Multi-objective Design Optimization of Sandwich Panel

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Abstract
In the scope of an R&D project a new floor system based on sandwich panel has been developed. The lightweight structural system shall be a competitive solution when compared to traditional rehabilitation technique of degraded timber floors in old buildings. The layout of the sandwich prototypes designed involved the use of steel face sheet and i) steel webs and polyurethane (PUR) foam core system, ii) glass fiber-reinforced polymer (GFRP) webs and PUR foam core system and iii) outer steel webs and balsa wood core. The design of the sandwich panels included an optimization procedure. A multi-objective genetic algorithm (GA) was developed for this purpose as it is a search method well suited for the solution of optimization problems. The multi-objective GA aims at the minimization of the three objective functions, i.e. cost, mass and environmental footprint of the sandwich panel. The definition of the main feature of the algorithm includes consideration about encoding procedure, fitness scaling, selection method and handling of constraints. The boundary conditions are imposed so that the retrieved solutions will represent a feasible solution to the problem. These boundary conditions are the analytical formulation of the serviceability, ultimate limit state and thermal transmittance verifications imposed by the building codes to sandwich panels. The present paper deals with the introduction of all the aspects of the optimization problems providing as an example the optimization of the panel with steel face sheets, webs and PUR foam.

Keywords: sustainability, sandwich panel, multi-objective optimization, genetic algorithm.

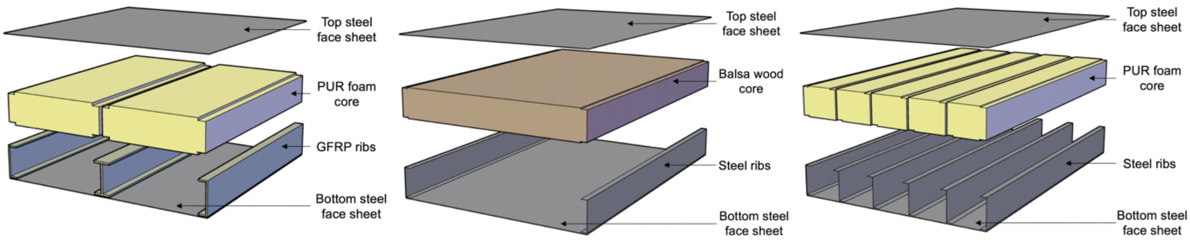
Introduction

Structural systems in old buildings are generally constituted by masonry walls and timber floors. In Portugal, building belonging to this typology were erected before the 1940s. Biological attack due to lack of maintenance results in excessive deformation (Costa et al. 2013) in traditional timber floor solutions. Furthermore, this type of floor frequently does not meet the minimum requirements related to structural safety, thermal and acoustic performance and fire resistance. This is a common scenario in Europe, especially in Portugal where it is estimated that around 1 million buildings are in need of urgent rehabilitation interventions. Common rehabilitation techniques involve the substitution of old timber floors with reinforced concrete slabs or composite concrete slabs supported by steel beams. However, these strategies present several disadvantages, namely i) significant load increase, ii) increase of the seismic vulnerability and iii) construction constraints. To tackle this issue, solutions based on sandwich panels have been proposed. The panels were designed to meet the ultimate state bending and shear verifications as well as thermal requirements imposed for new construction. The solutions are then optimized to reduce mass, cost and environmental footprint by means of a multi-objective genetic algorithm (GA).

R&D project

The Lightslab R&D project aims at the development of a new structural floor system based on sandwich panel. Despite the high strength-to-weight ratio of sandwich panels, their use as load bearing elements has been hindered so far by the high initial cost. After a careful literature review and taking into account the constraints of the manufacture company, three prototypes were developed (see Figure 1a, 1b and 1c), 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. The structural model adopted for the preliminary design is a single panel, simply supported at the ends, covering a span of 5.0 m, which is a relevant length for sandwich structures and for the proposed market of building rehabilitation. The solutions had to fulfill both structural and thermal requirements. The details of the different sandwich panels are presented in Table 1. A total height of 152 mm was adopted for SP1 and SP2, while 127 mm was used for SP3. The predesign considered a 40 kg/m^3 PUR foam density. The steel face sheets of all the solutions are 1 mm thick. In the scope of the present work SP1 was selected for the optimization process by means of GA.



a) b) c)

Figure 1. Layout of the prototypes, a) SP1, b) SP2, c) SP3.

