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Energy efficiencies of linear-shaped multi-residential apartment buildings built with hybrid structural systems

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ABSTRACT

The construction industry requires significant materials and energy, and has some of the most pressing needs for energy-saving initiatives to support sustainable development. This paper studies energy efficiency during the construction of structural systems for multi-residential apartment buildings using composite structural systems. For this purpose, nine linear-shaped apartment buildings originally designed as bearing wall systems were designed as flat slabs and hybrid composite frames to study the energy consumptions of such buildings during the construction phase. The energy consumptions were then compared in terms of structural system, number of floors, and area. The energy-efficient hybrid frame used structural steel, cast-in-place concrete, and precast concrete. The structural system proposed in this paper is intended to reduce energy consumption through the proper combination of structural steel, cast-in-place concrete, and precast concrete. It was found that a multi-residential apartment building constructed with an energy-efficient hybrid composite frame could save approximately 20% of the construction phase energy used in the conventional bearing wall system. This energy savings was made possible by the reduced use of form-work resulting from the utilization of precast members, and the reduced consumptions of steel and concrete resulting from the enhanced structural performance of the hybrid composite system. The energy-efficient hybrid structural system is expected to be an alternative for future multi-residential apartment buildings.

1. Introduction

Energy is necessary for any type of production. The construction industry is concerned with the production of buildings, and the amount of energy consumed in the process of building construction corresponds to its scale. For this reason, the energy-dependent construction industry is working to increase its sustainability. Sustainable construction is a new trend aimed at reducing environmental harm and improving the quality of life by revising the old construction paradigm of mass production and mass consumption [9]. Therefore, reducing energy consumption during construction is significant for sustainability. A wide variety of research projects have been carried out in order to reduce the energy consumption of construction from the planning phase through the construction phase to the maintenance phase. Suzuki et al. analyzed the amounts of energy consumed and carbon dioxide produced during construction according to the sizes of multi-residential buildings and the construction materials used [3]. Chen et al. investigated a national statistical system of energy consumption in the residential building sector of China [4]. Kang et al. evaluated the energy efficiencies of buildings with double-skin faced systems [2], and Lee and Yang estimated the energy consumptions and carbon dioxide emissions of public buildings using inter-industry analysis [1]. However, these studies were mostly limited to the development of plans to improve energy efficiency through the use of additional equipment, or the computation of energy consumption during the maintenance or usage phases. Little research effort has been applied to the study of construction methods that minimize energy consumption.

The research object of this paper, the hybrid structural system is an alternative method to bearing wall structural system. The bearing wall structural system has been applied to most of the popular apartment buildings in Korea; however, the bearing wall structural system has exhibited various problems due to its low durability, and many people increasingly believe that this construction system is unsuitable for multi-residential buildings. Many researchers have studied alternative systems to replace bearing wall structures. The flat slab structure, which is composed of columns and slabs, is gaining much attention as an alternative to the bearing wall system. The hybrid system is another alternative to the bearing wall system, and is estimated to be more efficient than the flat slab structure [2]. In this study, we computed the amounts of energy consumed during the construction phases of the bearing wall, flat slab, and hybrid

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systems. Based on the estimates, we plan to analyze the energy efficiency of the hybrid structural system and evaluate its feasibility as an alternative system.

2. Methodology

2.1. Technical significance

The slab is constructed on top of the beam members consisting of the reinforced concrete and steel structure. Importantly, the thicknesses of the beam member and slab influence the installation of various facilities, the finishing of the ceiling, and are closely related with story height. The first type of hybrid system combines W-shaped steel and a reinforced concrete beam to reduce the quantity of materials and energy consumed [5,6]. The lower part of the concrete of the beam is fabricated by a precast method, on which the slab is constructed, decreasing the story height of the building [7]. The second type of the beam eliminates the top flange of the steel, which does not influence the flexural resistance in the middle of the beam of Hybrid System 1 [10,11]. This type of beam is capable of the reducing the quantity of steel material and economic beam design [12,13]. The hybrid connection method is adopted for the connection of the beam and column. The column of the hybrid system is made by embedding an H-beam in the beam–column joint and preparing holes where reinforcing steels penetrates the steel web. High strength bolts and welding are used for the connection of the flange of the steel to column, while reinforcing steels pass through the holes prepared in the steel web. Fig. 1 describes the joint for a beam and column of the second type of Hybrid System.

