XIII Congresso Ibérico de Acústica
55º Congreso Español de Acústica
TECNIACÚSTICA 2024
Faro, 11 a 13 setembro 2024
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ACÚSTICA 2024

ACOUSTIC BEHAVIOUR OF THE EASYFLOOR GFRP-PUR WEB-CORE COMPOSITE SANDWICH PANELS

Proença M.[1,†,] Santos P.[2], Godinho L.[2], Neves e Sousa A.[1], Correia, J.R.[1], Garrido M.[1], Sena-Cruz J.[3]

[1] CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
{albano@civil.ist.utl.pt, joao.ramoa.correia@tecnico.ulisboa.pt, mgarrido@civil.ist.utl.pt}
[2] University of Coimbra, ISISE, ARISE, Department of Civil Engineering, Coimbra, Portugal
{psantos@dec.uc.pt, lgodinho@dec.uc.pt}
[3] University of Minho, ISISE, ARISE, Campus de Azurém, Guimarães, Portugal
{jsena@civil.uminho.pt}
†Deceased

Resumo

Este artigo apresenta a caraterização experimental e analítica do isolamento sonoro dos inovadores painéis sanduíche *EasyFloor*, constituídos por faces e almas em polímero reforçado com fibra de vidro (GFRP) e núcleo de espuma de poliuretano (PUR). O painel foi desenvolvido para a reabilitação de pavimentos de madeira antigos e inclui duas variações: (i) a solução de base (ii) e um painel híbrido, em que a face superior inclui uma camada de betão. A caraterização inclui a análise comparativa do isolamento a sons aéreos e isolamento a sons de percussão com base em ensaios experimentais em provetes à escala real. Para a estimativa e comparação das propriedades de isolamento acústico determinadas experimentalmente, foram considerados diferentes modelos analíticos, entre os quais, o modelo de Sharp foi o que forneceu melhores previsões tendo em conta uma adaptação que considera as frequências natural e de dilatação como a frequência crítica no modelo. A comparação dos requisitos estabelecidos no regulamento de construção com os índices sonoros normalizados de ruído aéreo e de percussão determinados experimentalmente mostra que a utilização dos painéis Easyfloor em cenários de reabilitação (bem como em construção nova) requer medidas de mitigação adicionais para garantir um isolamento sonoro adequado.

Palavras-chave: painel sanduíche; polímero reforçado com fibra de vidro (GFRP); núcleo de espuma de poliuretano (PUR); redução do ruído aéreo; nível de pressão sonora de impacto.

Abstract

This paper presents the experimental and analytical characterization of the sound insulation of the innovative EasyFloor sandwich panels made of glass fibre reinforced polymer (GFRP) face sheets and webs, and polyurethane (PUR) foam core. The panel was developed for the rehabilitation of old timber floors and include two variations: (i) the base solution (ii) and a hybrid panel, where the top face sheet comprises a concrete layer. The characterization includes the comparative analysis of the airborne sound reduction and impact sound pressure level based on experimental tests on full-scale specimens, which also includes a typical floor covering on the impact tests. Different analytical models were considered for the estimation and comparison of the acoustic insulation properties determined experimentally; from those, Sharp's model provided the most accurate predictions with an adaption that considers the natural and dilatation frequencies as the critical frequency in the model. The comparison of the requirements set in building regulation with the normalized airborne and impact sound indices determined experimentally shows that the use of the Easyfloor panels in rehabilitation scenarios (as well in new construction) require additional mitigation measures to ensure an adequate sound insulation.

Keywords: sandwich panel; glass fibre reinforced polymer (GFRP); polyurethane (PUR) foam core; airborne sound reduction; impact sound pressure level.

PACS no. 43.55.Rg, 43.58.-e

1 Introduction

Sandwich panels are composite-section building elements made of thin face sheets bonded to a low-density core widely used in civil engineering applications mainly as cladding elements, but also in other more demanding scenarios such as building floors. Typical materials include metal, wood or fibre-reinforced polymer (FRP) composites for the sheets [1] combined with lightweight cores, such as polyurethane (PUR) rigid foam [2]. FRP composites advantages face to other solutions include their lower self-weight, high strength-to-weight ratio, improved durability and reduced maintenance requirements [3]. This and other characteristics turn those panels into an interesting solution for rehabilitation of old building floors where the existing structural support members (stone-rubble masonry walls) have limited structural capacity and avoids affecting the original seismic performance of such buildings [4].

