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Acoustic performance of prefabricated reinforced concrete walls for modular constructions

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ABSTRACT

Modular construction is being promoted as a solution to the problem of housing crisis as the demand for new construction continues to rise. However, the performance of this construction approach must be competitive with conventional construction methods. Therefore, beyond structural performance and safety features, indoor comfort qualities such as thermal and acoustic insulation should be considered. Acoustic transmission loss phenomena are generally governed by mass, and reinforced concrete (RC) walls are considered massive elements compared to other conventional building materials. However, it is still necessary to enhance such elements with insulation materials. In this study, the acoustic performance of double-layer prefabricated RC wall elements with embedded insulation layers is assessed under different configurations. A 3D harmonic acoustic finite element (FE) numerical model is developed and verified to evaluate the sound reduction capability of the prefabricated double-layered concrete walls with different thicknesses. The effect of using various insulation materials is also discussed.

Keywords: *Acoustic performance, building acoustics, airborne sound, prefabricated RC walls, Finite element analysis.*

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1. INTRODUCTION

The construction waste, high labor costs in developed countries, and the sustainability considerations, promote modular construction as a possible approach to tackle these challenges. Adoption of modern techniques for development of mass buildings leads to affordable housing needed today for many countries. Hence, the efforts should generate solutions aiming to save energy and reducing the construction costs [1]. Maintaining quality and the level of comfort, such as thermal and acoustic comfort, etc., is essential and can't be disregarded. Pre-cast buildings minimize the construction time compared to conventional non-precast buildings which usually require multiple different phases for finishing the elements such as floors and walls, separately. However, while minimizing the number of phases in modular construction, the building must meet the construction provisions at the end of these phases [2]. Therefore, besides structural performance, considerations should be for thermal and acoustic isolations. Moreover, it is crucial to carefully configure their structural elements to avoid thermal and acoustic bridges. The insurance could be made by developing numerical analysis models, which are verified by performing experimental studies on scaled samples or using existing research data.

The literature includes limited amounts of data regarding the acoustic performance of concrete floor and wall systems. Proença et. al. [3] performed an experimental, numerical, and analytical study of the acoustic performance of light weight composite sandwich panels as floor system. The sandwich panels were comprised of two identical glass fiber reinforced polymer (GFRP) face sheets and a rigid polyurethane (PUR) foam core and placed firmly between two chambers for the acoustic test. Weighted sound reduction index (Rw) of 30 dB were reported by the test results. It was concluded that for such lightweight floor systems the performance index values did not fulfill the acoustic requirement of building standards. Ferreira et. al. [4] performed experimental tests of mechanical, fire resistance and airborne sound performance on sandwich panel system for non-loadbearing walls. The sandwich panels were comprised of two face sheets (gypsum board, fire resistant gypsum board, or magnesium oxide), glued to the extruded polystyrene (XPS) core and fixed by galvanized steel profiles. However, despite satisfactory results for other factors, the acoustic performance of the wall panels for the index of sound insulation was insufficient and it was proposed to add acoustic covering layers to the wall systems. Calleri et al. [2] characterized the sound insulation properties of innovative façade made by two-layer cast-in-situ light weight concrete wall with an insulation layer of non-woven fabric in between. Experimental tests were performed to evaluate the acoustic performance of this wall with or without window opening. R_w value of 48 dB were reported from the acoustic test of the façade system. Peng et al. [5], assessed the acoustic behavior of prefabricated composite wall panel, comprised layers of steel wire network, expanded polystyrene foam plastic (EPS), and fine aggregate concrete. It was reported that EPS board can enhance sound insulation in the middle (500 ~ 2000 Hz) and high frequency ranges (<2000 Hz). 42 dB of apparent sound reduction parameters were reported.

In this paper, a study on the acoustic performance of prefabricated double layer RC walls with insulation core is presented. FEM numerical acoustic model has been developed using ANSYS® software package and verified with the existing data on similar models. Then the harmonic acoustic simulation results for different thicknesses and insulation materials are analyzed. Finally, overall conclusions are drawn and suggestions for future work are given.

2. NUMERICAL MODEL

2.1 Materials and methodology

In this study, RC pre-fabricated wall panels featuring an isolation layer were modelled. The RC walls were of 3 m height, including two layers of RC wythe, with an insulation layer in between. The top and the bottom side of the walls were composed of RC section, resembling a beam section. Figure 1 shows the details of the modeled samples. The cross-sectional area as shown in Figure 1 could be of two proposed thickness, 160 mm (P18) or 220 mm (P22), including an insulation layer of 60 mm thick in between which serve as thermal and acoustic isolation, while reducing the weight of the wall system. The material of wall panels includes concrete of class C50/60. The insulation layer of EPS or PUR were considered in the modelling. Longitudinal and transversal steel reinforcement, and spatial trusses were also considered for the cross-section as shown in Figure 1. The proposed wall systems are considered be a segment of multi stories modular buildings.

