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SOUND INSULATION OF MODULAR CONSTRUCTIONS

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Abstract

As part of the research project "EcoBox" at the Stuttgart University of Applied Sciences, an innovative affordable timber-hybrid modular construction system is being developed in cooperation with the Ed. Züblin AG. The research focuses on several aspects including logistics, the application of BIM to ensure sustainable constructions, heating, ventilation and air conditioning (HVAC), building physics and acoustics. The main innovation lies in separating the construction into a primary and a secondary structure. The primary load-bearing structure consists of concrete columns, in which prefabricated room modules are suspended as the secondary structure. Each room module consists of a concrete floor as well as walls and ceilings manufactured using a novel timber interlocking system. The individual components of this system are cut from plywood sheets using a CNC machining centre and joined together with precision via milled tenons and mortises. Investigations of the airborne and impact sound insulation as well as some additional structure-borne sound measurements were carried out on a mock-up consisting of two modules arranged both side by side and one above the other. Furthermore, the use of elastic interlayers to decouple the modules of the support brackets was investigated to reduce the structure-borne sound transmission.

Keywords: *timber-hybrid constructions, sound insulation, modular buildings, elastic interlayers*

1. Introduction

In the context of an interdisciplinary research project [1] at the Stuttgart University of Applied Sciences, a timber-hybrid building system is being developed with the industrial partner Ed. Züblin AG. The distinctive feature of this building system is its division into a primary structure consisting of reinforced concrete columns and a secondary structure formed by the individual timber-hybrid modules. The intended application for the building system is rapid, cost-effective and sustainable housing construction. However, its use for accommodation facilities, student apartments and similar projects is also conceivable. As a later part of the project, a three-storey demonstration building comprised of five room modules should be constructed on the university campus, in which, amongst other things, long-term measurements are planned. The project is divided into the following work packages: development of the hybrid building system as well as planning and construction of the demonstration building (to be carried out mainly by the industrial partner), prefabrication and logistics, information management and sustainability in BIM, building physics and acoustics in timber-hybrid modular constructions and sustainable heating, ventilation and air conditioning.

2. Description of the building system

The primary structure consists of precast reinforced concrete columns with a cross-section of 400 mm x 400 mm and is structurally designed to accommodate buildings of up to three full storeys initially, and up to five full storeys at a later stage. Other precast elements, such as staircases, corridor ceilings and prefabricated roof elements, complement the primary structure. The individual room modules, which provide living or usable space, are mounted on steel angle brackets that are bolted to the reinforced concrete columns. The insertion of spacer plates allows for a certain degree of height adjustment of the brackets. In addition, appropriate elastic interlayers are provided between the brackets and the modules to ensure an acoustic decoupling.
The base plate of the individual room modules, which form the secondary structure of the building system, consists of a reinforced concrete ribbed floor slab with a 100 mm thick continuous section and integrated concrete core activation, as well as reinforcing ribs running around the perimeter and positioned in the centre of the long side, with an additional thickness of

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170 mm. The base slab measures 6.30 m x 3.95 m. The walls and ceilings of the room modules are constructed using a special interlocking system of 18 mm thick plywood panels. The individual plywood components are milled on a CNC milling centre from sheets measuring 2.50 m x 1.25 m and fitted with precisely matched tenons and mortises for a form-fit connection. The individual parts are additionally screwed together as required for structural stability. The resulting compartments are filled with insulation material. Figure 1 shows a detail of the interlocking system used for the module ceiling. The system was originally developed for (specialised) concrete formwork.

Figure 1. Interlocking system made from 18 mm thick plywood panels for constructing the wall and ceiling components.

Once the structural shell of the room modules has been completed, the interior construction is carried out at the factory, so that the individual modules can be delivered to the building site in a turnkey condition via special transport (due to their excessive width of about 4 meters). Depending on the configuration, it should also possible to combine two or three modules into a larger unit within the finished building. The façade cladding, for example made of wood, is pre-assembled on the external walls of the individual room modules and subsequently secured to the columns once the modular building has been erected.

3. Construction of a module prototype

Following extensive planning, a room module prototype was constructed during a workshop at the company's site by both project participants from the industrial partner and project staff from Stuttgart University of Applied Sciences. Figure 2 shows some images of the assembly process during the workshop.
The insights gained during the construction of the prototype regarding the construction process and design details were incorporated into the further planning of the subsequent room modules. In particular, aspects related to building service equipment, fire safety, and modular construction were taken into account.