A steel embedded in the beam–column joint enables the column of the hybrid system to be manufactured as long as 3-stories at a time. The column–column connections are classified as three types depending on how the main reinforcing steels of the top column are connected to the bottom column, as described in Fig. 2. The top and bottom column are connected by sleeve filled with non-shrink mortar with high pressure after the main reinforcing steel of the bottom column is inserted into the sleeve of the top column. The coupler type connects main top reinforcing steels to the plate of the bottom column by using couplers. The third type welds main top reinforcing steels to bottom columns with pressure.

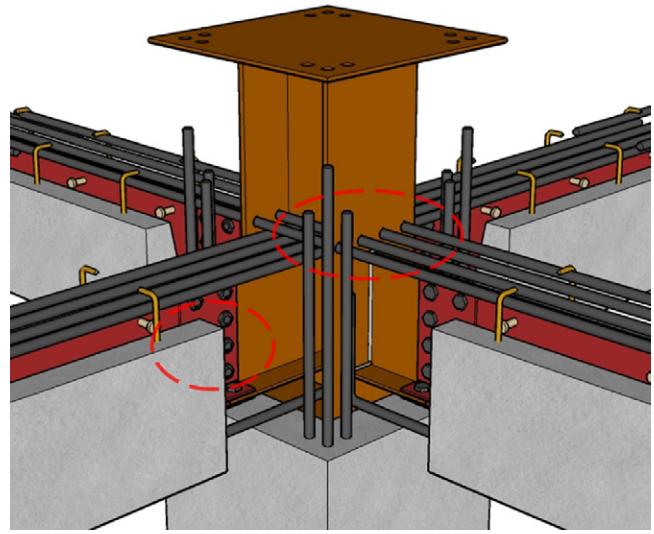

Fig. 1. Joint for beam and column in Hybrid System 2.

Fig. 3 shows the actual construction site with the hybrid system of the multi-story steel column. As seen in the figure, most of the beams and the columns of the hybrid system is fabricated in plants as precast concrete and transported to the construction site, reducing the construction period.

