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Cost Analysis of the Structural Work of Green Frame

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Abstract

The adoption of Green Frame is expected to provide economic benefits, since construction costs are reduced by the in-situ production of precast concrete column and beam. The cost reduction can ultimately be realized by saving transportation costs and the overhead and profit of PC plants. The cost structure of Green Frame, which is built up using composite precast concrete members, is similar to that of a bearing-wall structure, but the difference in construction process has resulted in some cost differences for a few items. In particular, production and installation is the principal work involved in Green Frame made by precast concrete members, while form and concrete work is the principal work for a bearing-wall structure. As such, the rental time and fee for a tower crane should be compared through time analysis. To verify reliability, this study focused on developed residential projects to estimate the construction costs. Through this analysis, it was found that the costs of Green Frame were 1.57% lower than the costs of bearing-wall structure. The results of this study will help in the development of a management plan for the structural work of Green Frame.

Keywords : cost reduction, green frame, precast concrete, residential buildings, in-situ production, structural work

1. Introduction

1.1 Background and objective

Green Frame (GF) is a precast concrete (PC) column–beam structure that addresses many of the disadvantages of the bearing–wall structure employed in most apartment buildings in Korea[8,9]. In particular, GF can resolve the most significant shortcoming of a column–beam structure; the increasing of floor height, GF can secure a floor height as high as that of a bearing–wall structure. In–situ production was adopted to produce the main structural members of GF, such as precast concrete column and beam, and a cost reduction can ultimately be realized by saving transportation costs and the overhead and profit of PC plants. For this reason, it is expected to secure economics compared to the bearing–wall structure[8]. The construction cost was calculated by Yune et al.[1], and by Kim[3] to verify the economics of GF. However, the studies do not offer a clear explanation of estimation of unit cost and quantity of specific items. In particular, the study conducted by Kim[3] is about the in–situ production of GF, which is similar to this study, but does not include tower crane rental fee and PC installation cost. That is, the previous studies did not provide detailed expenses related to the adoption of GF.

GF, a ramen structure, differs from the existing bearing–wall structure in terms of the work types

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and the cost structure. To verify the economics of GF, the cost structure of GF and a bearing–wall structure should be compared. However, the aforementioned studies have not given a clear explanation for the differences between them.

The cost breakdown of a bearing–wall structure largely consists of three work types: concrete work, reinforcement work and formwork; other costs, including the rental fee of tower cranes, should be included. The cost breakdown of GF built using composite PC members is similar overall to that of the bearing–wall structure, but different in some items due to differences in the PC production and installation. In particular, since PC columns and beams are produced on site, PC production and installation are major work, unlike the work processes involved with the bearing–wall structure, which mainly consist of formwork and concrete placing work. For this reason, a process analysis needs to be performed to compare with a bearing–wall structure to calculate the cost of rental fee and the period of use of tower crane.

Therefore, this study aims to analyze the cost of GF compared to a bearing–wall structure. The findings of this research provide increasing cost factors of a GF structure compared to a bearing–wall structure and certain technical improvements to reduce the cost, and these will be utilized as fundamental data to develop elemental technologies.

1.2 Research scope and method

The research examines the cost of GF and bearing–wall structure. A comparative analysis was conducted by calculating quantity for the ground structure; the basement and underground structures were excluded from the analysis due to there being marginal difference in quantity by structural type [9]. In addition, the core part was excluded because it is same for both structures. The masonry wall was categorized as finishing work rather than structural work, and was thus not included in the cost analysis. The composite PC members for GF are limited to those produced on site. The comparison of materials quantity and construction cost was done for one standard floor. The study proceeded as follows.

First, a comparison was done for the characteristics of and differences in the cost breakdown between GF and bearing–wall structures. Second, the quantity of structural materials was calculated by selecting a project designed with both bearing–wall structure and GF. In addition, additional quantity according to method characteristics was analyzed to ensure an equivalent comparison. Third, the structural work construction cost of GF and bearing–wall structure was compared. If there are differences in unit costs applied to GF and bearing–wall structure, a reliable comparison of construction cost cannot be made. Therefore, all the unit costs applied in this research were drawn through an interview with an expert in the field. In terms of the quantity of a bearing–wall structure, the actual unit costs were applied through an interview with experts, while as that of a GF, the unit costs were calculated and applied by establishing a production plan for the case project.

2. Theoretical studies

2.1 Characteristics of GF

As shown in Figure 1, the GF applied in this research is a column–beam structure consisting of composite PC beams installed on every floor and PC columns installed in one section of 3 floors. PC columns and beams have the characteristics of a framed structure and thus can be installed rapidly and accurately. Structural integrity is secured by placing concrete in conjunction with slab. GF can improve constructability and reduce the construction period through the application of such a hybrid connection method[5].

