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Design method of high performance precast external walls for warm climate by multi-objective optimization analysis

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A R T I C L E I N F O

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A B S T R A C T

Taking into account the global environmental problems, there is the urgent need to reduce energy consumption and the greenhouse gas emissions in the construction sector. Environmental awareness can be achieved through the extensive application of precast systems in buildings construction.

A multi-criteria analysis has been used to obtain energy-efficient precast walls for Zero Energy Building in warm climate focusing on eco-friendly building materials. The modeFRONTIER optimization tool, with the use of computational procedures developed in Matlab, has been used to assess the thermal dynamics of building components.

The optimization has been carried out in terms of steady thermal transmittance, periodic thermal transmittance, decrement factor, time shift, areal heat capacity, thermal admittance, surface mass, small thickness, eco sustainability score, light-weight and costs.

The best sequences of layers show repetitive features: high surface mass for the first layer (internal side), followed by eco-friendly insulating materials for the middle layer and common insulating materials for the outer layer.

The results illustrate that it is possible to obtain high performance precast multi-layered walls also with light and thin solutions; in particular, the superficial mass and the internal areal heat capacity have an important role to obtain the best performance in the warm climate.

1. Introduction

Climate change is one of the principal challenges that modern civilization faces. There is a growing concern and urgent need to reduce energy consumption and greenhouse gas emissions in the construction sector, because there is a clear association between climate changes, in particular temperature rise, and greenhouse gas emissions [1,2].

Nowadays, the aim is to limit the environmental pollution caused by fossil fuels. The energy saving becomes mandatory to reduce the amount of carbon dioxide, sulfur dioxide and particulates in atmosphere [3]. In such a contest, energy consumption in buildings is a crucial concern in Europe [4], in order to evaluate the contribution to the climate change [5,6].

In recent years, the construction sector has considerably increased the exploitation of natural resources in industrialized countries. It is assessed that this sector is responsible for the consumption of around 40%–70% of electricity and 12% of potable water [7]. The recent trend, encouraged by the European EPBD (energy performance of buildings directive), is focused on reducing energy consumption in the building sector [8].

The choice of construction materials plays a key role in the different phases of design, contributing to the reduction of energy consumption in a building [9–11] and it supports the design of nZEBs.

Several studies show that the precast system allowed important benefits compared to traditional walls built in situ [12]. In particular, it has been observed that the reduction is: in construction waste on-site by 56%, water consumption by 41%, construction time by 20% and labor requirement by 9.5%. Nevertheless, there has been an increment in energy consumption by 12%, and in construction cost by less than 1%. In any case, the prefabrication concurred to a cleaner and safer workplace, and to a reduction of construction time. Jaillon et al. [13] show that the increasing use of precast construction contributes to a more productivity and it is both easier to manage quality problems and monitoring of the project. Several studies [14–16] provide an analysis of the feasibility of adopting

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prefabrication in construction activities and evaluate the pros and cons on future developments, and studying financial analysis on a local case.

The aim of this paper is to define a method for the design of precast walls for warm climate among which the designer can choose the proper solution for his application.

By the use of optimization and prototyping systems, it is possible to reach a judicious choice of multi-layer exterior walls, followed by cost analysis.

A multi-criteria analysis was performed in order to identify energy-efficient precast walls for Zero Energy Building in warm climate, and the position of layers for some commercial and commonly used construction materials, focusing on eco-friendly building materials.

The construction materials have been selected considering the optimum balance between the energy performance and the environmental impact, avoiding the formation of thermal bridges and moisture during the assembly phase. The modeFRONTIER optimization tool, with the use of computational procedures developed in Matlab, has been used to assess the dynamics of building components.

This paper emphasizes and highlights a strong interest on the environmental impact of the buildings; the prefabrication seems a good solution for a sustainability evolution of buildings.

1.1. Precast system

Precast is a fabrication process in which different materials are combined to form a component of the final installation, in a factory or on site [17,18]. On the contrary, the term off-site is used when prefabrication and pre-assembly are integrated. In terms of it, Gibb [19] shows three categories of off-site fabrication, such as non-volumetric, volumetric and modular building.

