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MULTI-OBJECTIVE OPTIMIZATION ASSISTING DESIGN OF SANDWICH PANELS

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ABSTRACT

In the scope of a R&D project, the design of three new lightweight flooring panels with distinct characteristics was performed, namely: i) two steel face sheets, steel webs and polyurethane (PUR) foam as core system; ii) steel face sheets, glass fiber-reinforced polymer (GFRP) webs and PUR foam core system; iii) two steel face sheets and two steel outer webs enclosing a balsa wood core. The design of these panels included optimization procedures. The optimization method selected was a multi-objective optimization genetic algorithm (GA) which has proven to be well suited to solve this class of problems. The multi-objective function includes the minimization of the i) cost, ii) weight and iii) environmental impact. The objective functions are generally conflicting meaning that the minimization of one of the functions prevents the simultaneous minimization of the other ones. The definition of the multi-objective GA is presented and the implementation of its essential features, namely selection method, diversity maintenance and elitism is discussed. Boundary conditions are imposed so that the population will represent a feasible solution to the problem. These boundary conditions consist in the analytical formulation of serviceability, ultimate limit states and thermal transmittance verifications required by the building codes used in the design of the panels. The present paper deals with the introduction to all the aspects of the problem, then introduces, as example, the panel with two steel face sheets, steel webs and PUR foam as core system.

KEYWORDS

Sandwich panels, design, multi-objective optimization, hybrid structures.

INTRODUCTION

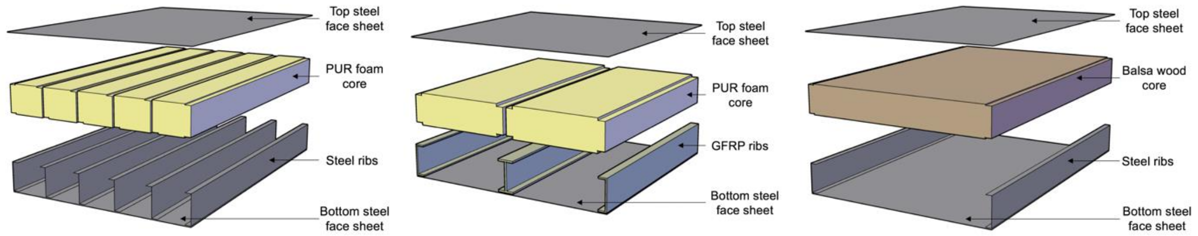
Generally, old buildings are composed of resisting walls in masonry and of floors being made of wooden systems. In Portugal, this typology corresponds to buildings built before the 1940s. The limited durability of the wood, mainly due to lake of maintenance, results in frequent biological attacks leading to the premature degradation of the floors. Additionally, these types of floors typically do not meet the current requirements in terms of structural, thermal and acoustic performances. This situation, which is found in Europe, is particularly serious in Portugal, where around 1 million buildings have rehabilitation needs, more than 40% of which require medium to large-scale interventions. Conventional solutions using traditional materials (e.g. reinforced concrete, steel and their combination) present several technical disadvantages, mainly, i) significant load increase, ii) increase of the seismic vulnerability and iii) constructive constraints. To overcome this, solutions based on sandwich panels have been proposed. In the present work, panels were designed to meet the ultimate limit state bending and shear verifications assuming reduced values of the materials strength to take into account buckling phenomena. The design is then optimized by means of a multi-objective GA with respect to the weight, cost and environmental footprint functions.

LIGHTSLAB R&D PROJECT

The LightSlab project aims to develop a new structural system, based on sandwich panels. It is an innovative concept for floors, in the context of applications, in which the overload of the structures is a limiting factor. Three different distinct solutions have been analysed, namely (see

(i) (ii) (iii)

Figure *1*): 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; iii) SP3 - two steel face sheets and two steel outer webs enclosing a balsa wood core. Predesign involved the study of a single panel, simple support at the ends, with a span of 5.00 m, fulfilling structural and thermal requirements. The total height of 152 mm was adopted for SP1 and SP2, while 127 mm was used in the case of SP3. A density of 40 kg/m^3 was adopted for PUR foam. All the top and bottom facing sheet have 1 mm of thickness. Table 1 resumes the principal characteristics of each sandwich panel obtained from the predesign carried out. In the scope of the present work, optimization genetic algorithm was developed to obtain an optimized solution for SP1. Details are given in the next sections.