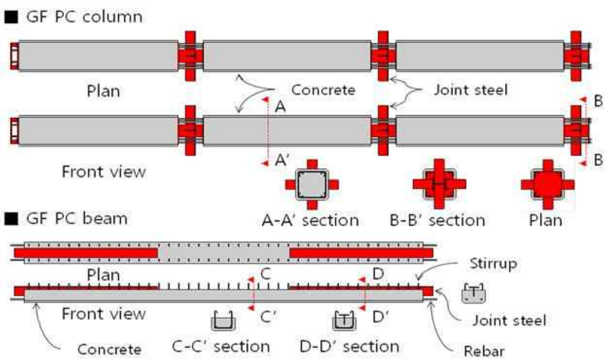

Figure 1 . PC column and beam of GF

When GF is applied to a residential building, a story height can be secured that is as high as a bearing–wall structure, while providing the flexibility of the ramen structure. In addition, when applied to the underground structure, it can reduce the volume that must be excavated [5].

2.2 Characteristics of the framework

2.2.1 Bearing-wall structural work

Figure 2 indicates the bearing–wall structure that consists of reinforced concrete (RC) walls and slabs. The structural work for bearing–wall structure is divided into 3 phases: concrete, reinforcement and formwork.

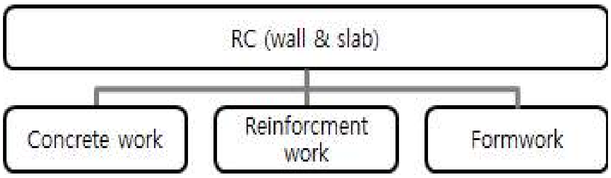

Figure 2. Structural work for bearing wall structure

Due to the characteristics of the bearing–wall structure, the wall and slab work are not distinguished clearly and done by story–unit. The order of rebar and formwork is determined according to the stage of construction. If the formwork is done, then the concrete shall be placed. When the concrete is hardened in the course of curing, construction on the upper story is carried out. In general, formwork is done for each 2– or 3–story unit. Gang forms divided by building type or form weight are hoisted by a crane. This bearing–wall structural work is usually done in wet construction, and despite the numerous studies that have been done on reducing the construction period, work still typically proceeds at a build rate of about 2.5 stories per month, on average.

2.2.2 GF structural work

As indicated in Figure 3, the GF structural work is divided into PC and RC. PC work is comprised of production and installation of composite PC members such as PC columns and beams. In–situ production of composite PC members differs from case to case, but the unit costs are calculated in a similar manner as for the bearing–wall structure, since the RC work is composed of concrete, reinforcement and formwork.

To produce PC members on site, developed in–situ forms were used. The composite PC members produced were lifted using a crane and installed. After the installation of columns and beams was finished, the deck plate was installed to place slabs. The developed joint form was used where the column and beam met. When all of the joint forms and deck plates were installed, the structure was integrated by placing concrete after finishing the placement of the top bars of slab. In the GF structural work, the lifting and installation of columns, beams and deck plates were the main process, unlike the bearing–wall structure whose main work is wet construction. The core part, which mainly used wet construction, was done in conjunction with the residential part. In this way, a shorter construction period was secured compared to the traditional bearing-wall structure. According to the study conducted by Lee et al.[7], 4 stories can be built in one month, with enough allowance time secured.

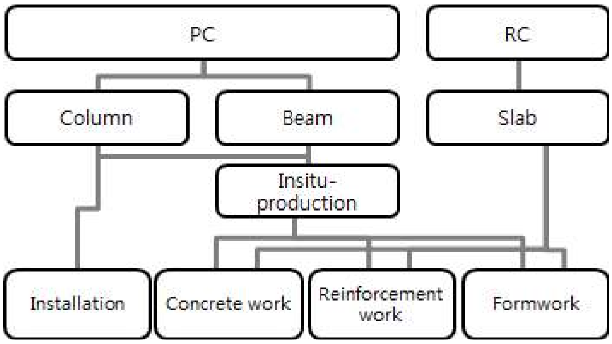

Figure 3. Structural work for GF

1) Steam curing of composite PC members

Concrete curing methods include wet curing, steam curing, electric curing, membrane curing, pre-cooling, pipe cooling, insulation heat curing, and heat supplying curing. Of these, steam curing, electric curing and heat supplying curing are the types that can be classified as accelerating curing. Steam curing provides the increased long-term strength of wet curing, as well as acceleration [10]. In the in-situ production of composite PC members, steam curing is used to develop the required strength of PC members at an early stage. The steel pipe for scaffolding was used as the steam curing sheet, and the oblique top cover was designed to deal with snow, rain and internal condensation, as seen in Figure 4.