Despite such advantages, and as a result of its lightweight nature, a weak point of this type of panels is the poor acoustic performance (both airborne and impact sound transmission), as reported in the work by *Proença et al.* [2] related to homogeneous-core GFRP-PUR sandwich panels. This means that additional sound transmission mitigation measures (false ceilings and/or floorings supported on a resilient layer) are required to fulfil user comfort levels for housing and office buildings.

In the follow-up of the development and study of GFRP-PUR sandwich panels [2], a novel GFRP-face and web and PUR-core composite sandwich panel design was proposed as a modular system, named as *Easyfloor*. Besides the base solution (designed for spans up to 4 m), referred hereby as “all-GFRP”, a hybrid sandwich panel with an additional top face sheet made of a thin layer of concrete (for spans up to 5) m was developed, referred hereby as “hybrid” (Figure 1).

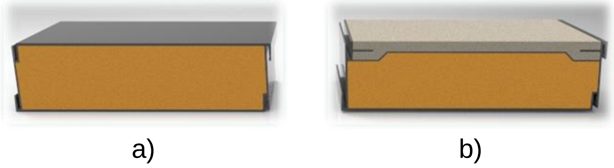
a) b)

Figure 1 - *EasyFloor* sandwich panel solutions: a) all-GFRP and b) hybrid.

This work presents the acoustic characterization of the *EasyFloor* panels namely: the airborne sound reduction and impact sound pressure level based on experimental tests on full-scale specimens (including typical floor covering on the impact tests); the comparison of the experimentally results with analytical predictions; and the verification of the compliance with building code requirements for the acoustic insulation.

2 Materials and methods

2.1 Test specimens

For both all-GFRP and hybrid panel solutions, two different plan dimensions were considered for the test specimens: 1.508 × 1.250 m^2 for the airborne sound reduction tests and 1.508 × 1.600 m^2 for the impact sound pressure level tests Figure 2). Each of the test specimens were composed of five panel segments (0.30 m of width) adhesively bonded with a two-component thixotropic epoxy adhesive (thickness of 2 mm) along the side edges.

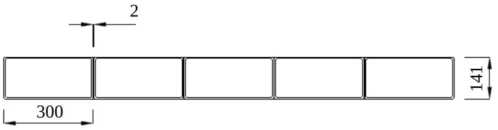

Figure 2 - Test specimen cross-section geometry (in mm).

The all-GFRP solution was composed of a PUR core (mean density of 70 kg/m^3) and GFRP face sheets and webs with thicknesses of 5.5 mm and 7.7 mm, respectively (mean tensile modulus in the longitudinal direction of 31.4 GPa and 26.0 GPa, respectively). The hybrid solution had an additional 20 mm thick layer of C30/37 concrete placed over the top GFRP face sheet (mean cylinder compressive strength of 42.3 MPa). The all-GFRP and the hybrid solutions had a mass per unit area of 41.7 kg/m^2 and 89.7 kg/m^2.

2.2 Airborne sound insulation tests

The airborne sound insulation tests were performed, according to ISO 10140-2 [8], in a chamber consist of two contiguous rooms (the source and receiving chambers) with internal volumes of 111 m^3 and 122 m^3, respectively, separated by a high sound insulation wall with an opening where the test specimen was placed. A reduced sized panel (1.5 m x 1.3 m) has been used, due to production limitations; although the standard accounts for this possibility, the interpretation of the results must be careful, particularly when the wavelength of the bending wave is higher than half of the minimum size of the panel (in the present case, 0.625 m). The positions of the microphones were located at least 0.8 m apart from the wall to mitigate close-to-wall effects according to ISO 10140-4 [10] and are presented in Figure 3.