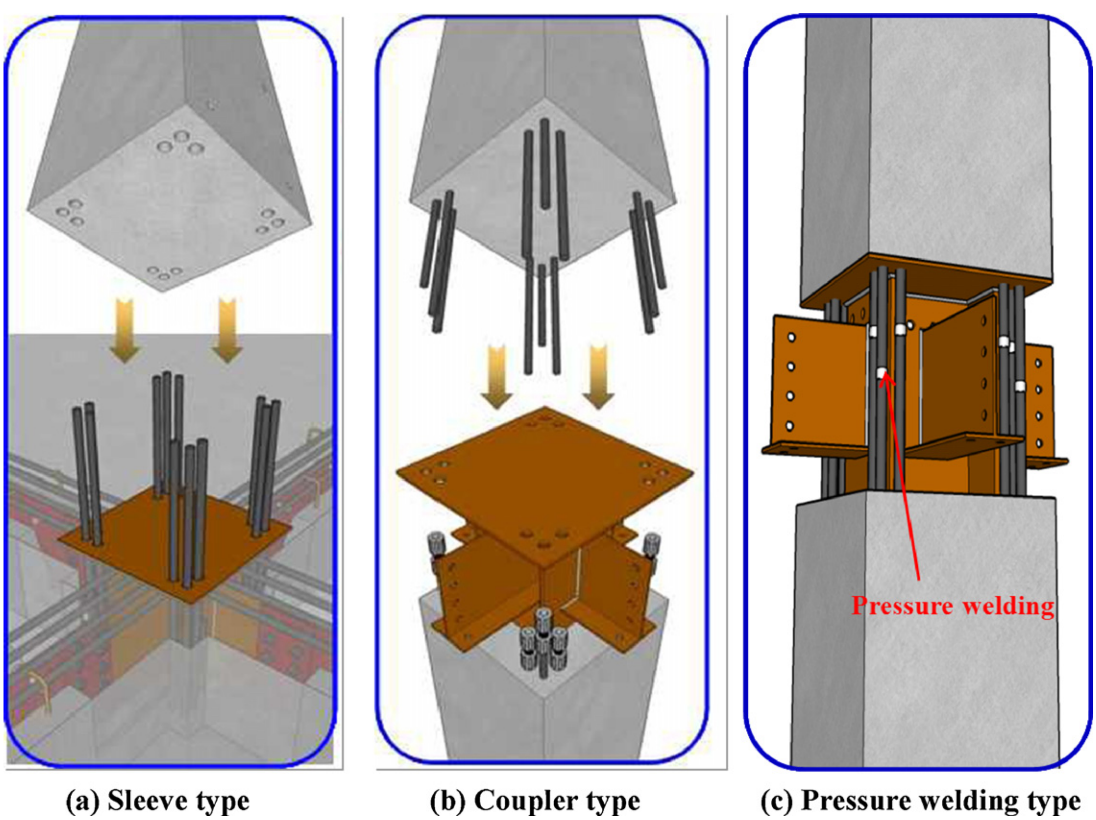

Fig. 2. Column–column connection in Hybrid System 2.

Fig. 3. Construction of Hybrid System 1.

2.2. Energy efficiency

In this study, we compared the energy consumptions of multi-residential buildings according to the type of structure in order to estimate the energy efficiencies of apartment buildings constructed using the hybrid structural system. The hybrid structural system is compared with the conventional bearing wall structural system and flat slab system. We chose nine linear-rectangular shape apartment buildings that were either completed or under construction, and redesigned them as multi-residential buildings with bearing wall, flat slab, and hybrid structures. Next, the energy consumption was computed during the construction phase of each building by the energy consumption per original unit of major construction materials according to inter-industry analysis. In order to estimate the energy efficiency in association with the height of a building, we selected apartments #1, #2, and #3 as 15-story buildings, #4, #5, and #6 as 20-story buildings, and #7, #8, and #9 as 25-story buildings.

2.3. Inter-industry analysis and functional units

Inter-industry analysis developed by Leontief refers to a practical analytical method that systematizes a country's economic activities into a structure of production technologies between industrial sectors, and clarifies the inter-industrial relationships. Components and parts are necessary to produce final goods, and raw materials are necessary to produce the components; these relationships connect the producers of raw materials directly or indirectly to other industries. The inter-industry analysis examines these relationships numerically, and allows for the computation of the energy consumption per original unit of construction materials. In this regard, this study calculates the energy consumption intensity using the Industrial Interdependence Table. For the calculation process, the method suggested by Lee and Yang [1] was adopted. First, the construction material and industrial sector were classified, and the final consumption of construction materials and resources were calculated. Next, the input per industrial sector for was evaluated, and the energy industry input was finally considered to determine the energy consumption intensity [1].

Fig. 4 shows the energy consumption per original unit of key materials calculated based on the Industrial Interdependence Table. According to the energy consumption per original unit of the calculated key construction materials, the energy consumption intensity of a steel and reinforcing steels is significantly higher than that of other materials because they require many resources in the production process. This means that a steel and reinforcing steels require large amounts of raw materials and go through a complex production process.

2.4. Characteristics of each multi-residential apartment

Bearing wall multi-residential apartments are the most common housings in Korea, and are composed of bearing walls and slabs. The bearing wall structure was first used in the 1960s, and it is popular due to its high construction quality based on its long experience. This type of structure is also inexpensive, and enables the construction of more the number of households than buildings with other structures because of the low height of each floor. However, bearing wall structures consume a large amount of concrete and are less flexible because of the bearing walls. Bearing wall structures also use water during the construction phase, making them susceptible to weather.

Flat slab multi-residential apartments are composed only of columns and slabs. The floor height of the flat slab structure is lower than the regular Rahmen structure because it does not include any beams. It can also be possible to remodel, and attracts much attention from builders as an alternative multi-residential housing system. However, the flat slab system becomes less economically efficient as an increasing amount of reinforcements are used, such as in the construction of high-rise buildings, making it less attractive for multi-story multi-residential buildings.

