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Comparative analysis of energy related performance and construction cost of the external walls in high-rise residential buildings

Sungho Lee, Sunkuk Kim, Youngju Na*

Department of Architectural Engineering, Kyung Hee University, Yongin 446-701, Republic of Korea

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A B S T R A C T

In the design phase of a high-rise residential building, stakeholders should adopt the proper external wall system by considering energy performance and IEQ as well as construction cost and structural stability. The energy related performance and construction cost of external walls affect the life cycle cost. Therefore, also a value analysis of the LCC in terms of the energy performance is required. The purpose of this study was to evaluate the energy related performance and construction cost of external walls in high-rise residential buildings, which are the currently staple external walls, using reinforced concrete (RC), glass fiber reinforced concrete (GFRC) and cellulose fiber reinforced cement (CFRC). All the wall systems have the same doors and windows in their bodies for equal comparison of energy efficiency and construction cost. The energy efficiency of the CFRC external walls was high while the construction cost for RC external walls was low. The value assessment considering the LCC and the residents' health revealed that RC external walls were most satisfactory up to 6 years after construction, GFRC from 6 years to 26 years, and CFRC thereafter, respectively. The findings of this research will be valuable for stakeholders deciding on an external wall system.

1. Introduction

According to data from the National Statistical Office (NSO), residential buildings account for 40% of construction projects [1]. Reinforced concrete (RC) bearing wall systems are often used to construct residential buildings rather than column-beam systems in terms of economic benefits [2–4]. However since the existing bearing wall system has limitations in vertical construction, the use of column-beam systems is on the rise, particularly for high-rise residential buildings [5–7].

Various types of external wall systems that comprise structural body, insulation layers, openings like doors and windows with various glazing types are used in high-rise residential buildings because dry light-weight members are advantageous compared to RC-based wet construction methods in terms of constructability [2,3]. Light-weight members, especially glass fiber reinforced concrete (GFRC) and cellulose fiber reinforced concrete (CFRC), are often utilized due to economics, constructability and texture.

When selecting the external wall system of buildings, energy performance and construction cost as well as and structural stability must be considered, in addition to indoor environment quality (IEQ) and life cycle cost (LCC), to ensure the optimum indoor environment of high-rise residential buildings [5]. Given the fact that Korea has four seasons, a considerable amount of energy is utilized for cooling and heating in order to maintain the residents' health and comfort.

During the life cycle, energy is consumed primarily in the maintenance stage in which, considering less energy use and the residents' health and comfort, finish materials, openings like doors and windows with various glazing types are selected for repair and replacement of external wall systems as time goes by [8]. In addition, due to Korea's climatic characteristics, the cooling load is higher than the heating load [9]. The indoor environment created by the external walls has a major influence on energy consumption, which directly affects the operation cost incurred by the user and will be reflected in the LCC. Therefore, a review of the energy related performance and the LCC of external wall systems is necessary in order to identify the optimum wall system [5,10]. Current studies on external wall systems of existing high-rise residential buildings focus primarily on the insulation thickness of the external wall [11,12], energy efficiency analysis, and energy reduction [13–19]. However, no study has evaluated energy related performance or conducted a value analysis considering construction cost of external wall systems.

* Corresponding author. Tel.: +82 31 201 3685; fax: +82 31 203 0089.
E-mail address: gomsam0106@hanmail.net (Y. Na).

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A building consumes resources and energy during its life cycle [20,21]. Through the Federal Leadership in Environmental, Energy, and Economic Performance, the United States mandates all buildings to achieve zero-net-energy by 2030 [22]. However, the discrepancy among environmental, energy, and economic performance happens throughout the design, construction and use of a building because stakeholders participate in different stages of the building's life cycle; their main concern in selecting construction materials is not energy performance, but initial construction cost-cutting although many countries mandate all buildings to achieve less energy use. A discussion on how to choose energy-efficient and economic resources for apartment buildings is needed. The value of construction resources can inform such discussions, and can be assessed by quickly calculating the LCC, which takes both energy performance and construction cost into account.