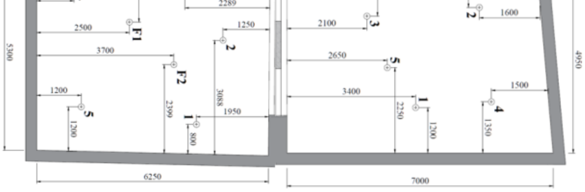

Figure 3 - Position of the microphones and sound sources in the source chamber (left, average height of 3.350 m) and receiving chamber (average height of 3.15 m) (dimensions in mm).

Measurements were performed considering two repetitions for each combination of: a) source position; b) microphone position in the source room, and c) microphone position in the receiving room. The determination of the reverberation time was performed for each 1/3 octave frequency band ranging from 50 to 5000 Hz by placing the sound source in the receiving chamber in two different positions and considering five microphone positions in the receiving chamber. According to ISO 10140-5 [11], the reverberation time (T_r) should be between 1 s and $2 \cdot (V/50)^{2/3} = 3.62$ s (V is the volume of the chamber). Only for the 50 Hz and 63 Hz frequency band the reverberation time exceeded the normative limit, however, these frequency bands were not included in the airborne analysis of sound reduction indices. The background noise was registered in both chambers, but no correction to the results was performed, as the difference between the background noise pressure level and the pressure level at each chamber was higher than the maximum difference value for which ISO 10140-4 [10] requires a background noise correction (15 dB).

2.3 Impact sound insulation tests

The impact sound pressure level tests were conducted on a reduced test chamber (with an internal volume of 2.73 m^3 and 10 cm thick chamber walls), for which, previous studies [7] demonstrated the reliability of such test setup. In the tests, the specimens were placed on top of the small-size test chamber over a resilient cork layer to reduce flanking transmissions and filled in the contour with a thin silicone line, thus further reducing flanking transmissions.

Inside the chamber, and following the provisions of ISO 10140-4 [10], the number of microphone positions was equal to the number of tapping machine positions (five positions) and were chosen with different distances to each orthogonal face of the chamber to minimize close-to-wall effects (Figure 4).

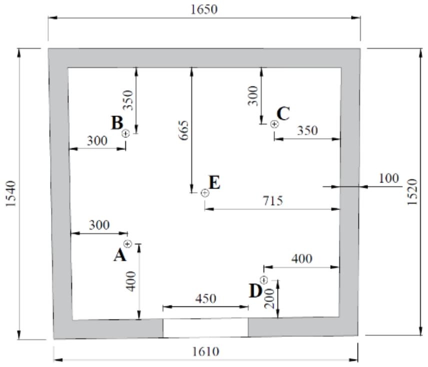

Figure 4 - Position of the microphones inside the acoustic chamber (height of 1500 mm) (dimensions in mm).

Also, three different orientations of the tapping machine were considered for each position: aligned, perpendicular and forming a 45° angle with the webs of the panels. For each tapping machine position, measurements were performed for the five different microphone positions.

Following the procedure described in [7], corrections were introduced to reduce the contamination of the measured sound pressure level inside the chamber by airborne transmission as well due to background noise (as described for the airborne sound tests).

The effects of a typical floor covering on the impact sound pressure level were also analyzed, by repeating the impact sound pressure level tests with a resilient floor covering applied on the top of the panels for the determination of the reduction of impact sound pressure level (ΔL) according to EN ISO 12354–2 [12]. A wooden floor covering composed of wood planks (thickness of 5 mm) glued to a resilient cork layer (thickness of 10 mm, mass of 172 kg/m^3 and dynamic stiffness of 190 MN/m^3), with an overall mass of 10.5 kg/m^2.

3 Results and discussion

3.1 Airborne and sound insulation tests

One-third octave frequency spectrum of the experimentally determined airborne sound reduction are presented in Figure 5, which also includes the results of a similar type of composite sandwich panel, but with homogeneous core, *RehabGFRP* (mass per unit area of 37.2 kg/m^2, more details in [13]) for comparative purposes.