Figure 2. Construction of the room module prototype - components on the base plate (top left), erecting the external wall with the window opening (top right), fitting the ceiling (bottom).

4. Measurements in a door test facility

Following the construction of the module prototype, preliminary measurements were performed in a door test facility to investigate the sound insulation between two room modules and also of the single wall of a module. Between the two modules there is a double layer construction comprised of an internal wall in each case, with a gap of 50 mm, as planned for the arrangement of the modules within the primary structural framework. The internal walls facing the adjacent module consist of two 18 mm thick plywood panels, which are joined together over their entire surface using an interlocking system and screws. On the inside, they can optionally be cladded with 12.5 mm plasterboard. For fire safety reasons, the outer side of the plywood is always cladded with 18 mm thick gypsum fibre boards, which also significantly increase the mass of the structure. Within the 50 mm cavity, 20 mm of mineral wool is installed on each side of the wall for cavity insulation. Figure 3 shows a schematic view of the structural layout of the partition wall between two room modules.

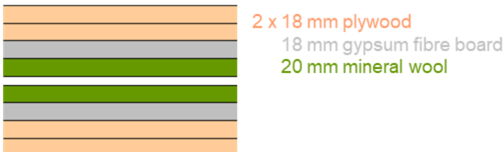

Figure 3. Schematic view of the partition wall between two room modules, which was preliminary measured in the door test facility in different variants.

Initially, the sound reduction index of one wall part (without mineral wool) was measured in accordance to EN ISO 10140-2 [2], the measurement result was R_w = 33 dB. Then, the second wall part was added at a distance of 50 mm, which increased the weighted sound reduction index to R_w = 52 dB. The addition of a single layer of mineral wool insulation (20 mm) resulted in an improvement to R_w = 63 dB. With a second layer of the same insulation, a weighted sound reduction index of R_w = 66 dB could be achieved. Figure 4 shows the measured sound insulation dependent on the frequency.

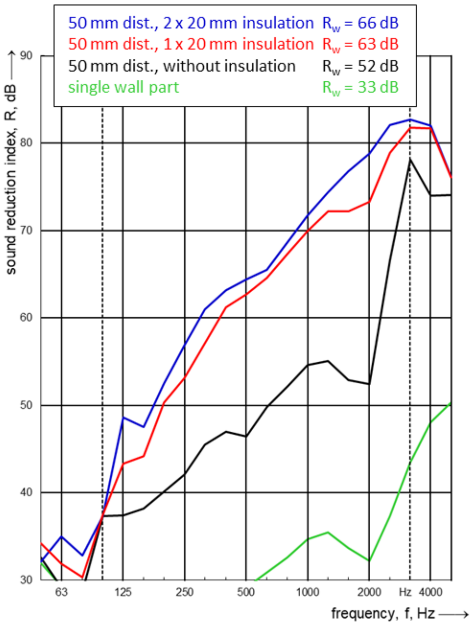

Figure 4. Sound reduction index of the double layer partition wall measured in the door test facility for different variants.

Although the spacing between the room modules had already been set at 50 mm during the design phase of the building system, additional variants with spacings of 100 mm and 200 mm, in each case with and without 2 x 20 mm mineral wool insulation in the gap, were also measured in the test facility. The results showed that the weighted sound reduction index (based on the values shown in Figure 4 for a 50 mm spacing) increased by 2 dB and 3 dB respectively when the spacing was increased to 100 mm, and increased by a further 1 dB in each case when the spacing was increased to 200 mm.

5. Measurements on a mock-up

At the site of the industrial project partner, a mock-up comprised of six precisely positioned reinforced concrete columns and two room modules, which could be arranged in various configurations within the columns, was prepared for carrying out airborne and impact sound measurements in accordance to EN ISO 16283, Part 1 [3] and Part 2 [4]. The two room modules were arranged either side by side for horizontal transmission or one above the other for vertical transmission. One module, the aforementioned prototype, was already largely complete (with floating parquet flooring), whilst the second module was still at the structural shell stage. Another key difference was that, for the second module, the upper ceiling was not constructed using the plywood interlocking system, but with an 80 mm thick cross-laminated timber (CLT) plate for a comparison. The individual room modules were hoisted by a large mobile crane to a height of approximately 11 - 12 m between the four columns and then slowly lowered until they could finally be placed onto the pre-assembled angle brackets (see Figure 5).