The hybrid multi-residential apartment has a Rahmen structure composed of steel, cast-in place concrete, and precast concrete columns [8]. The hybrid apartments can be constructed in a relatively short construction period because they use the semi-dry construction method. In addition, these systems are less sensitive to weather damage. The flexibility of Rahmen structure reduces the section sizes by using composite frame, enabling builders to apply the same floor height as that in the bearing wall structure. The hybrid structural system is classified into two types according to the shape of steel used in the composite beams. We refer to the

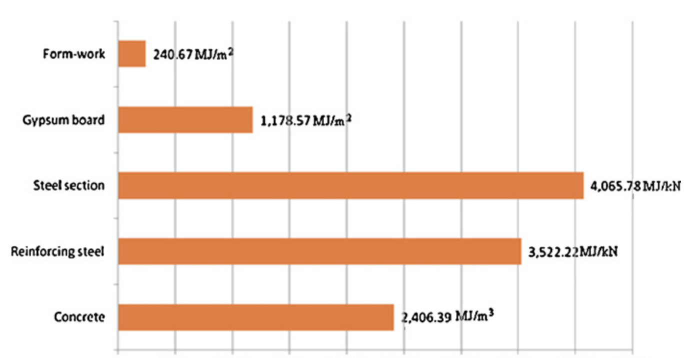

Fig. 4. Energy consumption per original unit from major construction materials.

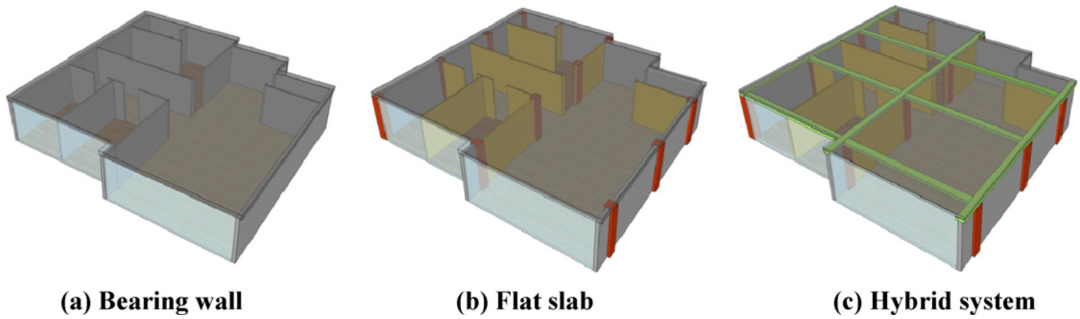

Fig. 5. Unit floor plans in bearing wall, flat slab and hybrid systems.

system with W-shaped steel as Hybrid System 1 and that with a structural tee as Hybrid System 2. Fig. 5 shows structural views of housing units in bearing wall, flat slab, and hybrid multi-residential apartments.

2.5. Analysis and results

In this section, we calculated the energy consumption of key materials for the structural systems. Using these calculations, we analyzed the trends in energy increase/decrease depending on the energy consumption characteristics of bearing wall apartments, flat-slab apartments, and hybrid apartments of various story heights.

2.6. Concrete

The concrete energy consumption per structural system is shown in Fig. 6. The average energy consumption due to concrete usage in the bearing wall system and flat slab system is 12548.62 GJ and 11694.99 GJ, respectively. These values are higher than those in Hybrid System 1 (8337.48 GJ) and Hybrid System 2 (8589.33 GJ). Hybrid System 1 and Hybrid System 2 are Steel Framed Reinforced Concrete (SRC) structures, which have high structural efficiency due to combination of steel and reinforced concrete. The use of SRC beams with sufficiently high structural efficiency decreases the section size of beams and reduces quantity of concrete. This reduction of concrete consumption is considered the key to the reduction of energy consumption in Hybrid System 1 and Hybrid System 2.