Table 1. Main characteristics of each sandwich panel

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

Multi-objective genetic algorithm

A multi-objective GA was developed for the optimization of the SP1 solution since this metaheuristic approach present intrinsic features which makes it particularly suitable for the solution of this class of problems. These optimization procedures often involve the use of different types of variables which can be easily handled by the GA (Coelho et al. 2014), as opposed to, gradient-based methods which are devoted to problems with continuous variables. GAs only consider the value of the function itself with no additional information required. This constitutes an advantage when dealing with non-differentiable or constrained objective functions (Custodio et al. 2011). They are also not easily trapped in local minimum when dealing with noisy and multi-modal objective functions as they are a population-based approach (Konak et al. 2006). GAs are based on the principle of natural selection. The improvement in the design of the sandwich panels is the result of the repeated selection and recombination of genetic information of the best performing designs. The performance of a sandwich panel is evaluated according to the objective functions. The cost of the sandwich panel is set as one of those given that the aim of the project is to develop an economically competitive new floor system. Another target is the design of a lightweight structural element which will offer advantages in terms of installation and safety against horizontal forces generated by earthquakes. The weight of the sandwich panels is thus set as the second objective function. Finally, as the Life Cycle Assessment (LCA) is becoming a powerful tool in the choice of sustainable building materials, the environmental footprint is also included as one of the objective functions.

Encoding procedure

In GAs a starting population of individuals or chromosome (Fonseca 1995) is made to compete with each other. The fittest are given higher chances to reproduce whereas the weakest may not reproduce at all. Since the new generation (offspring) is obtained through the recombination of the parents' genes, it is necessary to translate the characteristics of the sandwich panel governing its design in a chromosome-like structures. This procedure is generally called encoding and it is shown in Figure 2. The variables which completely define the sandwich panel are i) the total thickness, ii) the face sheets and web thickness and iii) the number of webs. The range of the total thickness is set to be similar to those of traditional building floor for similar span (50 to 200 mm with a step of ± 1 mm). The face sheet and web thickness do not take into account the thickness of the coatings (0.5 to 2 mm with a step of ± 0.1 mm). The outer webs are always included in the design of the panel. The maximum number of webs was set according to the possibility of easily accommodate them during the manufacturing process of the core system (3 to 7 with a step of ± 1 web).

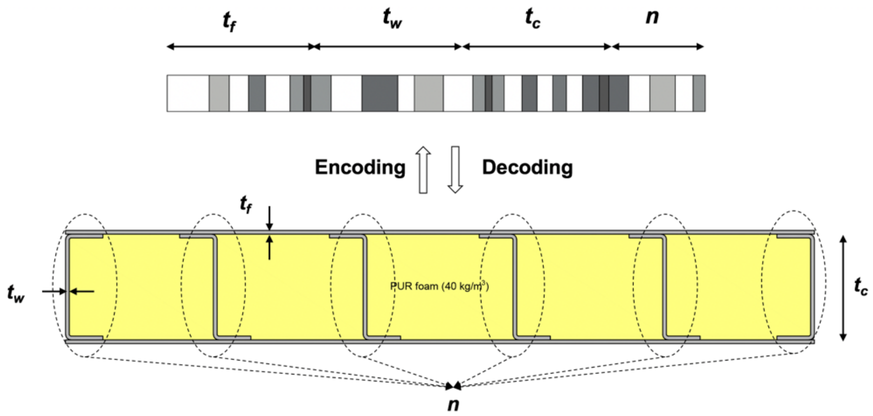


Figure 2. Encoding procedure of the characteristics of the sandwich panel (where t_f is the thickness of the face sheet, t_w is the thickness of the web, t_c is the thickness of the core and n is the number of webs).

Penalty function

Optimization problems must often satisfy a set of constraints which are represented by the structural and thermal requirements in the case of the new floor system. This can be achieved by embedding the constraints in the chromosome or by eliminating a priori infeasible solutions that the GA may produce during its run. Both strategies suffer from the same drawback, namely the optimum solution often lies near the boundaries of the feasible region (Siedlecki and Sklansky 1989). Excluding infeasible solutions may hinder the localization of the global optimum. In the newly developed multi-objective GA, the constraints are introduced by means of a penalty function. If the sandwich panel violates one of the requirements a quantity proportional to the distance from the limit imposed by the regulation is added to its fitness value (Coit et al. 1996). The structural requirements are represented by the verification of the resistance of the cross-section to bending and shear at the ultimate limit state and the vertical deflection at the serviceability limit state. The calculation of the resistance follows the Eurocode 3 Parts 1-3 and 1-5 considering a reduced cross-section of the cold-formed steel member due to buckling phenomenon. The thermal transmittance of the sandwich panel must satisfy the maximum value set by the Portuguese building code. This is estimated according to ISO 6946 (2017) taking into account the thermal bridges provoked by the webs' presence.