For frequencies above 630 Hz, the overall shape of the airborne sound reduction curves of the *EasyFloor* panels is quite similar; for the lowest frequency bands, the hybrid solution presents higher airborne sound reductions of about 5-6 dB when compared to the all-GFRP solution. This shows that the concrete top layer increases the noise reduction for frequency bands up to 630 Hz, from which the composite sandwich panel controls the shape of the sound reduction curve. Dips in the sound reduction curves (usually related with resonant behaviour phenomena) are observed, with a first dip from 250 to 500 Hz on the all-GFRP solution and a double dip along a wider frequency range, from 250 to 800 Hz in the hybrid solution. The differences between the airborne sound reduction spectra for the *EasyFloor* and *RehabGFRP* panels might be related with the panel structure (the presence of GFRP shear webs on the first) as well in the test methods and size of the samples used in each case.

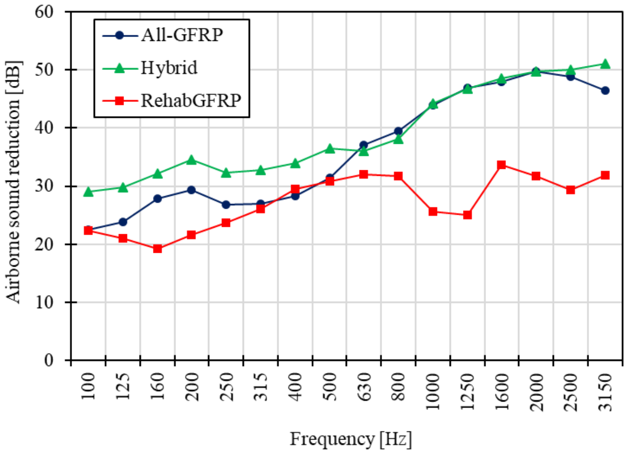

Figure 5 - Airborne sound reduction of the EasyFloor and the RehabGFRP panels.

The weighted sound reduction index R_w (C, Ct_r, $C_{100\text{-}5000}$, $C_{tr\ 100\text{-}5000}$) obtained for each solution, according to EN 717-1 [14], was 38 (-1, -5, -1, -5) dB and 41 (-1, -3, 0, -3) dB, for the all-GFRP and hybrid solution, respectively. Such results agree with the expected improvement due to doubling the floor mass. The EasyFloor panel's R_w compare to a much lower value of the RehabGFRP (32 dB), solution with slightly lower mass per unit area.

3.2 Impact sound insulation tests

The one-third octave spectrum of the impact sound pressure level (with and without a resilient floor covering) for the all-GFRP solution is shown in Figure 6 and for the hybrid solution in Figure 7.

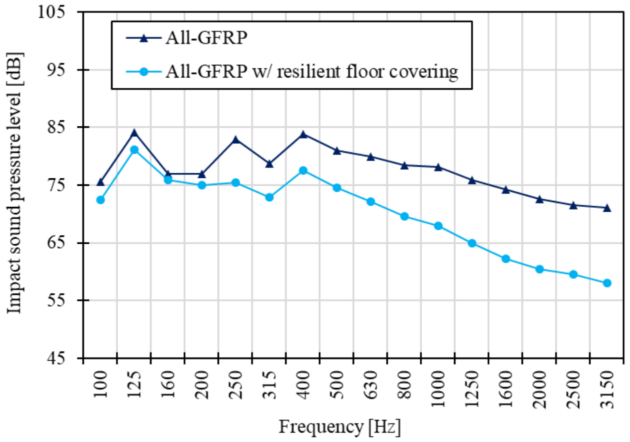

Figure 6 - Comparison of the impact sound pressure level of the all-GFRP sandwich panel with and without a resilient floor covering.

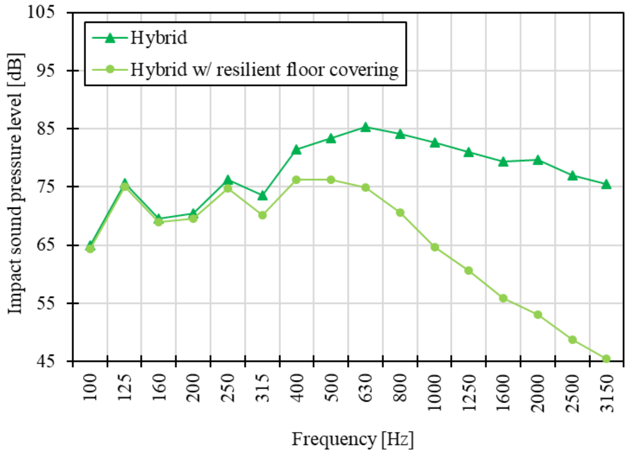

Figure 7 - Comparison of the impact sound pressure level of the hybrid sandwich panel with and without a resilient floor cover.