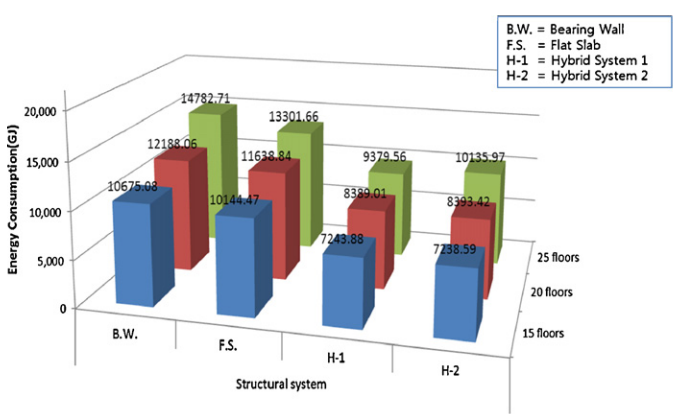

Fig. 6. Concrete energy consumption by structural system.

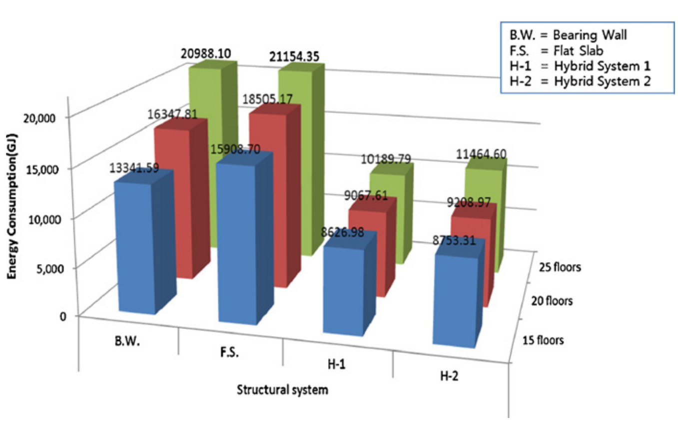

Fig. 7. Reinforcing steel energy consumption by structural system.

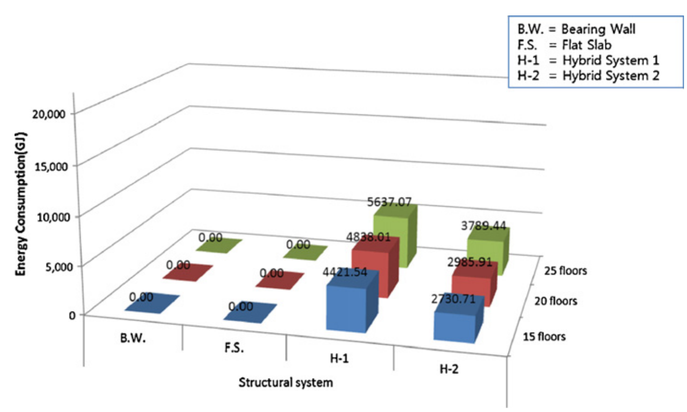

Fig. 8. Energy consumption of steel by structural system.

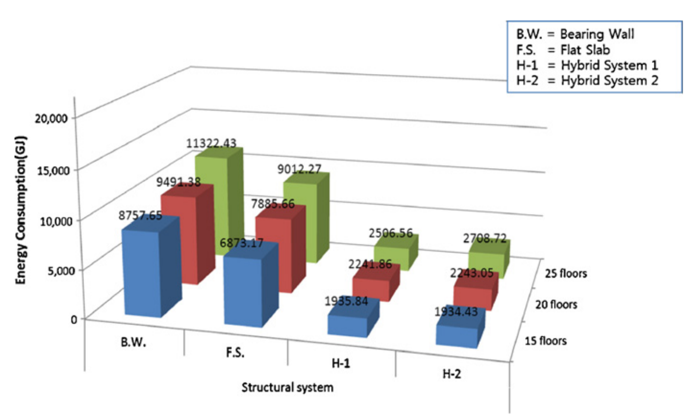

Fig. 9. Energy consumption of form-work by structural system.

Table 1
Energy consumptions for certain types of construction materials.