Evolutionary search process

The raw fitness of a solution is evaluated according to the weighted sum approach. The three different objective functions, namely cost, mass 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 raw fitness is modified by the penalty functions whose aim is to discourage the reproduction of individuals far from meeting the boundary conditions of the problem. According to the penalized fitness the individuals are sorted, and a rank is assigned to each solution. A new fitness value is then ascribed depending on the rank. This further step follows the exponential ranking method in order to keep constant the selective pressure throughout the whole run. The selective pressure is the degree to which the best individuals are favored in the reproduction. It is important to keep it constant in order to avoid both premature convergence at the beginning of the run and slowing down the search process at the end of the run when all the individuals have similar raw fitness (Kreinovich et al. 1993). The generation of new individuals is illustrated in Figure 3 and starts with the selection from (i) the initial ranked population of (ii) the mating pool. The sampling for the mating pool is achieved by stochastic universal sampling (SUS). SUS can be visualized as a spinning roulette with a certain number of equally spaced pointers. The slots of the roulette represent the chances of an individual to be selected. The mating probability is directly proportional to the fitness calculated according to the exponential ranking method. The gene information of the mating pool is recombined through crossover and mutation operators to produce the (iii) offspring population. The offspring receives an equal number of genes from the two parents' solution and it is subjected to a predefined rate of mutation. The worst half of the sandwich panels of the initial population is discarded whereas the (iv) best half (v) together with the new solutions form the (vi) new generation The technique of preserving the best genetic information found in the current population is known as elitism. GA implementing this technique have proven to outperform their non-elitist counterpart. The procedure described above is repeated until the optimal solution which minimizes the objective functions and satisfy all the constraints is reached (see Figure 4).

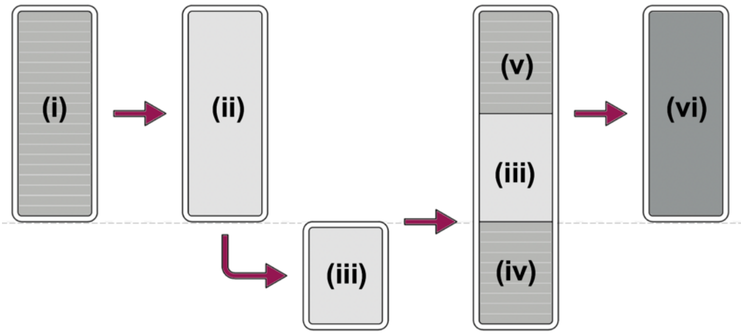


Figure 3. Reproduction strategy of the GA.

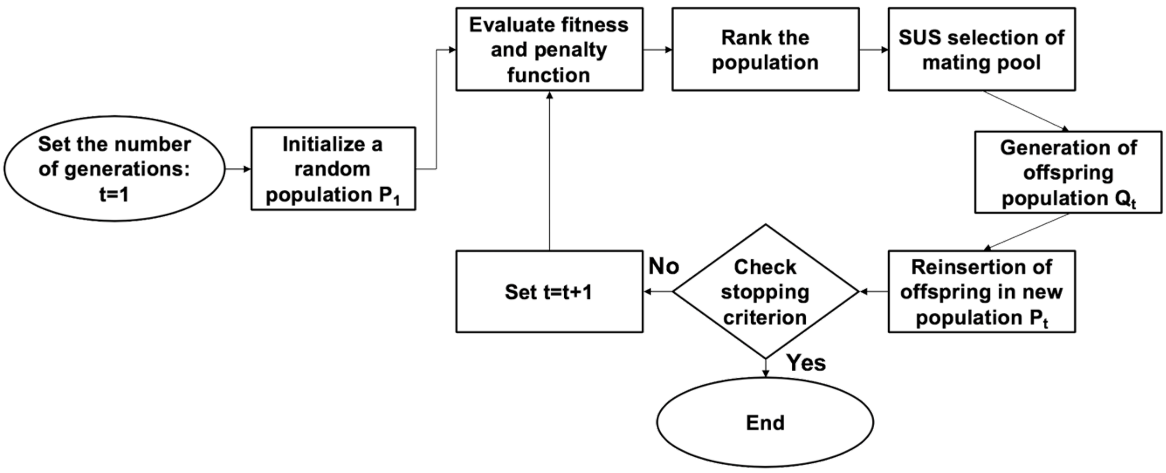


Figure 4. Multi-objective GA procedure.

