A New Lightweight Floor System Based On Sandwich Panel

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Abstract

A new lightweight floor system was developed to tackle the sustainability issue in the construction sector. The proposed flooring system is suited for rehabilitation of degraded timber floors in existing building. Despite the great potential that sandwich construction shows as load bearing elements their use has been hindered by the high initial cost. Three alternative architecture, all including steel face sheets, were envisaged, namely i) steel webs and polyurethane (PUR) foam core system, ii) glass fiber-reinforced polymer (GFRP) webs and PUR foam system and iii) outer steel webs and balsa wood core. The structural, thermal, acoustic and fire resistance requirements were identified in the Portuguese national codes. Particular attention is given to the description of the materials adopted for the different components with respect to the driving factors of the design of the panel, namely weight, cost, environmental impact, load bearing capacity, rigidity, thermal and acoustic properties and fire resistance. The preliminary design of the three sandwich panels is carried out considering the value of the actions established in the Eurocode standards. The final layout and cost estimate are the results of a parametric study aimed at retrieving the lightest and most economical solutions.

Keywords: sustainability, floor system, sandwich panel, limit states design.

Introduction

The construction sector has a great impact on the consume of energy, natural resources and the production of waste. Reuse of existing building allows to reduce the use of raw materials that would be spent in manufacturing new ones and the waste production due to demolition (Luechinger et al. 2015). A safety assessment of the building is required, especially for the horizontal structural elements, such as timber floors. They are particularly susceptible to biological attack as a result of lack of maintenance. Common rehabilitation approach involves the construction of new floors made either of concrete, steel or composite (timber-concrete) elements. These strategies present the disadvantage of increasing the structural mass and the potential seismic hazard in earthquake prone areas as well as requiring additional reinforcing intervention on the vertical elements of the structures. A new lightweight floor system based on sandwich panel is proposed to overcome this issue. The sandwich floor panel's materials and architecture are introduced. The preliminary design of the innovative flooring system is presented along with the requirements for such structural element.

Sandwich panel in building industry

Alternative forms of sandwich panels may be obtained by combining different face sheet and core materials. Metallic facings with low-density plastic or mineral wool core are mostly being used as secondary structural elements, such as roof and façade cladding system, due to their particular combination of properties. The metal face sheets ensure the necessary load bearing capacity and protection to the core materials which in turn provide thermal and acoustic insulation and corrosive protection on the inside (Davies 2008). GFRP face sheets sandwich panels with balsa wood core are increasingly being used as primary load bearing elements instead. They serve as bridge deck solutions both for rehabilitation and new construction. Their low self-weight allows to rapidly install them and minimize traffic disruption (Mara et al. 2014). They also offer a further advantage in aggressive environmental conditions due to their high corrosive resistance. Despite their great potential sandwich construction application as load bearing elements in building floor system is still limited. This is due to several reasons: i) the shear deformation of the core may greatly contribute to the overall vertical deflection especially in less slender beams (Correia 2009); ii) the stringent manufacture requirements; iii) and, above all, the high initial cost compared to traditional solutions. For what concern the core flexibility many authors proposed different reinforcing techniques. Core stitching and insertion of looped fabric in the inner surface of the face sheets (Kim et al. 2005 and Chen et al. 2014) to improve the connection between the different parts of the assemblage is too cumbersome and not fit for large-scale production. When balsa wood products are present in the core its dispositions may be tailored to enhance the resistance of the sandwich panels at particular locations (Osei-Antwi et al. 2013). The most promising solution so far is the insertion of longitudinal reinforcements in the shape of webs. This architecture layout was deemed the most appropriate for the new flooring system since i) it is cost efficient as it allows the use of economic and low strength core materials that are currently available in the market and ii) does not complicate the manufacture process of sandwich panels.

New lightweight floor system

In this work an innovative floor system based on sandwich panels is presented. Three different solutions were developed, namely i) SP1, two steel face sheets, steel webs and polyurethane (PUR) foam as core system, ii) SP2, steel face sheets, glass-fiber reinforced polymer (GFRP) webs and PUR foam core system and iii) SP3 two steel face sheets and outer webs enclosing a balsa wood core. All the panel architectures are based on the web-core system (see Figure 1) which different authors have demonstrated to be effective in improving the flexural strength and stiffness (Fam and Sharaf 2010, Liu et al. 2014 and Tuwair et al. 2015). The sandwich floor panels represent a prefabricated solution which allows for time and economic savings during the installation stage. Their low self-weight and suitability for highly standardized manufacturing process ensure material and energy consumption reduction. This work addresses the requirements that the new flooring system must fulfill. Advantages and disadvantages of the use of different materials with respect to the above-mentioned requirements are also presented.