Precast has been defined as the first degree of industrialization, followed by mechanization, automation, robotics and reproduction [20]. Byoung-Jun Lee et al. [21] noted that the phase of on-site assembly is an important phase to keep in mind, because the handling, lifting and connections of precast may give negative results on the thermal performance of the panels. Lu Ayea et al. [22] have quantified the embodied energy in prefabricated modular steel and wood. One of the benefits in the use of these building elements is that at the end of their useful life they can be re-used in another building.

Several studies [15,16] have recognized and analyzed the presence of ten obstacles for the prefabrication techniques. Particularly, it has been observed the limited flexibility to design modifications, the high initial cost, the lack of research information, the most time-consuming in the initial design development, the lack of consideration for the benefits in the adoption of construction methods on site, the limited site space for locating prefabricated building components, the leakage problems that will occur while joining the prefabrication, the absence of relevant experiences on the contractors, the issues related to the aesthetics of the building, the lack of demand for precast building components.

2. Sustainability protocol

The sustainability certificates state the performance and the environmental impacts of a building on a specific area, encouraging the implementation of measures that have a minimum impact on human health and on the environment. Furthermore, the aim is to promote a change on the housing market by the improvement of the energy efficiency.

The environmental issues consider the impact of operations, products and services related to construction on the environment and use of natural resources at the local and global level.

Worldwide, there are many protocols used to assess this evaluation, for example: the BREEAM (British BRE Environmental Assessment Method), the American LEED (Leadership in Energy and environmental Design), the Japanese CASBEE (Comprehensive Assessment System for Built Environment Efficiency) and the Italian ITACA Protocol.

2.1. ITACA protocol

The ITACA protocol is a system for environmental sustainability, developed by the Institute for the Transparency of Contracts and Environmental Sustainability [23].

As indicated in the SB-Method (Sustainable Building Method), the underlying principle is to share a common standard also valid at international level. The Italian Association of Regions has decided to adopt the SB-Method as a base to create an instrument for the evaluation of sustainability, the ITACA Protocol.

It suggests the re-use of recycled materials. Further points are awarded when materials come from renewable sources, that is, those products whose origin partly comes from plants or animals. The “locally sourced material” indicator, is given within a 300 km distance from the site. It has also been considered the percentage of walls that are treated with materials for decorations of local production, that is, materials produced within a 150 km range. Another criterion is called “eco-sustainable materials” which measures the percentage of eco-sustainable materials [23].

2.2. LEED protocol

The LEED certification system was created in the U.S. and is promoted by the US Green Building Council and it uses different protocols in relation to the building type. Actually, the GBC (Green Building Council) is moving on to adapt LEED to the Italian contest. The aim is to promote a change on the housing market by encouraging an economic aspect in the value of choices that lead to greater energy efficiency and improved sustainability [24].

The protocol is divided into large sections and each must meet certain mandatory requirements so that an assessment can be possible; at the same time, there are other optional requirements, defined as criteria. The fulfillment of these criteria, as judged appropriate by the customer and the planning team, will contribute to the reaching of the gold or platinum sustainability thresholds. Among the large sections envisaged by the LEED protocol structure there is one concerning the use of sustainable materials [23], especially locally sourced materials, that is, products that can be retrieved within a given range from the construction site, recyclable or recycled, as well as the use of certified wood.

In Italy, ITACA Protocol is currently preferred at public and regional level while LEED Protocol is privileged by the private and international sector. Both put great attention to materials encouraging the use sustainable materials, with the target to reduce waste and to improve the environmental quality.

3. Thermal characteristics of building components

The building envelope is in continuous interaction with the external environment. A great attention should be given to the design of external walls, because their thermal properties can change significantly the indoor environment. When the outside air temperature and solar radiation vary during the day, the temperature of the external surface wall is strongly influenced by the fluctuations of the heat flow that passes there through inside [25].