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Optimization based on life cycle analysis for reinforced concrete structures with one-way slabs

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ABSTRACT

This paper proposes a methodology devoted to finding and selecting the optimal solutions of reinforced concrete structures with one-way slabs with regard to the environmental impact caused by the production and building process. The paper analyses each possible alternative depending on the most important variables, such as the structural thickness, the material of the lightening element, and the disposition of columns.

This research is based on information from a representative sample of actual structures built for residential use during the last few years in Spain. This information provides data about variables of the problem, the definition of the geometry and the materials used in the different solutions. Once the structural analysis has been developed, the consumption of materials needed to build the structure is recorded, provided that the technical alternative is viable. Through the life cycle analysis (LCA) of the materials and methods used for the implementation of the different alternatives, a comparison is established using the Eco-Indicator '99 method.

The results show that the number of columns conditions the obtained impacts, and it is worth noting that the least-used option in real residential buildings has very attractive values in terms of environmental impact. The variations obtained in the different alternatives range up to 75%, showing that it is an important factor to consider because a bad choice can lead to a much higher impact. The proposed methodology favours the selection of the alternatives that have less environmental impact.

1. Introduction

The evolution of housing construction has been progressive, as result of the study of the behaviour of new materials and the apparition of new technologies. Similarly, the evolution of society is reflected in the requirements to be met: functionality, safety, economy, maintenance, comfort, sustainability, etc. Regarding developed and developing countries, an upward trend in sustainable development [1] based on the promotion of the principles of sustainable construction has been gradually gaining momentum during recent years [2,3]. One example is the ambitious climate and energy EU 20–20–20 targets for the year 2020. The environmental aspects have gained relevance in Spain over the past few years, and new concepts have arisen, such as sustainable construction. The energy consumption for the execution of a reinforced concrete structure represents 59.57% and 66.73% of the total consumption for the studied buildings [4].

The recycling of materials is the implicit acknowledgement of the impossibility of an unlimited extraction of materials from natural sources. The urban constructions represent 60% of the extraction of raw materials from the lithosphere, and the water consumption in Spain associated with these activities is 12% [5]. The situation is changing in the sector, and today, it is not uncommon to hear about construction oriented towards energy efficiency and the capability of re-utilizing materials.

LCA tools have been proven to be useful for the assessment of environmental impacts in the construction sector; furthermore, they can be used to improve process efficiency [6]. However, applying LCA tools to the construction sector requires adaptations [7]. There are very interesting previous studies on different building materials, as for example, the inventory of the materials incorporated in different buildings in Hong Kong [8], the optimization of

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the environmental impacts on sidewalks in Barcelona [9], and the sustainable design and analysis of energy consumption for structural components [10].

In the case of reinforced concrete structures, it is necessary to incorporate the analysis of the construction process. Previous studies have focused on specific aspects of LCA, such as reducing CO_2 emissions [11,12], embodied energy [13,14] or waste in the execution [15] and incorporating a more extensive environmental analysis performed comparatively between different structural solutions that implemented concrete cast-in-place or precast for one building [16] or buildings made with different structural materials [17]. The service life of the concrete, its local character and its technical features point it as a sustainable material [18]. In the future, the sustainability of reinforced concrete will improve by the recycling generalization of steel and aggregates, combined with the addition of silica fume and fly ash [19].

The research approach focuses on the structures of reinforced concrete made with one-way slabs. It takes into account the stage of production of the materials and the process of implementation in place of buildings, which is necessary to incorporate local information to the data provided by the databases [20]. The present paper combines the information related to the environmental impacts to select the optimal solutions based on this criterion. These solutions should be oriented towards the definition of the materials and geometry to be used in the reinforced concrete structure. The definition of materials is performed using its technical performance, and the contribution of the recycled materials is considered constant.

In the last hundred years, the slabs more often used in construction have been those of reinforced concrete, particularly one-way slabs. Based on this fact, this work focuses on this typology. When one-way slabs were first used in Spain, approximately in the 50–60s, everything was built cast-in-place. For that purpose, formwork had to be incorporated into the whole slab surface. Beginning from the 80s, the sector opted for two types of beams: pretensioned and lattice. The type of lightening material could be ceramic, vibro-compressed concrete or expanded polystyrene. The thickness of the slab frequently used in residential buildings is 30 cm.