(i) (ii) (iii)

Figure 1. Sandwich panels configurations (i) SP1, (ii) SP2 and (iii) SP3

Table 1. Main characteristics of each sandwich panel

Panel	Solution	Type	LL [kN/m^2]	δ_{max} [mm]	Total cost [€/m^2]
SP1	Steel + PUR	4 internal ribs	2.7	13	32
SP2	GFRP + steel + PUR	1 I-beam 150×75×8×8	3.4	13	93
SP3	Steel + Balsa wood	--	8.4	19	128

Notes: according to the Eurocodes (EN 1991-1-1:2002, NP-EN 1993-1-1:2010, the characteristic value of the live load (LL) on floor is 2.0 kN/m^2], and the maximum deflection is 20 mm (span / 250).

OPTIMIZATION STRATEGY

Description

The raw fitness of each individual is a linear combination of the weight, cost and environmental footprint functions. The GA presented in this work modify the raw fitness using two fitness assignment techniques sequentially. The first is the adaptive penalty function method whose aim is to discourage the reproduction of individuals which are far from meeting the boundary conditions of the problem. The second one, which operates on the value produced by the first, is the exponential ranking method. The individuals are sorted, and a rank is assigned to each individual. A new fitness value is then ascribed according to the rank. According to Kreinovich et al. (1993) this prevents that at the beginning of the run a “super-fit” individual would rapidly dominate the search. Also, at the end of the run (when the population is converging and the difference between the individuals is small) it will give advantage to the best individual. Once the fitness is assigned the next generations is produced. Half of it is made of the best individuals found in the current generation. Konaka et al. (2006) states that GA including this technique, known as elitism, have proven to outperform their non-elitist counterpart. The other half of the population is the result of the operations of crossover and mutation applied to a group of individual, namely the mating pool, selected by stochastic universal sampling (SUS). SUS guarantees that individuals are given a chance to participate in the production of offspring proportional to their fitness with a minimal selection error according to Fonseca (1995). The offspring receives an equal number of genes from the parent A and B. The mutation takes place at a predefined rate in all the genes after the crossover. The steps listed above are repeated until the optimal solution which minimizes the objective function and satisfy all the boundary conditions is found.

Variables

The problem's must be translated into a chromosome-like structure according to Goldberg (1989). GA operators such as crossover and mutation manipulate this information to produce improvement in the population. The variables, which completely define the possible solution, namely the sandwich panel, are i) the total thickness, ii) the face sheet and web thicknesses and iii) the number of webs. However, this last variable was user-defined before each run in order to obtain optimized solutions for a range of number of webs (3 to 7, with a step of ± 1) - the outer webs are always included in the architecture of the panel. The range of the total thickness is set to be similar to those of traditional floor solutions (50 to 200 mm, with a step of ± 1 mm). The face sheet and web thicknesses do not take into account the thickness of the coatings (range of 0.5 to 2 mm, with a step of ± 0.5 mm).

Structural and thermal requirements

The structural and thermal requirements are introduced in the GA as penalty functions. If a solution does not match a requirement a quantity proportional to the distance from the boundary condition is added to its fitness value as described in Coit et al. (1996). The structural requirements are the bending and shear verifications at the ultimate limit state and the vertical deflection at the serviceability limit state. The calculations are carried out according to the EN 1993-1-1 and 1-5 considering a reduced cross-section of the steel cold-formed member due to local buckling phenomena. A perfect adhesive bonding connection is assumed between the face sheets and the webs. The thermal transmittance of the panel is calculated according to ISO 6946:2017 which takes into account the effect of the thermal bridges represented by the webs.