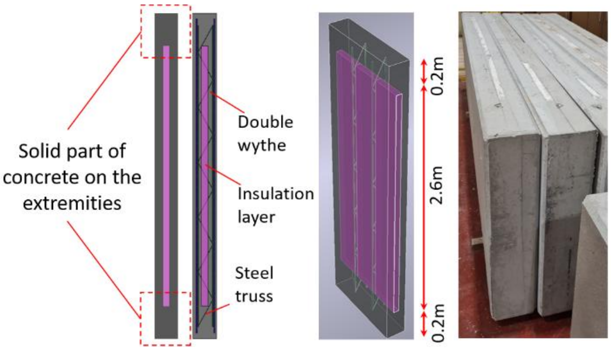

Figure 1. Description of the modelled pre-fabricated RC wall panels.

2.2 Description of the numerical model

A 3D FE model using ANSYS® was used to assess the acoustic performance of the pre-fabricated wall panels. Finite element model for the acoustic harmonic analysis of the airborne sound reduction of the pre-fabricated RC walls are shown in Figure 2. The airborne sound source of 0.01 Kg was simulated as nodal acoustic mass, which was placed in one top corner of the emitting room (Figure 2).

The relevant properties of different materials used in the model are shown in Table 1.

Both emitting and receiving chambers were of 3×3×3 m^3 dimensions. Pre-fabricated RC walls were modelled with 3 m height and 3 m width. The concrete wall panels were considered fixed in top, bottom, and sides as the displacement boundary condition of the geometry. A fluid-structure interface (FSI) was considered at the contact surfaces of the acoustic chambers and the RC wall. Absorption coefficients (α) based on different frequencies (*f*) which are shown in Table 2, were applied in the acoustic medium (air chambers) surfaces.

The model was meshed using ANSYS FLUID220 (20-node acoustic element) and SOLID186 (20-node structural solid element) element types were used, respectively for acoustic and structural domains. Mesh size of 125 mm was adopted for all elements of the geometries which led to a total number of 41580 elements.

As shown in Figure 3, six random nodes in each of the emitting and receiving chambers were considered as microphone positions to report the sound pressure level

(SPL). The selection of these nodes was adopted based on the recommendations of BS EN 20140-9 [6].

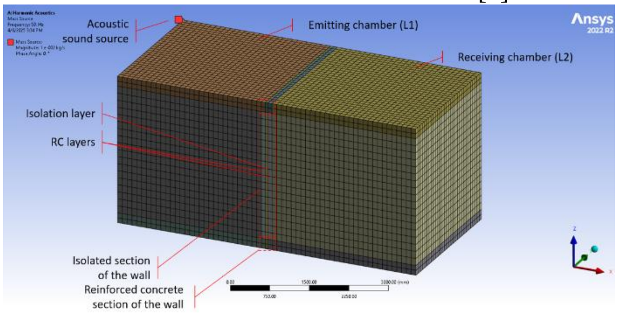

Figure 2. Meshed FE model of the pre-fabricated RC wall, between the two chambers.

Table 1. Material properties of different elements.

Properties	Air medium	Concrete	EPS	PUR
Density [Kg/m³]	1.225	2400	30	100
Elastic Modulus [MPa]	-	30×10^3	3.9	25.9
Poisson's ratio	-	0.2	0.1	0.495
Speed of sound [m/s]	343.2	-	-	-

Table 2. Acoustic absorption coefficient.

f [Hz]	125	250	500	1000	2000	4000
α [-]	0.03	0.03	0.02	0.03	0.04	0.05

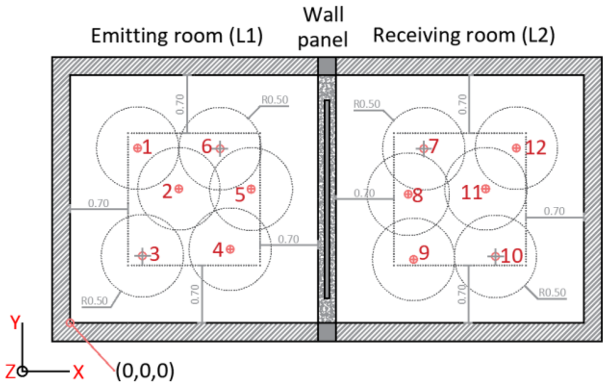

Figure 3. Microphone locations in the emitting and receiving rooms for SPL measurement.