Therefore, the purpose of this study was to evaluate the energy performance and cost of external walls of high-rise residential buildings, which are currently the staple external wall systems, comprised of RC, GFRC and CFRC. This research is conducted with the change of structural bodies under the same condition of opening parts because the different detail of external wall bodies shows the great influence on energy related performance and construction cost.

To this end, we determined the LCC by calculating the construction cost and operation cost by external wall types used in apartment buildings located in Seoul. The operation cost was calculated based on the energy performance of the external wall using virtual environment (VE) software. We then performed a value assessment of the external wall using the value for money (VFM) approach. VFM is originally defined as a utility derived from every purchase or every sum of money spent and VFM is based not only on the minimum purchase price (economy) but also on the maximum efficiency and effectiveness of the purchase [27]. In this paper, VFM approach is used for the assessment of energy related performance derived from the construction cost of selected external wall systems. The results can inform stakeholders' choice of an external wall system. They will also be utilized in developing a simulation model that can easily determine the LCC or implement value analysis in the event of a design change following the application of new design components.

2. Preliminary study

2.1. Value for money

VFM is a term used to refer to the highest value for a payment. This is an idea similar to value engineering, which refers to an effort to achieve necessary functions at the lowest cost across overall industrial production [23–25]. The concept is shown in Eq. (1) below.

$$V = F/C \tag{1}$$

where V: value
F: function
C: cost

For instance, the function of residential building space is to provide the same level of service with differing costs of creating and maintaining the space depending on the construction material used, which results in a change in value.

The VFM analysis was carried out in three phases. First, a function setting was implemented, and a project that offers the same level of function, cooling and heating services as shown in Table 6, is referred to as the reference project. Second, a cost analysis was performed in order to compare the difference between raw costs that are incurred for each reference project. Third, the various reference project-related risks were quantified such that they could be reflected in the analysis. These risks included repair and replacement, heating and cooling, and the increase in the raw cost of cooling energy [23]. The overall results were compared and evaluated.

2.2. Literature survey

Current studies on external wall systems focus primarily on achieving optimum energy performance rather than calculating the cost in terms of life cycle. Sismana et al. analyzed the optimum insulation thickness [12]. In addition, studies have been conducted to assess building energy performance and the energy-saving effects of green roofs and different types of slabs. Niachou et al. and Poela et al. explored the energy performance and change in the indoor environment when a green roof is used [13,16], and Deng and Burnett analyzed the energy performance depending on the type of flooring in a hotel [14]. Olesen, Jaggs and Palmer assessed energy performance and effects on the indoor environment [15,17]. Balocco investigated the connection between the natural ventilation of a double façade and energy performance [18], and Sekhar et al. determined the energy performance and LCC when a smart window system was applied [19]. However, no study has determined value using VFM or performed an energy performance assessment with consideration for the construction cost of resources.

3. Energy performance and construction cost analysis

3.1. Energy performance and construction cost analysis procedure

The procedure illustrated in Fig. 1 was utilized to identify the value of external wall systems. The building and external wall data to be analyzed was defined, and then the analysis proceeded in three subsequent steps. Energy performance and construction cost were analyzed in Steps 1 and 2, respectively. Step 3 consisted of estimating the LCC using the results of Steps 1 and 2 and determining the VFM of each external wall system.

The procedural details are given below.

Step 1: energy performance analysis

(1) Implement a simulation model for the selected space using the VE program.
(2) Enter the physical properties of the implemented model's space components through VE.
(3) Enter various indoor heating load elements that are directly related to building heating and cooling based on weather conditions and regulations.
(4) Identify the amount of energy consumption and annual energy cost associated with the external wall system of the test household using weather data for Seoul and an energy simulation.

Step 2: construction cost analysis

(1) Identify the construction area in order to calculate the construction cost of each external wall.
(2) Analyze the unit price per unit area of each external wall. The unit price is calculated using material and labor costs.
(3) Determine the construction cost using the construction area and unit price of an external wall.

Step 3: VFM analysis