Multi-objective optimization method

The developed GA follows the weighted sum method. The objective functions, namely weight, cost and environmental footprint, are combined into a single composite function by assigning a weight to each one of them according to the user priority. The GA will return a single solution at the end of each run. Runs with different weight combinations shall be performed to obtain a wide spectrum of solutions

RESULTS AND DISCUSSION

Five sandwich panel architectures including three to seven webs were optimized. For each architecture three runs were carried out setting three different weight combinations. These were defined in order to retrieve the extremes of the solution space, namely the lightest, the most economic and the least polluting sandwich panel as shown in Table 2. The GA found that the lightest solution is also the most economic one. It is an expected result since the cost is proportional to the material mass. The least polluting solutions are less thick than their correspondent lightest solutions. This is due to the fact that the PUR manufacturing process produces more CO_2 than steel. Therefore, the algorithm minimizes the volume of PUR by decreasing the total thickness. It can be noticed that as the number of webs increases the thickness of the cross-section decreases. The reason is that the webs offer a stabilizing effect to the top compressed face sheet. The buckling compressive stress is increased thus the thickness of the plate can be reduced. For what concern the six and seven webs architecture the GA found the same solution for all the minimization problem. As the number of webs increase the lightest solution can take advantage of the moment of inertia of the webs thus reducing the total thickness. On the opposite the trend of the least polluting solutions is to increase the total thickness as the number of webs increases. This is due to the fact that webs represent thermal bridges and decrease the thermal transmittance of the panel.

CONCLUSIONS

The GA presented in this work have proven to be a reliable tool for the optimization of sandwich panel. The convergence has been reached for all the runs and all the weight combinations of the objective function. An optimal solution with respect to the weight and cost has been found with a seven webs configuration. At the same time this solution is also the least polluting for this type of architecture whereas the overall least polluting configuration involve the use of three webs.

ACKNOWLEDGEMENTS

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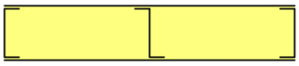
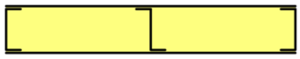
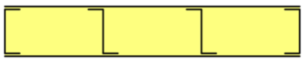
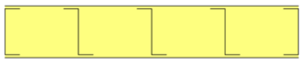
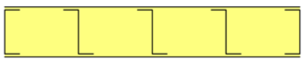
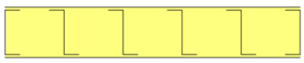
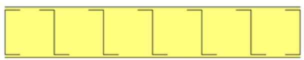
Table 2. Sandwich panels optimized solutions

n° of webs	type of solution	Dimensions and thermal transmittance		Objective functions	
3	W and C 	h_{tot}	187 mm	Weight	159.91 kg
		$t_f = t_w$	1.1 mm	Cost	33.25 €/m^2
		U	0.25 W/m^{2}K	Environmental footprint	31.49 kgCO_2eq/kg
	E 	h_{tot}	162 mm	Weight	173.24 kg
		$t_f = t_w$	1.3 mm	Cost	34.44 €/m^2
		U	0.30 W/m^{2}K	Environmental footprint	27.41 kgCO_2eq/kg
4	W and C 	h_{tot}	178 mm	Weight	144.66 kg
		$t_f = t_w$	0.9 mm	Cost	30.43 €/m^2
		U	0.27 W/m^{2}K	Environmental footprint	29.97 kgCO_2eq/kg
	E 	h_{tot}	167 mm	Weight	164.66 kg
		$t_f = t_w$	1.1 mm	Cost	33.25 €/m^2
		U	0.30 W/m^{2}K	Environmental footprint	28.24 kgCO_2eq/kg
5	W and C 	h_{tot}	177 mm	Weight	140.87 kg
		$t_f = t_w$	0.8 mm	Cost	29.78 €/m^2
		U	0.28 W/m^{2}K	Environmental footprint	29.81 kgCO_2eq/kg
	E 	h_{tot}	168 mm	Weight	150.59 kg
		$t_f = t_w$	0.9 mm	Cost	31.01 €/m^2
		U	0.30 W/m^{2}K	Environmental footprint	28.37 kgCO_2eq/kg
6	W, C and E 	h_{tot}	170 mm	Weight	146.75 kg
		$t_f = t_w$	0.8 mm	Cost	30.47 €/m^2
		U	0.30 W/m^{2}K	Environmental footprint	28.70 kgCO_2eq/kg
7	W, C and E 	h_{tot}	172 mm	Weight	140.84 kg
		$t_f = t_w$	0.7 mm	Cost	29.59 €/m^2
		U	0.30 W/m^{2}K	Environmental footprint	29.02 kgCO_2eq/kg

Notes: W is the lightest solution, C is the most economical solution, E is the least polluting solution, h_{tot} is the total thickness of the panel, t_f and t_w are the face sheet and web thickness respectively and U is the thermal transmittance.

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