2.3 Model validation

Results from the Proença et al. [3] was used to validate the presented numerical model. The study included experimental and numerical investigation of the acoustic performance of composite sandwich panels with GFRP and PUR core for lightweight floor systems. All the reported data on geometry and mechanical properties of materials were used to develop a FE model for validation. Figure 4 shows the comparison of the FEM model results, presented in this study *vs.* experimental and numerical results reported by Proença et al. It is observed that for frequencies below 1000 Hz, the FEM model shows good agreement with the experimental results. All three curves exhibit a noticeable drop in the 1000–1250 Hz range, likely due to a coincidence frequency, although some slight variations are present. While differences become more apparent at higher frequencies, the overall trend of the FEM model remains consistent with the results obtained by Proença et al., indicating acceptable predictive behavior.

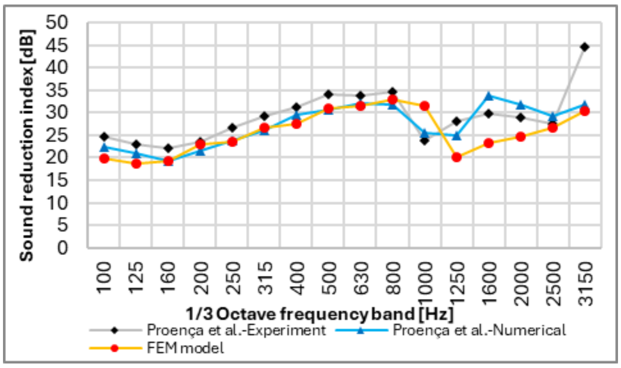

Figure 4. Numerical results of presented FE model vs. the results reported by Proença et al.

3. RESULTS AND DISCUSSION

Figure 5 and Figure 6 show the narrow bound results of the numerical model for pre-fabricated wall panels of 220 mm and 180 mm thicknesses (P22 and P18), with EPS and PUR core insulation layer. The Rw index (Table 3) was calculated using ISO 717-1 reference curve (Figure 5) and based on the methodology provided by this standard [7]. The P22 sample with EPS insulation showed relatively good behavior with Rw equal to 48 dB. Legal requirements for airborne sound transmission in most countries (as Rw indicator) are in the range of 45-55 dB [8]. The P22 sample with PUR core showed a significant acoustic performance of Rw equals to 54 dB. Both P22-EPS and P22-PUR showed a relatively similar behavior in very low and high frequencies. However, in the range of 160-1000 Hz, the P22-PUR outperformed the P22-EPS sample. For the pre-fabricated walls of 180 mm thickness, both P18-EPS and P18-PUR showed similar behavior in the small frequencies

(100-160Hz). However, the P18-EPS showed a higher drop in Rw index at 200 Hz, compared to the other and recovered this difference gradually until 1250 Hz. P18 samples show similar performance in frequencies above 1250 Hz. However, considering their calculated Rw indexes (40 and 42 dB, respectively for P18-EPS and P18-PUR), they can be used as interior walls within dwellings.