Within each solution, the trend throughout the frequency spectrum is similar for both situations tested (with and without resilient floor cover) up to the 200 Hz (all-GFRP solution) and 315 Hz (hybrid solution) frequency bands; such result shows that the noise transmission from the tapping machine to the interior of the chamber is mainly governed by the panel, as expected. Also, as expected, the presence of the resilient floor covering provided gains in the insulation. The maximum impact sound pressure level in the specimens without floor covering occurred at frequencies of 125, 250 and 400 Hz (all-GFRP solution) and 125, 250 and 630 Hz (hybrid solution). The peak at the 125 Hz band relates to the first acoustic normal modes in each direction and at 250 and 400 Hz bands relates with the resonant behaviour in the plate combined with a plate-room coupling effect [15], which is more significant at the 250 Hz than at the 400 (or 630) Hz band. The weighted normalized impact sound pressure level $L_{n,w}$, according to EN 717-2 [16], for the all-GFRP solution without floor covering resulted in 81 dB, while the addition of the same resulted in 72 dB; for the bare hybrid solution a result of $L_{n,w}$ = 85 dB and 69 dB were obtained, respectively. The 85 dB which is slightly worse result than the all-GFRP solution, mainly due to significant modal behaviour up to 2000 Hz, namely with resonances leading to higher sound pressure levels above 500 Hz. This discrepancy is related to the fact that in the all-GFRP solution the top face sheet is less stiff than in the hybrid solution, which increased the panel eigenfrequencies; another possible cause is the fact that the tapping machine generated impacts mainly located in more damped areas, namely above the PUR foam rather than above the GFRP webs; in that sense, in the hybrid panel, the concrete layer allows for a more efficient distribution of energy to the ribs due to the increased stiffness on the top layer. In the case of the hybrid panel, the results agree with the predictions obtained from the mass law together with the reciprocity principle [17]. Figure 8 presents a comparison of spectrum of the impact sound pressure level of the *EasyFloor* and *RehabGFRP* panels (the last tested in a normalized full-scale chamber, with 10 m^2 of plan area).

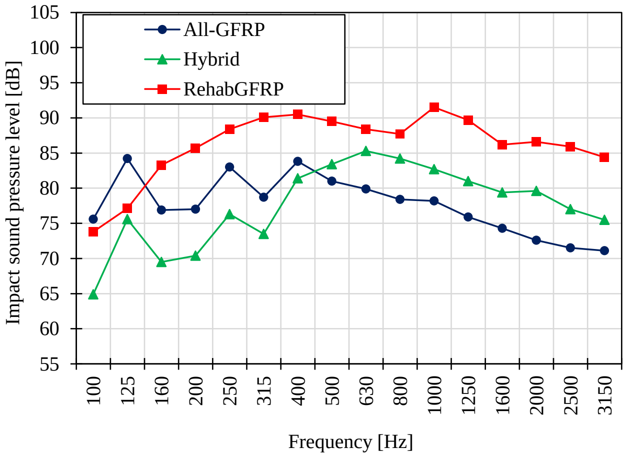

Figure 8 - Comparison of impact sound pressure level of various solutions.

The *RehabGFRP* panel presents the worst overall performance, whereas the hybrid solution exhibits the best performance (up to the 1000 Hz band) while the all-GFRP solution performs better from that frequency band onwards. The differences on the overall shape of the impact sound pressure level spectra of the *EasyFloor* and *RehabGFRP* panels might be related with the presence of GFRP webs on the first as well in the test methods and size of the samples.