Optimized solutions

The extreme of the solution space were retrieved running the GA three times. In each run a different objective function was set as the dominant one. The results are three optimized sandwich panels with respect to the cost, mass and environmental footprint as shown in Figure 5. The optimized panels are highly influenced by the input parameters. The most economical solution has four webs and a face sheet and web thickness of 0.9 mm. Despite the fact that it involves the use of more material compared to the lightest solution, the most economical has less webs. This reveals that the cost of the adhesive connection in the top face sheet (the mechanical one for the bottom face sheet is neglected) plays an important role in the overall price estimation of the panel. The lightest solution has seven webs and a face sheet and web thickness of 0.7 mm. The use of the maximum number of allowable webs is due to the stabilizing effect that these offer to the face sheet under compressive stress state with respect to buckling. The effective area is increased along with the moment of the inertia of the cross-section thus allowing to reduce the overall thickness of the panel. Finally, the least polluting solution has three webs and a face sheet and web thickness of 1.3 mm. This is an expected result as the carbon footprint of PUR is larger than that of steel. However, a more accurate evaluation of the steel carbon footprint is envisaged as it currently does not take into account the CO_2 emissions due to transportation.

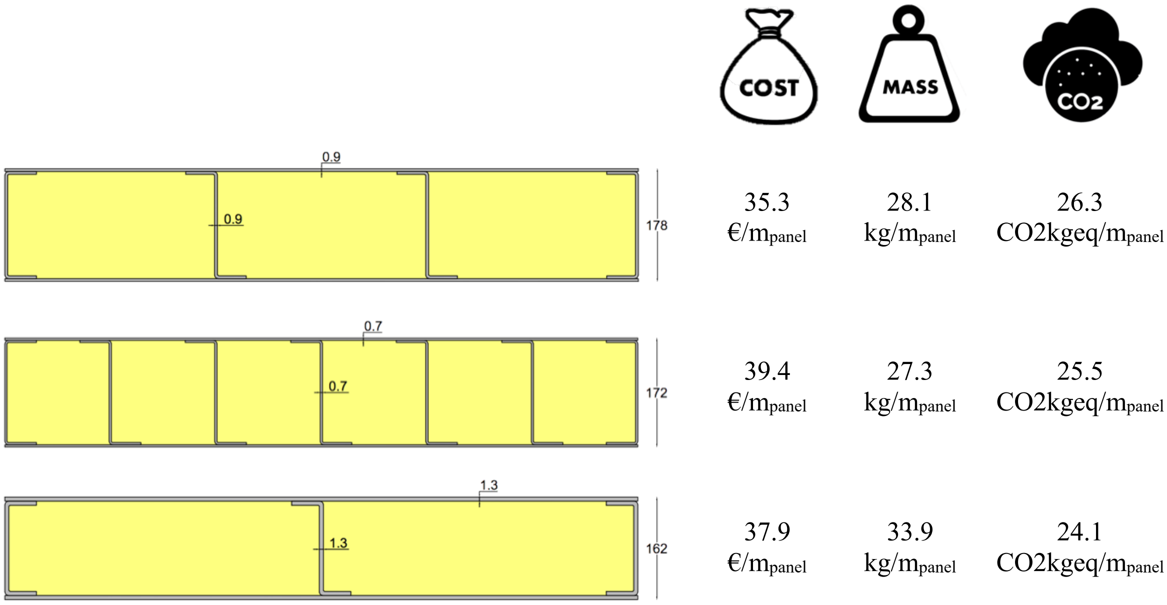


Figure 5. Optimized sandwich panel with respect to cost, mass and environmental footprint.

Conclusions

The newly developed GA proved to be a reliable tool for the optimization of the design of sandwich panels. Convergence was reached for all the runs and different weight combination of the composite objective function. The multi-objective GA provides insights as to how each variable can be used to reach a specific target. For what concern the optimized solutions, when compared to the one obtained by the preliminary design, the GA was capable of retrieving a solution 15% less expensive and one 16% lighter. There is no large difference in terms of environmental footprint between the analytical and optimized solution. This is due to the fact that the optimized solution is subjected to more strict constraint regarding the thermal requirement as opposed to the analytical one.

Acknowledgements

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