2) in-situ production Form of the composite PC membersWhen producing PC in a PC plant, a heavy and large-volume mold is used. If it is applied to the in-situ production as it is, heavy equipment shall be required. For this reason, it can cause a safety problem as well as an increased construction cost due to production of the mold.

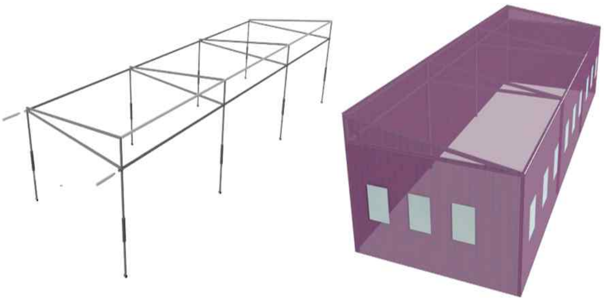

Figure 4. Steem curing sheet

In order to replace the mold used in a PC factory, if plywood forms are used to produce PC members, a lot of manpower is required, the construction duration is extended due to its low constructability, and the quality is also deteriorated. In addition, the low workability of the plywood forms results in a large volume of construction waste.

For these reasons, the forms were made in steel, taking constructability and economic feasibility into account[8]. The forms for the in-situ production are shown in Figure 5, and two columns and 3 beams were produced from a production module.

To improve the productivity of the in-situ production, PC members were produced, laid on the ground, and the bottom forms and side forms were needed. The bottom forms were defined as the palette[8], which was not moved from the beginning to the end of structural work. The palette was installed on the floor to bear the weight of form and members, and had sufficient stiffness and better workability than the side form. The side forms need to be disassembled and assembled repeatedly during the whole structural work. The side form buttressed the side pressure, and was designed to be lightweight so that workers could carry it in consideration of productivity.

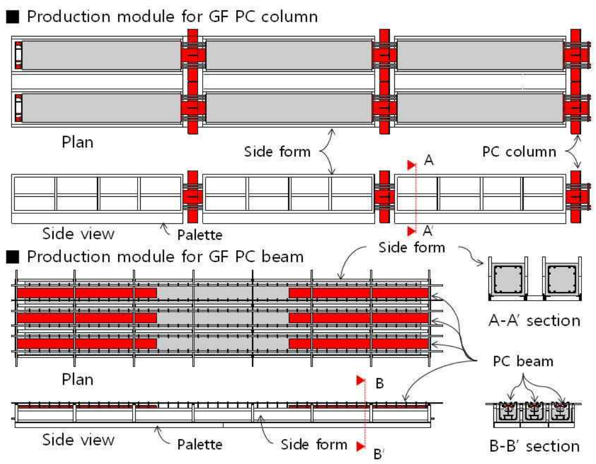

Figure 5. In-situ production module for GF[4]

3) Joint form

The connection joint of PC column and beam is generally complex. For this reason, when the plywood form is used on there, a lot of manpower is required, the construction duration increases due to its low constructability, and the quality is also deteriorated. In addition, disassembling the form could cause a safety problem, and the disassembled form is unable to be used again, resulting in a large quantity of construction waste. Using the joint form developed in the study by Kim[4], both eco–friendliness and constructability can be improved. The joint form can be installed by a team of two workers. Forms that have been made in a factory are carried in and installed on the site[11].

2.3 Review of previous studies

Previous studies related to GF construction cost calculation were reviewed. Yune et al.[1] proved the economic feasibility of using GF beams compared to using framed beams. However, the study was conducted on the beams only, and thus its scope was different from that of this study, which aims to calculate the actual costs of GF construction. In addition, Lee[2] performed a comparison of construction costs between GF and bearing–wall structure as well as flat plate structure. However, in that study the site production was not considered, and thus its scope differs from that of this study. Meanwhile, Kim[3] compared the total framework construction cost of GF and bearing–wall structure in consideration of the in–situ production of GF, which is similar to the scope of this study. However, it failed to provide a detailed explanation and consider PC installation cost and tower crane rental fee.

As seen above, few studies have provided a detailed calculation of construction cost taking the in–situ production of GF into account. In particular, the study by Kim[3] provided a conceptual introduction to the in–situ production of GF first, and calculated the construction cost. But it did not consider the peculiarities of in–situ production when calculating the unit costs, and the calculation can hardly be considered accurate. Thus, a comparative study of the construction cost should be done based on an accurate calculation of quantity and unit cost, in consideration of the in–situ production of GF.