Figure 5. Lifting a room module into the primary structure of the mock-up using a mobile crane.

Depending on the configuration under investigation, the room modules were supported on the brackets either rigidly or decoupled by pre-selected elastic interlayers.
The expected airborne and impact sound insulation was estimated theoretically in advance. For the airborne sound insulation, a weighted sound reduction index of R_w = 51.3 dB was obtained for the continuous (100 mm thick) section of the reinforced concrete floor slab with a mass per surface area of 240 kg/m². The concrete ribs were not taken into account in this calculation. The improvement provided by the ceiling of the module below was set at R_w = 19.2 dB, based on the distance and partial cavity insulation. This resulted in a sound insulation index of $R_{w,est}$ = 70.5 dB for the vertical transmission. For the impact sound insulation, a normalised impact sound level of $L_{n,w}$ = 80.7 dB was obtained for the continuous section of the floor slab. Taking into account the improvement provided by the ceiling of the lower module, a standard impact sound level for the entire structure was estimated to be in the region of $L_{n,w}$ = 50 dB. As it was therefore to be expected that compliance with the German requirements $L'_{n,w} \leq 50$ dB for residential buildings would be borderline, and as to keep the production cost low, no additional floating floor was planned in the modules, elastic mounting of the room modules on the support brackets was provided for. The aim was to tune the natural frequency to 20 - 25 Hz. Based on a module mass of m = 15000 kg and four steel brackets, each measuring 275 mm x 145 mm, the contact pressure was calculated to be approximately 0.9 N/mm². For this application, a suitable 12 mm thick elastic interlayer from the company Regupol was selected. A calculated

natural frequency of approximately 21 Hz was determined for this material configuration.
In addition to the influence of the elastic mounting of the room modules, the influence of insulation in the ceiling cavity between two modules was investigated. The measurements on the mock-up began with the horizontal arrangement of the two room modules within the primary structure (see Figure 6).

Figure 6. Horizontal arrangement of the room modules in the primary structure of the mock-up.

For the horizontal configuration, the airborne and impact sound insulation were measured both with and without elastic interlayers on the brackets. The source room was Module 2 (without additional floor), whereas Module 1 (in a fitted-out state) was the receiving room. The total gap of 50 mm between the two modules was filled with 20 mm mineral wool insulation attached to one wall. On the second module, the insulation was omitted for practical reasons, as otherwise there would have been a risk of the insulation being sheared off due to the small residual gap of only 10 mm when the modules were lifted into place by the mobile crane. Figure 7 shows the normalised impact sound level with and without elastic interlayers.

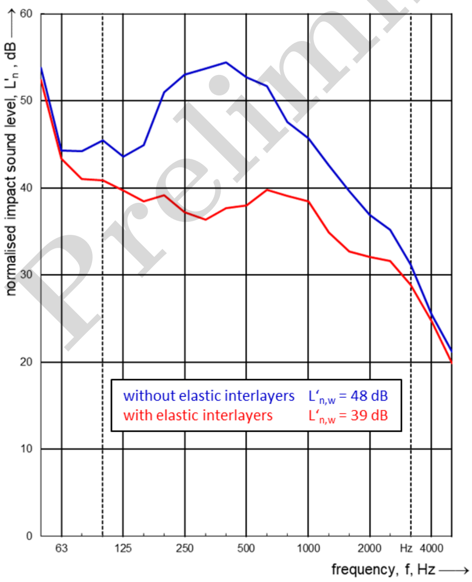

Figure 7. Normalised impact sound level with and without elastic interlayers for horizontal transmission.