4 Analytical model

4.1 Models

Several simplified analytical models have been proposed in order to predict the sound reduction characteristics of sandwich panels, which include combination of the mass law and the effect of different resonant frequencies: natural frequencies (f_n), which depend on the bending stiffness, the mass and the dimensions of the panel; critical frequency (f_c), dependent on mass and bending stiffness; and dilatation frequency (f_{dil}) dependent on the mass of the face sheets and the stiffness of the core. In this study the

Sharp's model [9] is considered including some adaptations: besides the original model (which considers the critical frequency as the main resonant frequency), two variations of the original Sharp's model were considered, based on *Santos et al*. [7]: replacing the critical frequency (f_c) by the first natural frequency ($f_{1,1}$) or the dilatation frequency (f_{dil}). The dilatation frequency was calculated according to Krakers [4].

4.2 Comparison with experiments

Figure 9 and Figure 10 compares the analytical predictions obtained from Sharp's model with the experimental results for the all-GFRP and hybrid solutions.

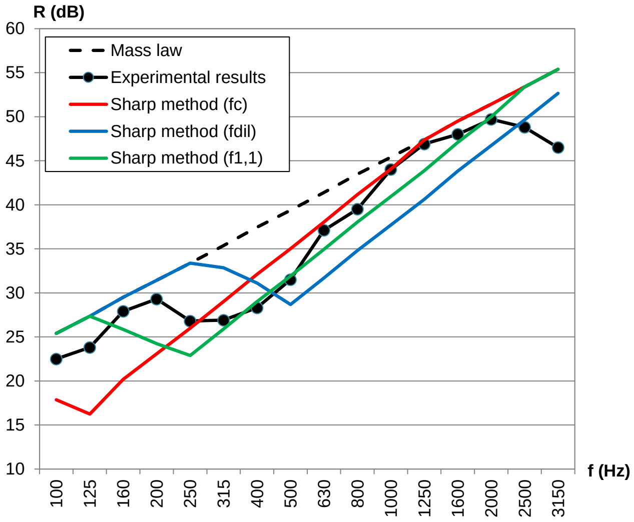

Figure 9 - Comparison of Sharp's analytical model with experimental results for the all-GFRP solution.

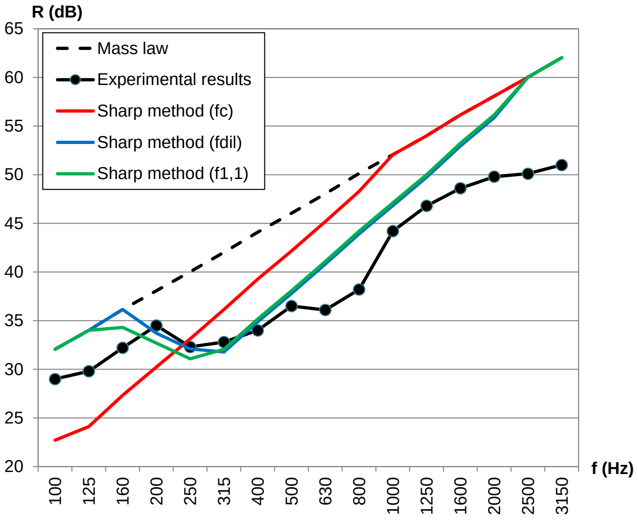

Figure 10 - Comparison of Sharp's analytical model with experimental results for the hybrid solution.

As seen in the figure, the Sharp's original model leads to a noise reduction curve that differs significantly from the results obtained experimentally. Indeed, for low critical frequencies, mass law' deviations are controlled by natural frequencies corresponding to bending vibration modes and dilatational resonances (84.8 to 157.0 Hz in the all-GFRP solution and 78.6 to 119.8 Hz in the hybrid solution). In the all-GFRP solution, considering the natural frequency or the dilatation frequency in the Sharp model leads to predictions that are close to the experimental results, which, in the first case, captures very well the first dip in the noise reduction curve. The same is conclude about the hybrid panel, however none of the models describes the second dip observed. These results highlight the complexity of this type of structural floor system (web-core sandwich panel) regarding the prediction of their acoustic response; a possible alternative for the prediction of the airborne sound insulation of this type of system seems to be a semi-empiric or hybrid model.