3. Quantity of structural materials by characteristics of each structural type

3.1 Description of the case project

The case project was performed in a apartment building in Gyeonggi–do. At the time of construction approval, the project was expected to have a heavy deficit based on a business economics analysis[8]. For this reason, the bearing–wall structure in Figure 6 was re–designed at the request of the owner, as shown in Figure 7, with a view to allowing greater flexibility of residential spaces, improving seismic performance, and reducing the selling price.

The case project originally designed in a bearing–wall structure had 11 buildings with volume of 208.96% as indicated in Table 1. It was re-designed to have a volume of 227.87%, and typical floor plans were provided based both on a bearing-wall structure and a GF under the same condition.

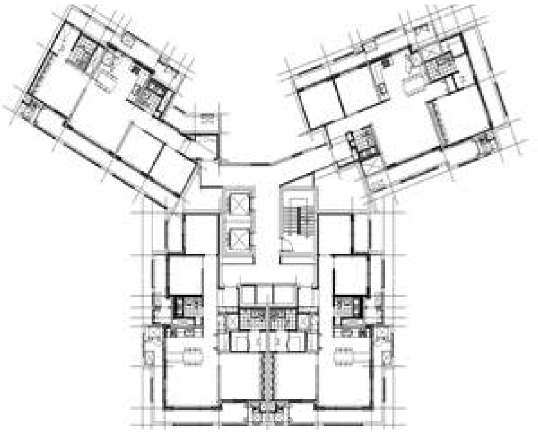

Figure 6. Typical floor plan of bearing wall structure

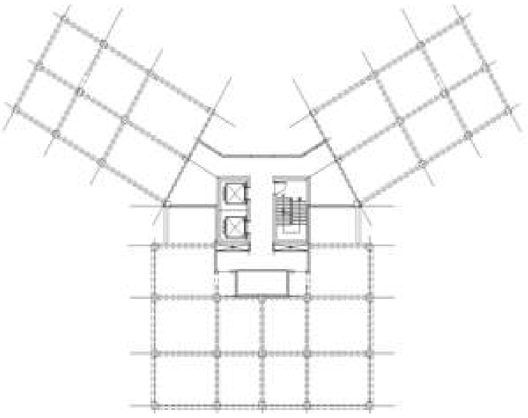

Figure 7. Typical floor plan of GF

Table 1. Brief description of a case project

Description	Before	After
Structure type	Bearing wall	GF
Location	00 City, Gyeonggi-do	
Site area (㎡)	57,333	
Total floor area (㎡)	167,064	180,498
Volume (%)	208.96	227.87
Building area (㎡)	9,532	10,841
Building coverage (%)	16.63	18.91
Number of Buildings	11	13
Stories	F27, B2	F25, B2

3.2.1 Quantity of structural materials of the bearing-wall structure

Table 2 indicates the quantity of structural materials of the bearing-wall structure of the case project.

For the reinforcement work, the material costs were assigned by dividing rebars by their diameter, and items were divided to assign assembly costs for the total weight of rebars. For the formwork, each of the unit costs was set separately because each form had a different unit cost, and the cost for the supports was added.

Table 2. Quantity of the structural work (bearing wall structure)

Classification			Quantity
Work	Item	Unit	
Con'c work	Con'c	m^3	255
Reinforcement work	HD10	ton	11.7
	HD13	ton	10.0
	HD16	ton	1.4
	Fabrication	ton	23.1
Formwork	Outer form of ext. wall	m^2	314
	Form for int. wall	m^2	701
	Form for slab	m^2	565
	Shoring work	m^2	565

3.2.2 Quantity of structural materials of the GF

As mentioned earlier in Section 2.2, the quantity of structural materials was divided into PC part and RC part. However, the classification of the bearing-wall structure was used to compare costs with the bearing-wall structure.

To calculate the quantity of materials used in the case project, the materials for the PC work and for the RC work were calculated separately and then added.

Tables 3 and 4 are the analytical results of PC members to calculate the quantity of materials for the PC construction.