		Energy consumption (GJ)					Total energy consumption (GJ)	Comparison
		Concrete	Reinforcing steel	Steel section	Form-work	Gypsum board		
#1	B.W.	9833.5	10843.5	0.0	7955.3	7083.1	35715.4	100.0%
	F.S.	9517.8	14335.4	0.0	6448.5	9689.3	39991.1	112.0%
	H-1	6956.4	7742.9	3261.2	1859.0	9689.3	29508.8	82.6%
	H-2	6959.5	7851.7	2015.4	1859.8	9689.3	28375.9	79.4%
#2	B.W.	8828.6	10243.0	0.0	7268.7	7839.0	34179.2	100.0%
	F.S.	8771.8	11864.6	0.0	5943.1	11573.3	38152.8	111.6%
	H-1	6350.0	6915.9	3728.3	1697.0	11573.3	30264.5	88.5%
	H-2	6328.1	6927.2	2302.9	1691.1	11573.3	28822.5	84.3%
#3	B.W.	13363.2	18938.3	0.0	11049.0	11555.8	54906.3	100.0%
	F.S.	12143.9	21526.1	0.0	8227.9	16606.7	58504.5	106.6%
	H-1	8425.3	11222.2	6275.1	2251.5	16606.7	44780.8	81.6%
	H-2	8428.2	11481.0	3873.9	2252.3	16606.7	42642.1	77.7%
#4	B.W.	13964.3	20432.1	0.0	10778.5	10492.2	55667.0	100.0%
	F.S.	12823.9	22210.8	0.0	8688.5	15509.5	59232.7	106.4%
	H-1	9314.7	10363.8	6203.6	2489.2	15509.5	43880.7	78.8%
	H-2	9317.6	10464.5	3919.0	2490.0	15509.5	41700.6	74.9%
#5	B.W.	14081.5	18089.4	0.0	11042.0	11271.5	54484.4	100.0%
	F.S.	14097.6	20620.1	0.0	9551.6	16770.8	61040.2	112.0%
	H-1	10095.3	10804.8	5059.0	2697.9	16770.8	45427.7	83.4%
	H-2	10097.7	10931.9	3066.0	2698.5	16770.8	43564.9	80.0%
#6	B.W.	8518.4	10521.9	0.0	6653.6	6837.7	32531.7	100.0%
	F.S.	7995.0	12684.6	0.0	5416.8	10775.4	36871.8	113.3%
	H-1	5757.1	6034.3	3251.4	1538.5	10775.4	27356.6	84.1%
	H-2	5765.0	6230.5	1972.7	1540.6	10775.4	26284.2	80.8%
#7	B.W.	15952.2	22038.2	0.0	12316.9	12564.9	62872.2	100.0%
	F.S.	14562.0	25332.9	0.0	9866.2	18688.2	68449.3	108.9%
	H-1	9976.9	11059.4	6825.6	2666.2	18688.2	49216.3	78.3%
	H-2	9942.7	11521.5	4190.6	2657.1	18688.2	47000.1	74.8%
#8	B.W.	18229.6	26885.5	0.0	13737.4	13589.6	72442.1	100.0%
	F.S.	16572.6	25156.4	0.0	11228.5	19935.8	72893.3	100.6%
	H-1	12098.9	12921.3	6666.7	3233.3	19935.8	54855.9	75.7%
	H-2	12127.3	13383.7	4115.4	3240.9	19935.8	52803.0	72.9%
#9	B.W.	10166.3	14040.6	0.0	7913.0	7729.9	39849.8	100.0%
	F.S.	8770.3	12973.8	0.0	5942.1	11661.2	39347.4	98.7%
	H-1	6062.9	6588.7	3418.9	1620.2	11661.2	29351.9	73.7%
	H-2	6075.7	6604.2	2104.4	1623.6	11661.2	28069.1	70.4%
Avg.	B.W.	12548.6	16892.6	0.0	9857.2	9884.9	49183.2	100.0%
	F.S.	11695.1	18522.7	0.0	7923.7	14578.9	52720.3	107.2%
	H-1	8337.4	9294.8	4965.5	2228.1	14578.9	39404.7	80.1%
	H-2	8337.9	9488.5	3062.3	2228.2	14578.9	37695.8	76.6%

B.W., bearing wall; F.S., flat slab; H-1, Hybrid System 1; H-2, Hybrid System 2.