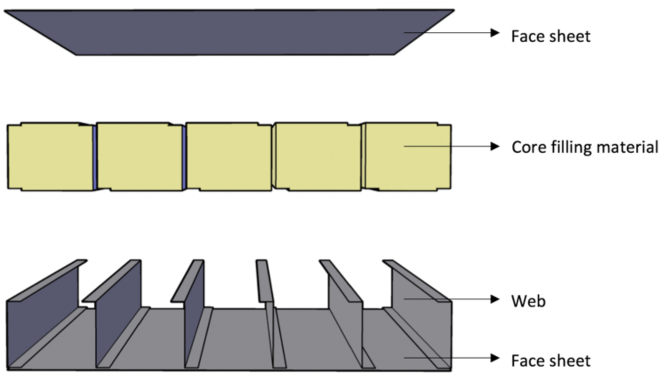

Figure 1. Web-core system sandwich panel.

Building floor requirements

In order to develop a lightweight floor system based on sandwich panel the structural, thermal, acoustic and fire resistance requirements were identified. The structural requirements are established in the Eurocodes, the relative transposed Portuguese norms (Eurocode 3 Part 1-3 2006, Eurocode 3 Part 1-5 2006 and Eurocodigo 1 Part 1-1 2009, the European Recommendations for Sandwich Panels (ECCS/CIB 2000 and the literature regarding the design of cold-formed steel (Ziemian 2010), fiber-reinforced polymers and sandwich panels (Ascione et al. 2007 and CNR 2007. The structural design is divided into two main parts, namely i) the ultimate limit state (ULS) verifications and ii) the serviceability limit state (SLS) verifications. For what concern the ULS the verification can be divided into two main groups: i) one related to the resistance of the cross-section and ii) one related to the occurrence of instability phenomena. The resistance of the cross-section is generally checked for bending moment and shear, a combination of the previous two, crushing/crippling of the webs, core shear failure, web and/or core

crushing at the supports and debonding between the core and face sheets. The instability phenomena are related to local buckling of the face sheets and webs, wrinkling of the face sheets, lateral-torsional buckling of the sandwich panel. The SLS verifications are necessary to ensure the comfort of the users and are mostly concerned with the vertical deflection and the natural frequency of the sandwich panel.
In order to ensure the good thermal performance of the building, with respect to the energy efficiency, as well as the minimization of condensation phenomena a maximum limit value of the thermal transmittance of opaque horizontal element is set in the Portuguese building code (Portaria 379-A 2015). The value depends on the climatic region where the building is located.
The acoustic behavior and the fire resistance of the flooring system are extremely important for building floor application, but they are not the main topic of this work. Nevertheless, the requirements were identified and might offer a cue for future research. The acoustic environment comfort is measured in terms of airborne and impact sound reduction between floors. The reduced self-weight of the sandwich floor panels constitutes a disadvantage as the sound insulation is proportional to the mass. The fire resistance is expressed in terms of resistance to collapse or excessive deformation, resistance to flame and gas penetration while maintaining structural integrity and the insulation offered to the unexposed face as not to ignite material in contact with it. These criteria must be satisfied for a certain period of time according to the risk category of the building which in turn depends on the height of the building, number of stores, gross floor area and number of occupants.

Suitable materials for web-core system sandwich panel
The web-core system consists in the addition of thin-walled profiles in the longitudinal direction connecting the core and the face sheets. In SP1 and SP3 solutions the webs are made of structural steel sheet. Cold-formed members can be produced at a reduced cost and with a high manufacturing accuracy, thereby facilitating the joining of the webs and face sheets of the sandwich panel. However, they require adequate coatings to prevent corrosion and ensure the connection with the core and the webs. Typical section of cold-formed profiles are channel and Z-type sections. Their ultimate strength is reduced by the local and distortional buckling phenomena. One of the solutions proposed to improve their performance is cutting holes in the web plates (Kujala and Klanac 2005). These would also benefit the thermal behavior and fire resistance since the holes will decrease the thermal conductivity of the webs.
In SP3 solution the webs are GFRP profiles. GFRP is a material which allows the integration of structural, architectural and building physics functions. In comparison to steel it present several advantages: lightweight, good thermal insulation and anti-corrosive resistance. However, the advantages are balanced by the higher cost of the raw material and the difficulties in the recycling.
The core material selected both for SP1 and SP2 solution is PUR foam. It has the highest thermal insulation properties among core materials due to their closed cell microstructure. Indeed, the gas contained in the cells provides additional thermal transmittance. Nevertheless, the fire reaction properties of PUR foam are poor. The mechanical properties increase along with the increase in the density. The challenge is to achieve the desired properties with the smallest density, since the cost of the raw material is more significant than the manufacture process. In solution SP3 the core material is made of balsa wood layers. It has a higher density compared to other core materials, yet the additional weight is compensated by its excellent mechanical properties. These properties are highly dependent on the direction of the grain which is usually perpendicular to the face sheet of the sandwich panel. This disposition ensures great resistance against indentation and wrinkling.