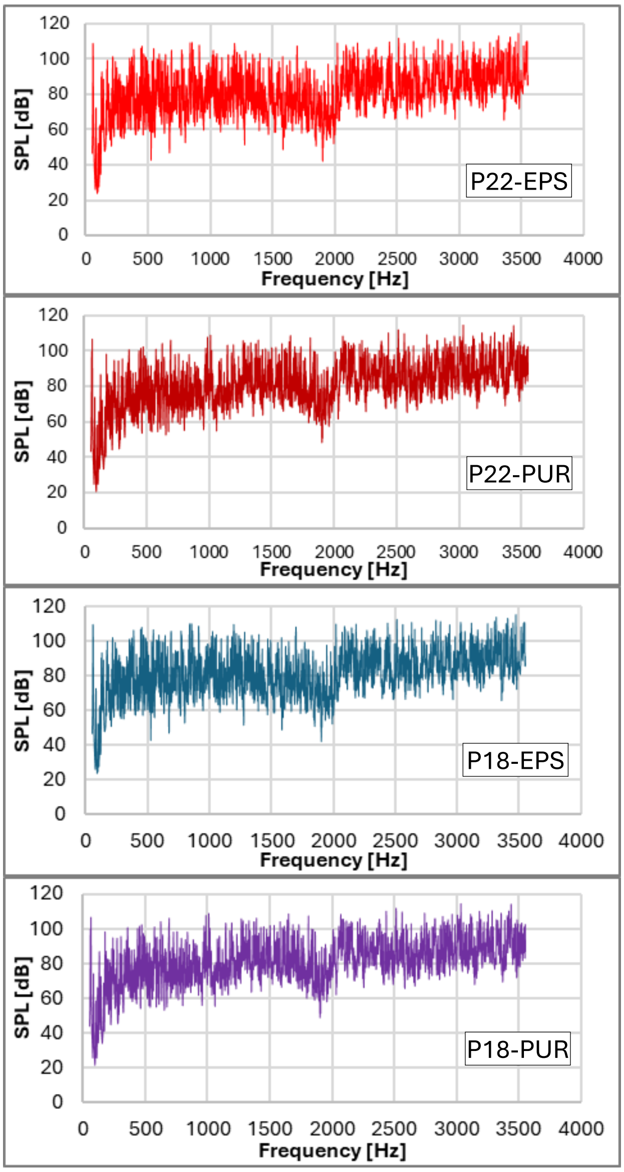

Figure 5. Narrow band results for SPL in receiving room (L2) for different samples.

The critical frequency (f_c) where coincidence effect occurs in a homogenous rectangular plate, can be calculated with the following equation [9]:

$$f_c = \frac{c^2\sqrt{3}}{\pi c_L h} \quad (1)$$

where c is the sound velocity in air (343.2 m/s), c_L is the longitudinal wave speed in plate, and h is the thickness of the plate. Considering h, as 8 mm and 6 mm thick concrete plate, for one layer of the pre-fabricated wall system, and the c_L as 4000 m/s (according to [10] for the relatively similar concrete strength) for the concrete double layer wall here. The critical frequency for the layer of the prefabricated wall where the sound is radiated would be 203 Hz and 271 Hz, respectively for P22 and P18 samples. Therefore, the dip of the transmission loss curve which is shown in Figure 6 might be attributed to the coincidence effect.

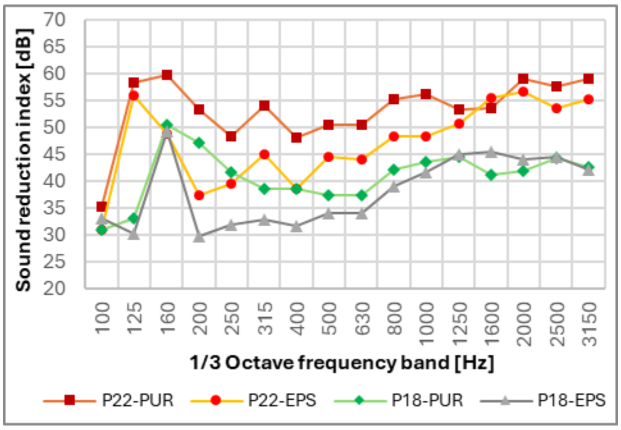

Figure 6. Microphone locations in the emitting and receiving rooms for SPL measurement.

Table 3. Rw index for different modelled samples.

Sample	P22-EPS	P22-PUR	P18-EPS	P18-PUR
Rw [dB]	48	54	40	42

4. CONCLUSIONS

In this paper, a 3D FE numerical model to evaluate the acoustic performance of pre-fabricated double-layer RC wall panels for modular construction was presented. Acoustic performance of pre-fabricated RC walls of 180 mm (P18) and 220 mm (P22) thicknesses, with EPS and PUR as core insulation material, was assessed.

Results showed that core insulation materials have significant influence on acoustic performance. PUR significantly outperforms EPS in both P22 and P18 samples. Moreover, P22 walls shown to offer noticeably better performance in low-frequency insulation, following the mass law principle. P22-PUR was the most robust and versatile for acoustic demands. However, P22-EPS sample also showed a relatively acceptable response, close to the requirements of the building codes. P18 samples may only be viable as internal walls or where cost or weight savings outweigh performance. Moreover, a dip in transmission loss which probably caused by coincidence effect were observed in lower frequencies (about 200 Hz) for all samples.

Future works considering the flanking effects are recommended, since it is an important concern in modular buildings and solutions should be provided to avoid acoustic bridges. This study is part of a bigger project on the development of pre-fabricated concrete wall systems for modular construction. Therefore, further numerical and experimental studies are being carried out to investigate the acoustic performance of the double layer concrete wall system, comprehensively.

5. ACKNOWLEDGMENTS

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