Table 3. PC member list (beam)

PC member	Name	No.	Size (mm)		
			H	W	L
Beam	B1	8	210	350	5450
	B2	6	210	350	3900
	B3	5	210	350	4175
	B4	5	210	350	4475
	B5	2	210	350	4200
	B6	2	210	350	2100
	B7	6	210	350	4075
	B8	6	210	350	4650
	B9	6	210	350	6320
	B10	8	210	350	4000
	B11	8	210	350	4350
Total(per floor)		62			

Table 4. PC member list (column)

PC member	Name	No.	Size (mm)		
			W1	W2	H
Column	C1	10	500	500	8700
	C2	4	450	450	8700
	C3	3	450	450	8700
	C4	12	500	500	8700
	C5	6	450	450	8700
	C6	4	400	400	8700
Total(per every 3 floors)		39			

Concrete, rebars and steel frame were added based on the PC member lists and calculated as 45 m^3, 10 tons, and 6 tons, respectively. In addition, steel form to produce PC on site was calculated as 515 m^2. The curing item was added since it was planned to develop the strength of the members at an early stage using steam curing.

The quantity of materials used in the RC work was calculated by adding up the slabs and PC connected parts on the list, while excluding PC members like columns and beams. From the results, concrete and rebars were calculated as 83 m^2 and 1.5 tons, respectively. In terms of form, the number of joint forms to connect column and beam was calculated as 39 EA, which was the number of columns. The slab was calculated as 565 m^2, assuming deck plate was used and not including the areas of columns and beams in the floor area. Table 5 indicates the calculated results in an identical form with the bearing-wall structure. The rebar item was added for the bearing-wall structure.

Table 5. Quantity of the structural work(GF)

Work	Item	Unit	Quantity
Con'c work	Con;c	m^3	128
	Curing	m^3	45
Reinforcement work	HD10	ton	2.8
	HD13	ton	0.3
	HD16	ton	-
	HD19	ton	3.5
	HD22	ton	5.0
	Fabrication	ton	11.6
	Steels of column	ton	4
	Steels of beam	ton	2
Formwork	Joint form	EA	39
	Steel form	m^2	515
	Deck plate	m^2	565

3.3 Additional quantity by characteristics of each structural type

As GF is a ramen structure, gangform(outer form of external wall) and euroform(form for internal wall) used to build the walls in a bearing-wall structure were not needed. The concrete wall was replaced with light-weight dry wall. To compare the quantities needed to make an equivalent output, the quantities added or subtracted according to the characteristics of each structural type should be considered, rather than simply comparing the quantities for each structure.

1) Surface treatment and light-weight dry wall

For the bearing-wall structure, when the forms are disassembled after concrete placement, some of the materials are segregated to make the surface rough. To make the surface smooth, surface treatment is needed. But for GF, there are no walls, and surface treatment is not needed, but light-weight dry walls are required.

2) PC installation and tower crane

A tower crane is used to install columns and beams produced on site. In particular, a tower crane is placed for each building to distribute lifting load. Both the number of tower cranes needed and the construction duration are different between the bearing-wall structure and GF, which means that the equipment cost of tower cranes is also different. Thus, to take into account all the costs of making an identical output, PC installation cost and tower crane cost were additionally considered. Table 6 is the additional quantity related to the characteristics of each structural type.

Table 6. Additional quantity related to the characteristics of each structural type

Work	Item	Unit	Quantity	
			Bearing wall	GF
Finish work	Surface treatment (ext. wall)	m^2	475	-
	Surface treatment (int. wall)	m^2	419	-
	Dry-wall (ext. wall)	m^2	-	213
	Dry-wall (int. wall)	m^2	-	370
PC installation		m^3	-	45
Tower crane		floor	1	1

4. Comparative analysis of construction costs by structural type

4.1 Calculation of unit costs

To perform a reliable comparison of construction costs, an identical cost system should be applied to the quantity of structural materials. For this reason, each unit cost was calculated by analyzing productivity for each item through advice from an expert.

4.1.1 Unit cost of concrete work

From the analysis of the expert' s advice and actual construction specifications, the unit cost of concrete work per 1 m^3 was shown as KRW 54,300 for materials cost and KRW 8,000 for placement. So, KRW 62,300, the sum of the two costs, was applied as the unit cost of concrete work.

The unit cost of steam curing was calculated based on depreciation cost caused by the purchase of a boiler, expenses of fuel and electricity, and curing sheet materials. A 10% depreciation rate was applied to the boiler purchase cost of KRW 12,000,000, and calculated as KRW 1,200,000, which was divided by 1,135m^3 for the quantity of PC materials needed for a building, and the unit cost of the boiler per 1 m^3 of PC member was KRW 1,057. To calculate the expenses of fuel and electricity, data were collected from 10 construction sites similar to the case project, and then analyzed. From the result, KRW 3,808 and KRW 346 were calculated as fuel and electricity costs per 1 m^3 of PC member. The installation and dismantling costs of curing sheet per building were KRW 2,000,000 and KRW 7,500,000, respectively. The sum of the two costs was divided by the quantity of PC materials to get KRW 8,368 per 1 m^3 of PC member. As a result, a cost of KRW 13,597 per 1 m^3 of PC member was obtained by adding all of the unit costs, including depreciation, fuel and electricity, materials, installation and dismantling of the curing sheet.