2.7. Reinforcing steel

Fig. 7 shows the energy consumption of the reinforcing steel used in each structural system. This value is highest for the flat slab structural system, which averages 18522.74 GJ. In the hybrid apartment, the load is delivered to the footing through the beam and column at the slab. Meanwhile, the flat-slab structural system supports the load without a beam, but with only a slab and column. In this regard, the arrangement of shear reinforcing steel that aims to prevent punching shear in the flat-slab structural system is considered the cause to the increase in energy consumption. In addition, we compared the energy consumptions of 15-story apartment and 25-story apartment buildings depending on the use of reinforcing steel and concrete. The analysis shows that the bearing wall system has the largest gap of 11754.14 GJ, mainly because of the increased quantity of reinforcing steel required for lateral resistance as the story height of the building increases.

2.8. Steel section

Fig. 8 shows the steel energy consumption depending on the structural system. Since a steel is not used in bearing wall and flat-slab systems, energy is not consumed. Because the steel-frame reinforced concrete composite beam was applied, the energy consumption of the steel in Hybrid System 1 increased by 4965.54 GJ compared to that of the bearing wall and flat slab systems. However, the energy consumption of concrete and reinforcing steels decreased by 12585.45 GJ compared with flat slab apartments. As a result, the energy consumption of the Hybrid System 1 decreased by 7619.91 GJ compared to the flat slab system. Given that the energy consumption intensity of steel is higher than that of concrete and reinforcing steels, the hybrid system is considered to have higher energy efficiency than the other structural systems. Hybrid System 2 shows higher energy efficiency than Hybrid System 1. The quantity of steel of Hybrid System 2 is less than that of Hybrid System 1, while the quantity of reinforcing steel and concrete is higher than those of Hybrid System 1. However, the total energy consumption decreases by 5%, since the energy consumption intensity of steel is higher than concrete and reinforcing steels.

3. Form-work

Fig. 9 shows graph of the energy consumption of form-work depending on the structural system. Energy consumption of form-work for the bearing wall apartment is the highest, with an average of 9857.15 GJ. The bearing wall system is composed of a reinforced concrete bearing wall. Thus, a large quantity of form-work is required for the construction of the bearing wall. The form-work energy consumption of the flat slab system is 7923.71 GJ, which is a considerable difference compared to the energy consumptions of

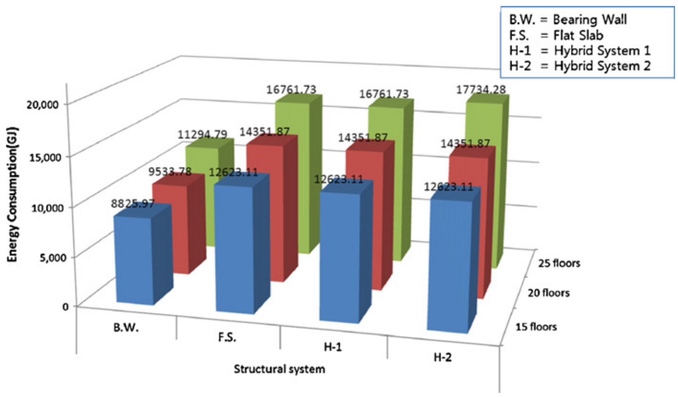

Fig. 10. Energy consumption of gypsum board by structural system.

Hybrid System 1 (2228.09 GJ) and Hybrid System 2 (2295.40 GJ). Since most of the beams and columns of the hybrid systems are made as precast concrete, the quantity of form-work required is reduced. This is mainly caused by the reduction in energy consumption with decrease of a form-work.

3.1. Gypsum board

Fig. 10 shows the energy consumption of gypsum board depending on the structural system. The average energy consumption of gypsum board for the bearing wall system is 9884.84 GJ, which is about 67.8% of the value for other structural systems (14578.90 GJ). This is because bearing wall apartments share the same floor plan both with flat slab and hybrid apartments with the use of the same amount of ceiling finish material. However, the amount used for the partition wall of the bearing wall system decreases since the bearing walls are used as partition wall, indicating that bearing wall apartments have less architectural flexibility than other structural systems.