When measured without elastic interlayers, the normalised impact sound level of $L'_{n,w}$ = 48 dB is only slightly below the requirements for residential buildings (in Germany $L'_{n,w}$ ≤ 50 dB). With the elastic interlayers, a significantly lower normalised impact sound level could be achieved, particularly in the mid-frequency range, resulting in a reduction of 9 dB in the single-number value. This ensures a good margin of safety, even if the façade cladding, which may require an additional connection between the modules, is added during the subsequent construction phase.
Figure 8 shows the measured airborne sound insulation with and without elastic interlayers. For a comparison, the results from the door test facility (see also Figure 4), which features a design, that is in principle very similar, are also shown.
The elastic mounting of the two room modules also improves the airborne sound insulation, mainly at higher frequencies, which results in a 2 dB higher value of the weighted apparent sound reduction index. The previously measurement carried out on the door test facility using a similar setup (without 12.5 mm plasterboard cladding on the inside) shows a fairly good correlation in terms of the trend. The lower sound insulation between 400 Hz and 1000 Hz of the mock-up measurements is likely due to transmission via the primary structure.

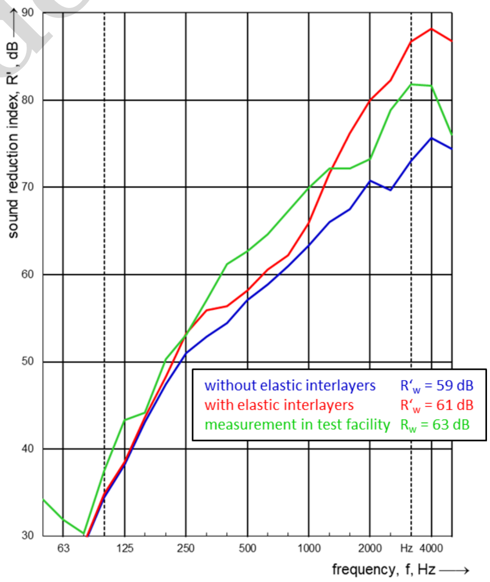

Figure 8. Sound reduction index with and without elastic interlayers for the horizontal transmission, compared with measurements from a very similar construction in the door test facility.

Subsequently, the modules were stacked on top of one another within the primary structure and, based on the results of the horizontal transmission, placed directly on the elastic interlayers. In this arrangement, the second module, with the 80 mm thick cross-laminated timber plate as its ceiling, was positioned at the bottom. Two variants were investigated, one without cavity insulation and one with a 120 mm layer of mineral wool insulation on top of the cross-laminated timber plate (see Figure 9).

Figure 9. Side view of the ceiling cavity without (left, blue) and with (right, red) 120 mm mineral wool insulation, with the modules arranged vertically.

The weighted normalised impact sound level $L'_{n,w}$ was reduced by 7 dB due to the additional cavity insulation. Figure 10 shows the corresponding measured frequency-dependent values of the normalised impact sound level.

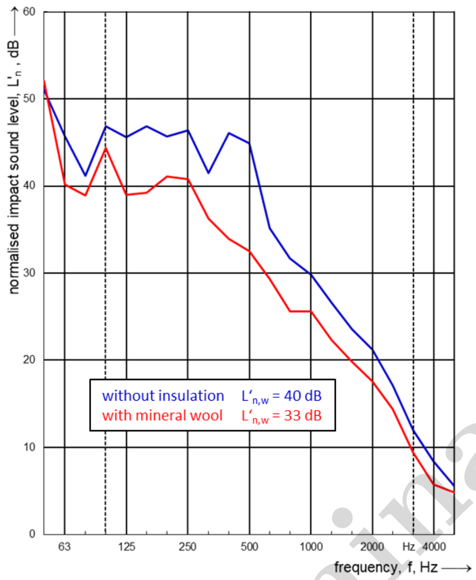

Figure 10. Normalised impact sound level with and without mineral wool insulation in the ceiling cavity - vertical transmission.

For both impact sound as well as airborne sound insulation (see Figure 11), the mineral wool insulation in the ceiling cavity results in a significant improvement starting at 125 Hz.
With the mineral wool in the ceiling cavity a weighted sound insulation index of R'_w = 71 dB could be achieved. This corresponds very well with the value of $R_{w,est}$ = 70.5 dB estimated in advance based on the available component data.