Currently, the formwork covers the whole floor and is safer to the worker. This has made possible the apparition of another important group of slabs: cast-in-place ribs, which do not use any precast elements except for the lightening elements. This last group is also included in this research because its implementation is expected to increase in the next few years.

An assessment of the different solution alternatives for a reference building modifying the columns arrangement, geometry and materials is proposed. The main objective of this research is to obtain the best structural definition, minimizing the environmental impact of the construction and execution processes of the structural solution.

The methodology used in this paper is presented, highlighting the definition by means of a series of finite alternatives that simulate the possible infinite alternatives of structural solutions that can be stated for the cited reference building. The alternatives are fractioned in the first level based on the number of columns in the structural definition; within each level, the LCA is systematically used to select the optimal solution between the different geometries and materials.

2. Methodology

The types of one-way slabs more often used in concrete structures are the "In situ" slabs and those using precast elements. The objective of this article is to analyse one-way slabs and their use as secondary elements supported in a primary structure of beams and columns. The different lengths of beams and one-way slabs affect the consumption of materials. The solutions of this type of structures have a wide range of alternatives. This work is focused on a representative sample of this infinite universe by means of a series of discrete cases.

Taking these facts as a basis, the main objective stated is to develop a methodology to facilitate for the designers and promoters the systematization of the decisions over the type of one-way slab selected, taking into consideration the environmental impact.

2.1. Identification of the case studies

The first step in this methodology is the definition of the geometry and the materials used in the different solutions.

The methodology is applied to a reference building with dimensions of 18 m $\times$ 12 m. To configure an average stiffness of the columns, an intermediate slab of average floor size has been considered. The layout of the columns of the building provides (Fig. 1) two values of length, long and short, for both beams and one-way slabs, providing four representative cases of the aforementioned infinite universe. These cases are within the usual values for reinforced concrete structures: Beams of 4.5 and 6 m (short beams SB, and long beams LB) and one-way slabs of 4 and 6 m (short slabs SS, and long slabs LS).

Below, the geometric definition of the structural elements under study (Fig. 2) is enumerated:

The columns have all been considered equal with dimensions of 30 $\times$ 30 cm; the amount of steel used will vary depending on the structural stresses in each case study.
One-way slabs: The thickness of the total slab is of 25, 30 and 35 cm. Different widths of beams are used. This variable starts with 30 cm and increases up to a width of 90 cm. Interaxis considered for the one-way slab is of a fixed value of 70 cm.

The materials used in the configuration of the different elements are as follows:

Concrete HA-25/B/20/I in columns, beams and one-way slab.
Concrete HP-45/S/12/I in pretensioned joists.
Vibro-compressed concrete HNE-15/S/6 in the elaboration of lightening blocks.
Expanded polystyrene for the elaboration of lightening blocks.
Rebar steel B500S in columns, beams and one-way slabs.
In the pretensioned joists, the active rebar steel Y-1770 C has been used.

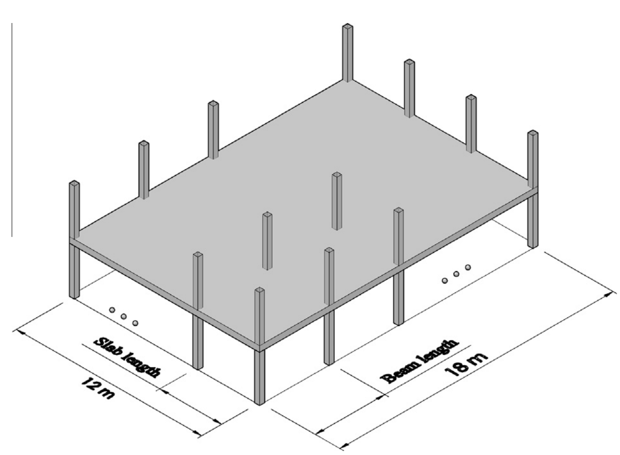

Fig. 1. Layout of the possible column lengths in the building.