4.1.2 Unit cost of reinforcement work

The material cost of rebars was analyzed based on the expert' s advice and actual construction specifications to get KRW 840,000 per 1 ton as the standard unit cost. Unit costs of KRW 150,000 and KRW 860,000 were applied to HD13 and HD10, respectively. However, the unit cost of GF columns and beams was applied differently based on a productivity analysis, since they were produced on the ground and their work process was simple.

First, from the analysis of the unit cost paid at site, the assembly cost was about KRW 180,000, assuming a unit cost of KRW 5,000 per 1 ton for consumables like rebar tire wire. The unit cost of consumables was subtracted from the assembly cost to get KRW 175,000. Based on KRW 150,000 of labor cost paid to an iron worker at site, the number of iron workers needed per 1 ton was calculated as 1.16 people. In the standard estimating system, it is stipulated that 1.84 iron workers are needed per 1 ton. Considering the standard estimating system produces high estimates, the number of iron workers drawn in this study is relatively accurate. However, there was a similar type of in–situ production of PC that indicated a very high productivity of 0.45 workers needed per 1 ton. It is believed that unlike this case project, the longer the diameter of rebars for the factory–type apartments, the higher the reported productivity. In this study, 0.7 workers was set as needed for the assembly of the rebars with PC members produced on site per 1 ton. From this process, the assembly cost of rebars was calculated as KRW 110,000 by adding the labor cost for 0.7 workers and KRW 5,000 for the cost of consumables.

The equation of the steel frame was KRW 1,400,000 per 1 ton, as provided by a steel frame company, based on the GF type and the total quantity needed for the case project.

4.1.3 Unit cost of formwork

The unit cost per 1 m^2 was calculated as KRW 25,000 for gangform for external walls, KRW 15,000 for euro form for internal walls, KRW 18,000 for the plywood form for slabs, KRW 1,000 for form cleaning and KRW 5,600 for application of the release agent used for the bearing–wall structure. The unit cost per 1 m^2 was calculated as KRW 21,000 for deck plate used for GF in the same fashion. The materials cost, installation cost and dismantling cost were included in the unit costs.

The costs of the joint forms and steel forms used for GF were estimated by analyzing the materials costs and productivity, based on the assumption that they were custom–made. The cost estimation process for the forms is as follows.

1) Joint form

The manufacturing cost of a joint form was KRW 40,000. The joint form was made of waterproof plywood with a steel plate attached. Unlike a general form, it was not thrown away when dismantled, and could be reused about 25 times without any concern of form damage. In addition, the joint forms used for a story can also be used immediately after disassembly for the next story. The number of joint forms needed per one story of a building was 39. Therefore, the making cost was divided by 25, the number of times of a form could be used, to get KRW 1,600 as the unit making cost per EA.

A joint form was installed where column and beam met, and 39 joint forms shall be needed. A carpenter can install 15 joint forms a day and dismantle 43. In other words, 2.6 carpenters were needed to install 39 joint forms and 0.9 carpenters were needed to dismantle them, which means a total of 3.5 carpenters were needed. As the unit cost paid at site for a carpenter, KRW 130,000, was applied, the total labor cost for the carpenters amounted to KRW 455,000. KRW 455,000 was divided by 39 required for one story to arrive at KRW 11,667 per installation or dismantling of a joint form. Therefore, the unit cost of joint form work was calculated as KRW 13,267 by adding

KRW 1,600 for manufacturing cost per joint form and KRW 11,667 for installation or dismantling cost.

2) Form of in-situ production

When GF was applied to the case project, we got the quotation for the total quantities of 5,538 EA(167,276m^3) from a steel frame processing company, amounting to KRW 1,259,283,168. In the quotation, the number of reuses of in-situ production forms was not considered. Assuming the number of reuses of the steel forms is 100 times for palettes and 50 times for side forms, the material cost amounted to 19,798,125. Considering the number of reuses, the material cost was divided by the total area of steel forms, 12,843m^3 , to get KRW 1,542 as the material cost per 1m^3 of the in-situ production form.