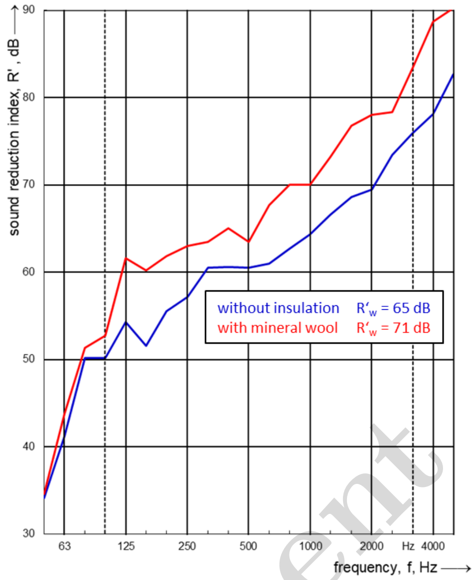

Figure 11. Sound reduction index with and without mineral wool insulation in the ceiling cavity - vertical transmission.

To expand the data set, the influence of the elastic mounting of the room modules on vertical transmission was also investigated on the mock-up. Figure 12 shows the normalised impact sound level with the largely completed module (prototype) at the bottom. For this arrangement, the insulation in the ceiling with the interlocking system of the lower module acts as cavity insulation. In one case, both room modules were mounted on elastic interlayers, in the second case, only the lower module was mounted on elastic interlayers.

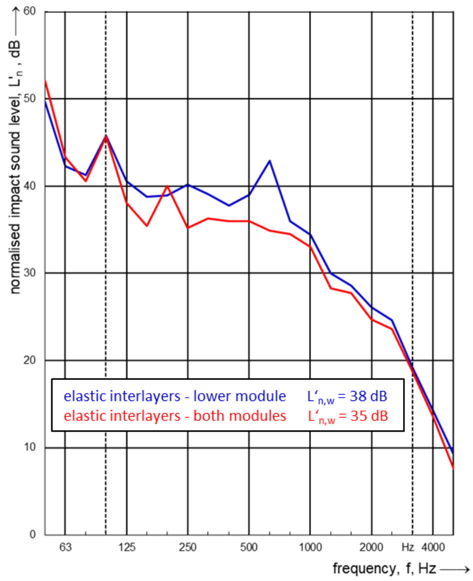

Figure 12. Normalised impact sound level with both modules decoupled in comparison to the decoupled lower module - vertical transmission.

If both room modules are installed with elastic interlayers, this results in a 3 dB lower value for the weighted normalised impact sound level compared to the decoupling of only the lower room module. In terms of airborne sound insulation, the decoupling of both modules results in an improvement of only 2 dB for the singular value (see figure 13). Here, the cavity insulation is evidently already so effective that the additional decoupling of the upper module (source room) no longer results in any significant improvement.

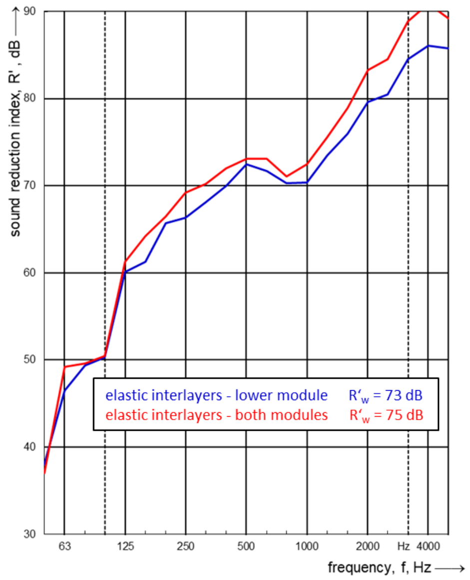

Figure 13. Sound reduction index with both modules decoupled in comparison to the decoupled lower module - vertical transmission.

6. Summary and Outlook

Due to the high degree of prefabrication of the building components, the newly developed modular hybrid construction system could enable a rapid, cost-effective, and sustainable construction of buildings consisting of smaller individual units. The separation of the primary and secondary structures provides excellent airborne sound insulation between the room modules, ensuring that even increased sound insulation requirements, such as those specified in the German standard DIN 4109-5 [5], can be easily met. By mounting the modules on suitable elastic interlayers, a normalised impact sound level that also reliably meets the increased requirements of DIN 4109-5 can be achieved even without an additional floating floor.
Further investigations should be conducted primarily on a demonstrator building. In addition to further building acoustics measurements between the modules, the sound insulation of the finished façade should also be measured there. Furthermore, measurements of installation noise transmission should be made. Additionally, an investigation into vibrations caused by people could be also possible.

7. Acknowledgments

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