Preliminary design and cost estimate

Sandwich panels SP1, SP2 and SP3 were preliminary designed according to the structural requirements and their cost estimated and compared. The structural model adopted for the preliminary design of the different solutions is a single panel, simply supported at the ends (see Figure 3). The prototypes are designed to cover a span of 5.0 m. It is a significant length, as to the best of the authors knowledge, no sandwich panel has been designed so far for this span. Additionally, this span is probably the upper bound expected in rehabilitation of degraded timber floor market. The actions, expressed in terms of load per unit area, taken into account are i) the self-weight of the sandwich panel, ii) the self-weight of the non-structural members, which was set equal to 1.5 kN/m^2 and iii) the variable load which includes the live load for a residential type of building, which is set equal to 2.0 kN/m^2 (according to the Eurocode standards). The self-weight of the non-structural member envisages the possibility of using additional systems such as floating floors, drop-down ceiling, sprinklers and detectors to compensate for the poor acoustic performance and fire resistance of the sandwich floor panel.

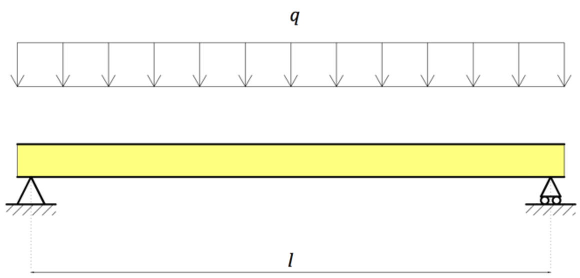

Figure 2. Simply supported beam structural model used for the preliminary design.

The design approach consists in calculating the cross-section resistance to bending moment and the web resistance to shear. The live load bearing capacity of the panel with respect to bending moment (LLB) and shear (LLS) can be obtained solving the equation of the fundamental combination at the ULS established in the Eurocodes for the live load, as follows (Eqs. 1-2):

$$(LLB - \gamma_G \times G_k) / \gamma_Q \geq Q_k = 2.0 \text{ kN/m}^2 \quad (1)$$

$$(LLS - \gamma_G \times G_k) / \gamma_Q \geq Q_k = 2.0 \text{ kN/m}^2 \quad (2)$$

where G_k is the sum of the structural and non-structural elements self-weight, Q_k is the live load and γ_G and γ_Q their corresponding partial factors. The SLS are considered fulfilled if the vertical deflection δ_{max} of the panel is less than the maximum value imposed by the national code for generic floors (Eq. 3).

$$\delta_{max} \leq L / 250 \quad (3)$$

where L is the span length of the floor. The mechanical properties used for the calculation were estimated according to values found in the technical literature as well as technical documents from several manufacturing companies (see Table 1).

Table 1. Mechanical properties and density of the sandwich panel materials

Material	Young's modulus [MPa]	Shear modulus [MPa]	Tensile strength [MPa]	Compressive strength [MPa]	Poisson's coefficient	Density [kg/m^3]
Steel (S220GD+Z)	2.1×10^6	-	$f_u = 300$	-	0.3	7850
			$f_y = 220$			
GFRP (Class E 23)	$E_L = 23$	3.8	240	-	$\nu_{LT} = 0.25$	1800
	$E_T = 7$				$\nu_{TL} = 0.08$	
Balsa wood	$E_{x,y} = 75$	210	0.35	0.10	-	136
	$E_z = 1900$					
PUR foam	-	-	-	-	-	40

Note: f_u and f_y are the steel ultimate and yielding strength, the subscript L and T in the GFRP properties stand for longitudinal and transverse, the subscript x, y and z in the balsa wood properties stand for the in-plane and out-of-plane direction respectively.

SP1 solution was designed according to Eurocode 3 Parts 1-3 and 1-5 (2006). In cold-formed member the driving design factor is the instability phenomenon. The cross-section is reduced to take into account the local buckling mode through an iterative procedure. SP2 solution was design according to CNR DT250/2007 (2007). Its design was driven by the SLS as it is often the case with FRP materials. The already low Young's modulus has to be further reduced for the calculation of the long-term deflection to take into account degradation effect in the FRP. SP3 solution was designed according to the CEN WG4 scientific and technical report (2016). The cross-section resistance considered a reduced ultimate strength of the steel compressed face sheet to take into account the occurrence of wrinkling phenomena. The final prototypes are the result of a parametric study carried out by changing the number and size of internal webs (while keeping constant the width of the panel), the thickness of the core and the thickness of the faces. In Table 2 the results of the parametric study of SP1 are provided. As it can be seen the design governing factor is the resistance to bending moment rather than vertical deflection.