In terms of in-situ production form, 60 column forms were installed for three stories while 42 beam forms were installed for one story. A total of 7 carpenters were needed for the column form work since the quantities used for three stories were installed at once: 5 for installation and 2 for dismantling. A total of 5 carpenters were needed for the beam form work: 4 for installation and 1 for dismantling. The column forms need to be installed a total of 9 times considering that the building is 25 stories tall. Considering all of the 13 buildings, a total of 819 carpenters were needed. The beam forms need to be installed for every floor, and considering all of the 13 buildings, a total of 1,642 carpenters were needed. Therefore, the total number of carpenters for form work needed by the completion of the framework amounted to 2,444 workers. Assuming the unit cost paid to a carpenter at site is KRW 130,000, the total cost spent on the form work amounted to KRW 317,720,000. The unit cost of installation per 1m^3 was KRW 1,899, calculated by dividing the labor cost of KRW 317,720,000 by the entire installation area of forms of 167,276m^3 .

The construction cost for the in-situ production form per 1m^3 was KRW 3,441, and was calculated by adding the unit manufacturing cost of KRW 1,542 to the unit cost installation or dismantling of KRW 1,899.

In Table 7, the unit costs of structural work (GF and bearing-wall structure) calculated considering the work productivity and material costs are summarized.

Table 7. Unit cost of the structural work(GF)

Work	Item	Unit	Unit cost		
			Materials	Labor	Total
Con'c work	Con'c	won/m^3	54,300	8,000	62,300
	Curing	won/m^3	6991	6,606	13,597
Reinforcement work	HD10	won/ton	860,000	-	860,000
	HD13	won/ton	850,000	-	850,000
	HD16~	won/ton	840,000	-	840,000
	Fabrication (RC)	won/ton	5,000	175,000	180,000
	Fabrication (PC)	won/ton	5,000	105,000	110,000
	steel	won/ton	-	-	1,400,000
Form work	Outer form of ext. wall	won/m^2	-	-	25,000
	Form for int. wall	won/m^2	-	-	1,5000
	Form for slab	won/m^2	-	-	18,000
	Cleaning and form oil	won/m^2	-	-	1,000
	Shoring work	won/m^2	-	-	5,600
	Joint form	won/EA	1,600	11,667	13,267
	Steel form	won/m^2	1,542	1,899	3,441
	Deck plate	won/m^2	-	-	21,000

4.2 Structural work cost of typical floor (bearing-wall structure)

The unit costs analyzed in Section 4.1 were applied to the quantities of the structural work (bearing-wall structure) calculated earlier. Table 8 indicates the structural work cost of typical floor (bearing–wall structure), amounting to KRW 73,100,162.

Table 8. Structural work cost of typical floor (bearing wall structure)

Unit : 1,000 won

Work	Item	Unit	Qnt	Unit price	Cost
Con'c work	Con'c	m^3	255	62	15,907
Reinforcement work	HD10	ton	11.7	860	10,081
	HD13	ton	10.0	850	8,458
	HD16	ton	1.4	845	1,203
	Fabrication	ton	23.1	180	4,157
Form work	Outer form of ext. wall	m^2	314	26	8,176
	Form for int. wall	m^2	701	16	11,221
	Form for slab	m^2	565	19	10,733
	Shoring work	m^2	565	6	3,163
	Total				73,100

Table 9. Structural work cost of typical floor(GF)

Unit : 1,000 won

Work	Item	Unit	Qty	Unit price	Cost
Con'c work	Con'c	m^3	128	62	7,973
	Curing	m^3	45	14	617
Reinforcement work	HD10	ton	2.8	860	2,362
	HD13	ton	0.3	850	262
	HD16	ton	-	845	-
	HD19	ton	3.5	845	2,974
	HD22	ton	5.0	845	4,244
	Fabrication (RC)	ton	1.6	180	280
	Fabrication (PC)	ton	10	110	1,105
	Steel of column	ton	4	1,400	5,712
	Steel of beam	ton	2	1,400	3,282
Formwork	Joint form	EA	39	13	517
	Steel form	m^2	515	3	1,771
	Deck plate	m^2	565	21	11,862
	Total				42,960

4.3 Structural work cost of typical floor (GF)

The unit costs shown in Table 7 were applied to the quantities of the structural work (GF) calculated earlier. The structural work cost of typical floor (GF) of the case project is shown in Table 9, amounting to KRW 42,960,063.

4.4 Analysis of additional cost by characteristics of structural type

KRW 2,500 was applied as the actual cost of the surface treatment per 1m^2 added to the bearing–wall structure. KRW 32,000 was applied as the actual cost of light–weight dry wall per 1m^2 used for GF. For the cost for the external wall per 1 m^2, KRW80,000 was applied, which was given by a manufacturer. Likewise, as the PC installation cost per 1m^2, KRW 46,000 of the actual unit cost was applied.