3.2. Energy consumption by structural system

Table 1 shows the energy consumptions of the nine apartment buildings according to structural system. The average energy consumptions of Hybrid System 1 and Hybrid System 2 were 80.1% and 76.6% compared with the bearing wall system, respectively. These reductions resulted mainly from the decreased quantity of concrete and reinforcements, both of which have high energy consumption per original unit. The flat slab buildings were estimated to consume 7% more energy than did the bearing wall buildings.

The number of floors does not affect the energy efficiency of a flat slab apartment compared to the bearing wall apartment. However, the energy consumption of 20-story Hybrid System 1 apartment was decreased 2.1% and 25-story Hybrid System 1 apartment was decreased 6.1% compared with the energy consumption of bearing wall apartment with the same number of floors. The energy consumption of 20-story and 25-story Hybrid System 2 apartments were also reduced 1.9% and 5.8% compared with the bearing wall apartment, respectively. These results suggest that energy consumption can be further reduced when high-rise multi-residential apartments are constructed using a hybrid structure. This result is expected to benefit the current trends toward taller multi-residential apartments. Fig. 11 shows the energy consumptions in multi-residential apartments according to the number of floors.

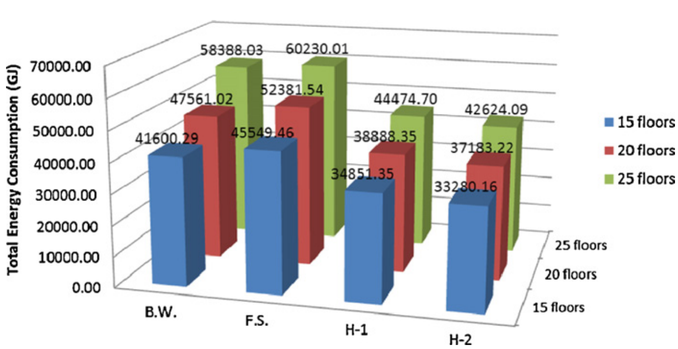

Fig. 11. Comparison of energy consumptions for different apartment heights.

4. Conclusions

This paper investigated the energy efficiencies of multi-residential apartments with a variety of structural systems to reach the following conclusions.

(1) According to the analysis of energy efficiency depending on the average quantity of concrete and reinforcing steels, the energy consumption of Hybrid System 1 is about 60.97% and 60.32% compared with the bearing wall system and flat-slab system, respectively. The energy consumption of Hybrid System 2 is 61.52% and 60.86% compared with the bearing wall system and flat slab system, respectively. Energy consumption is reduced because of the decrease in beam size due to the significant structural efficiency of the hybrid structures of Hybrid System 1 and Hybrid System 2.
(2) Additional energy consumption of Hybrid System 1 and Hybrid System 2 is generated by steel, since steel beams are the important structural elements which are not used in the bearing wall system or flat slab system. The energy efficiency of the hybrid system is significantly high even if the additional energy consumption in Hybrid System 1 and Hybrid System 2 is less than the decreased energy consumption from concrete and reinforcing steels. This is because that the energy consumption per original unit of steel is higher than concrete and reinforcing steels. The additional steel quantity of Hybrid System 2 can be saved compared with Hybrid System 1.
(3) As most of the beams and columns in the hybrid system are produced as precast concrete, the quantity of form-work can be decreased significantly compared with other structural systems. Accordingly, the energy consumption of form-work in the hybrid system is about 22.60% and 28.12% compared with the bearing wall system and flat-slab system, respectively.
(4) The energy consumption of multi-residential apartments constructed with Hybrid System 1 and Hybrid System 2 reduced an average of 19.9%, 23.4% compared with bearing wall apartments, and 25.3%, 28.5% compared with flat slab apartment, respectively.
(5) The 20-story and 25-story Hybrid System 1 and 2 buildings reduced energy consumption by 2.1%, 6.1%, and 1.9%, 5.8% respectively, compared with the 15-story building. These results suggest that the hybrid precast structure is more energy efficient than bearing wall structure for the use in high-rise buildings.

In general, the hybrid structural system is expected to support the environmental friendly, sustainable apartment buildings based on its high energy efficiency. The results of this paper will be useful as basic data for developing environmental friendly, sustainable multi-residential apartment buildings.

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