Table 2. Results of the parametric study on SP1 (in bold character the value not satisfying the verification)

Panel	Type	LLB [kN/m^2]	δ_{max} [mm]
SP1	5 Z-section webs	3.35	11
	4 Z-section webs	2.67	13
	3 Z-section webs	**1.97**	16

The architecture layout of the solutions SP1, SP2 and SP3 are shown in Figure 3a, 3b and 3c. Their main characteristics are summarized in Table 3. These three solutions represent the best solutions (for each type) that fulfill the minimum structural requirements. The SP1 solution resulted the most economical one.

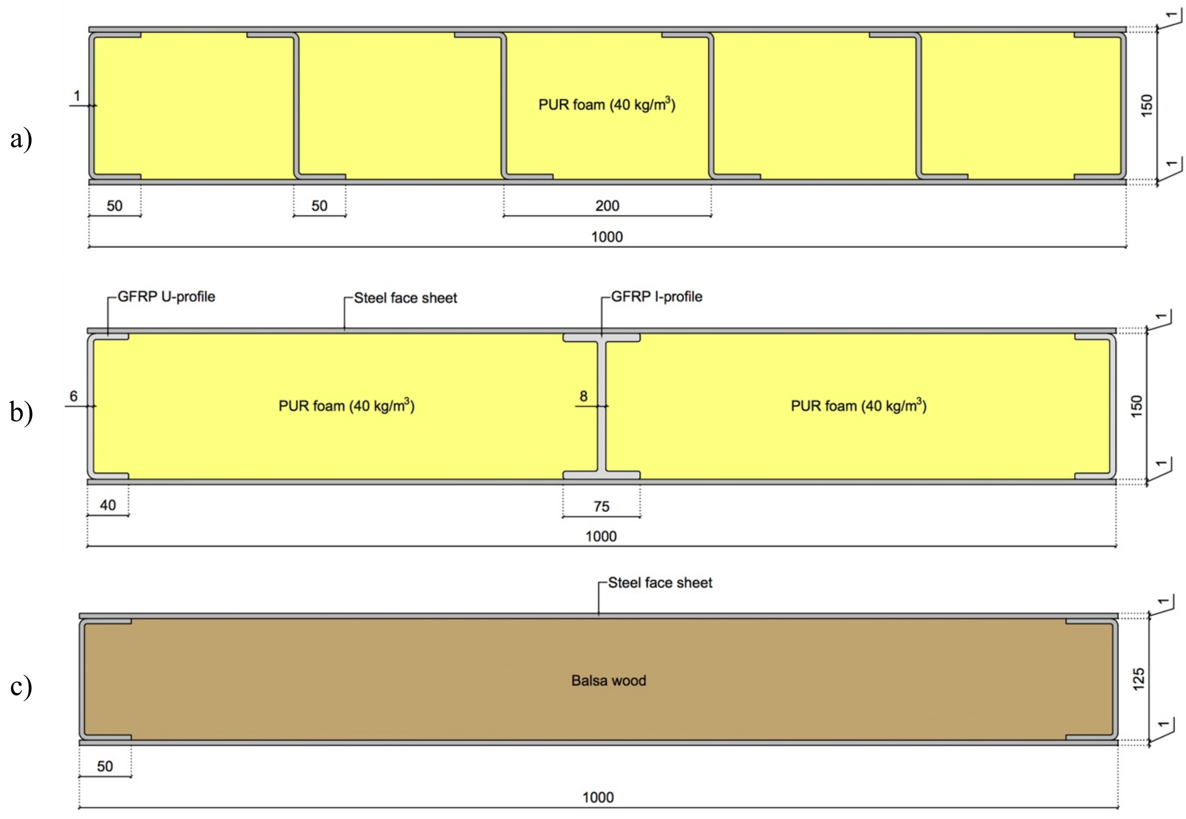

Figure 3. Architecture layout of solution a) SP1, b) SP2 and c) SP3. All units in [mm].

Table 3. Main characteristic of solutions SP1, SP2 and SP3

Panel	Solution	Type	LLB [kN/m^2]	LLS [kN/m^2]	δ_{max} [mm]	Cost [€/m^2]
SP1	Steel + PUR foam	4 Z-section webs	2.7	8.4	13	41.6
SP2	GFRP + Steel + PUR foam	1 I-profile web	3.4	8.6	13	99.4
SP3	Steel + balsa wood	-	8.4	3.4	19	131.2

Conclusions

In this work an alternative solution based on sandwich panel to the traditional flooring system for the rehabilitation of existing building was presented. A comprehensive analysis of the requirements for developing the building floor system is described. The challenges and opportunities offered from sandwich floor panels are discussed with respect to the requirements previously identified. The preliminary design showed that the most competitive solution from the economical point of view is constituted by steel face sheets and webs and PUR foam core.

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