to notice that, for the material displaying the higher dynamic stiffness, doubling the static load did not produce any appreciable increase in the attenuation performance. This might be related to the fact that the screws were not removed from the floor prior to the increase of the static load, which have prevented the additional load to fully transit to the underlying structure. This highlights an interesting problem relative to the application of resilient strips in CLT buildings; the temporal priority that is given to the connection might have the structure fixed before the full application of the permanent static loads. This would prevent the resilient material from working properly, for all the static loads would be transmitted to structural carpentry that is not dimensioned nor meant to deal with such loads. The attenuation of the vibrational field deriving from the use of resilient strips also emerges from the analysis of the wall-wall junction. Here, the mechanical characteristics of the strip are less significant but an increase in attenuation is registered between 630 and 2,000 Hz.

4 Conclusions

This paper reports some results that emerged from the flanksound project, an investigation devoted to analyse the vibration reduction indices for a variety of junctions tested on CLT panels provided by seven different manufacturers. The measurement setup is described and tested versus the traditional measurement equipment and technique. Given the great availability of data, comparisons were carried out on a “X” vertical junction, which was replicated for four CLT
manufacturers, pointing out the peculiar trend in frequency which characterises each transmission path. The effect of the addition of angle brackets on a wall-ceiling junction was studied on test configurations assembled with different kinds of screws (partially and fully threaded) and the results are discussed with reference to the actual on-site mounting conditions. Finally, the use of resilient interlayers at the wall-floor junction was tested comparing three strips and a configuration with an increased static load. Further work is required to investigate in detail some of the spot characteristics and will hopefully continue with the study of the radiation characteristics of the panel and with an insight into the low frequency resonances.

Acknowledgements

The flanksound research project was promoted and funded by Rotho Blaas srl. The authors gratefully acknowledge A. Fink and R. Ianes for the precious assistance provided in mounting the test configurations.

References