5 Regulation compliance

The developed panels were developed for the rehabilitation of degraded timber floors in ancient buildings, including the improvement of the acoustic insulation of such structures. Due to the uncertainty in quantify the acoustic properties of timber floors, the design objectives of the *EasyFloor* project regarding the acoustic insulation, for both the all-GFRP and hybrid solutions, were to reach the Portuguese acoustic legal requirements for rehabilitation of residential buildings (3 dB lower than the requirements for new construction [19]), reduced by 12 dB in the case of airborne sound and increased by 21 dB in the case of impact sound. Table 1 presents a compilation of the acoustic insulation requirements for building floors considered in the development and analysis of the *EasyFloor* system based on different indicators across the world [10][19][20][21]. In Portugal, such requirements are the Weighted Standardized Level Difference ($D_{nT,w}$) and the Weighted Normalized Impact Sound Pressure Level ($L'_{nT,w}$). As the different insulation descriptors used assume roughly the same value in laboratory, they can be used for comparison with R_w and $L_{n,w}$ estimates with no need for further conversion.

Table 1 - Acoustic insulation requirements and experimental sound insulation indices.

Sound transmission	Legal requirements for new construction – Portugal (other Countries)	Design objectives	Experimental			
			all-GFRP		Hybrid	
			Bare panel	With resilient floor covering	Bare panel	With resilient floor covering
Airborne sound reduction	$D_{nT,w} \geq 50$ dB (R_w, $D_{n,w}$, $D_{nT,w}$, $FSTC \geq$ 45-55 dB)	$R_w \geq 38$ dB	38	-	41	-
Impact sound pressure level	$L'_{nT,w} \leq 60$ dB ($L'_{n,w}$, $L'_{nT,w} \leq$ 43-68 dB)	$L_{n,w} \leq 81$ dB	81	72	85	69

Both solutions (all-GFRP and hybrid) meets the design objectives for the airborne sound reduction index; only the hybrid solution without the resilient floor cover fails to meets the impact sound pressure level requirement. These panels would also certainly meet the Portuguese building comfort requirements for new construction with the addition of noise mitigation elements, such as false ceilings with one inner layer of mineral wool and a resilient floor covering (a false ceiling would typically increase R_w by 10-

15 dB and decrease $L_{n,w}$ by 5 dB). With such mitigation measures, the estimations would be for the base-solution, R_w = 53 dB and $L_{n,w}$ = 67 dB, and for the hybrid panel, R_w = 56 dB and $L_{n,w}$ = 62 dB.

6 Conclusions

The results of the acoustic airborne and impact insulation experiments performed on the *EasyFloor* web-core sandwich panels made of GFRP, PUR plus concrete (hybrid solution) are reported. The experimentally determined airborne sound reduction spectra of the panels were compared with predictions obtained from different analytical models. From those, Sharp's model modified to consider the natural and dilatation frequencies replacing the critical frequency to characterize deviations to mass law provide the best approximation. The findings of the analytical and experimental study revealed the complexity of web-core sandwich panel acoustic behaviour and the difficult in describe such behaviour with existent analytical formulations. With the bare panel solutions, it is possible to meet the objectives put forward in the design stage of the *EasyFloor* project; however, for new construction, where building comfort requirements are stricter, mitigation measures are needed.

Acknowledgements

This work was partly financed by FCT / MCTES through national funds (PIDDAC) through the R&D Unit Civil Engineering Research and Innovation for Sustainability (CERIS), reference UIDB/04625/2020, and the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), reference UIDB / 04029/2020, and the Associate Laboratory Advanced Production and Intelligent Systems (ARISE), reference LA/P/0112/2020. This work is part of the research project ‘‘EasyFloor – Development of composite sandwich panels for rehabilitation of building floors”, involving the company ALTO – Perfis Pultrudidos, Lda., CERIS/Instituto Superior Técnico and ISISE/University of Minho, supported by FEDER funds through the Operational Program for Operational Program for Competitiveness and Internationalization (POCI) and the Portuguese National Innovation Agency (ANI) – project no. 3480 (POCI-01-0247-FEDER-003480). The authors would like to acknowledge to company Tecnipor for the support provided, namely in providing and casting the concrete layer of the hybrid panels.

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