The unit cost of tower crane equipment was calculated by dividing the total equipment cost spent for the entire construction by the number of stories.

1) Tower crane cost of structural type (bearing–wall structure)

Han et al.[6] suggested 12 days taken to do structural work for an apartment as the optimal process. However, in this study 13 days were applied as the construction duration per floor of the bearing wall structure, considering float time. Therefore, assuming 30 days are taken to complete the bottom floor, 13 days are taken to complete a standard floor and 30 days are taken to complete the top floor, it takes 372 days or 12.5 months to complete the framework of a 25–story building. According to the construction plan of the case project, a total of 8 tower cranes were used, costing KRW 1,082,766,000 when transportation cost, installation and dismantling cost and rental cost of tower cranes is taken into account. The tower crane cost per floor is shown in Table 11, and amounts to KRW 3,331,588, which is calculated by dividing the total cost of tower crane equipment by 25 stories of 13 buildings.

2) Tower crane cost of structural type(GF)

Lee et al.[7] suggested 4 days as the shortest construction period for GF. However, in this study 7 days were applied as the construction duration per floor, considering the time taken for the curing and installation of dry walls. Therefore, if we assume 15 days taken to complete the bottom floor and 7 days taken to complete a standard floor, it takes 183 days or about 6 months to complete the framework of a 25-story building. To deal with the increase in lifting load caused by the PC installation, one tower crane was used for each building. The total cost of tower crane equipment was calculated as KRW 1,133,226,000. The tower crane cost per floor was shown in Table 10, amounting to KRW 3,486,846 and calculated in the same manner as for the bearing wall structure.

Table 10. T/C cost per floor

Structural type	Bearing wall	GF
T/C type	LIEBHERR 290HC	LIEBHERR 290HC
No. of T/C	8	13
Months of operation	12.5	6
Total equipment·months	100	78
Rental cost (won)	1,082,766,000	1,133,226,000
Rental cost per floor (won/floor)	3,331,588	3,486,849

In this way, when the additional costs by characteristics of each structural type are applied to the quantities obtained earlier, the cost was calculated as KRW 5,566,753 for the bearing-wall structure and as KRW 34,469,460 for GF.

Table 11. Additional cost caused by characteristics of each structural type

Unit : 1,000 won

Work	Item	Unit	Bearing wall			GF		
			Qty	Unit price	Cost	Qty	Unit cost	Cost
Finish work	Surface treatment (ext. wall)	m^2	475	2.5	1,187	-	-	-
	Surface treatment (int. wall)	m^2	419	2.5	1,048	-	-	-
	Dry-wall (ext. wall)	m^2	-	-	-	213	80.0	17,055
	Dry-wall (int. wall)	m^2	-	-	-	369	32.0	11,839
PC installation		m^3	-	-	-	45	46.0	2,089
Tower crane		floor	1	3,332	3,332	1	3,487	3,487
Total					5,567			34,469

4.5 Comparison of construction cost

Table 12 shows the results comparison between the construction cost considering construction cost and additional cost of each structural type together.

Compared to the bearing-wall structure, the construction cost of GF was reduced by KRW 30,140,099, or 41%. This was due to the characteristics of GF, including the fact that the walls were replaced by columns and beams, that the slabs were thinner to reduce the quantity of concrete and rebars used, and that the forms were reused several times.

To conduct an equivalent comparison, the additional costs were considered: the tower crane cost was added differently according to the characteristics of each structural type, the surface treatment cost was added for the bearing-wall structure, and the light-weight dry wall cost and the PC installation cost were added for the GF structure. When the additional costs are considered, the cost of GF increased by approximately 419% compared to the bearing-wall structure. This is because dry walls are much more expensive than the cast-in-place concrete system.

However, in terms of the entire construction cost determined by adding all the expenses, the construction cost of GF is reduced by KRW 1,237,392, or about 1.57% compared to the bearing-wall structure.

Table 12. Cost comparison of the structural work

Unit : 1,000 won

Description	Work	Item	Bearing wall	GF	Difference
Structural work	Con'c work	Con'c	15,907	7,973	- 7,934
		Curing	-	617	617
	Reinforcement work	HD10	10,081	2,362	- 7,719
		HD13	8,458	262	- 8,197
		HD16	1,203	-	- 1,203
		HD19	-	2,974	2,974
		HD25	-	4,244	4,244
		Fabrication (RC)	4,157	280	- 3,878
		Fabrication (PC)	-	1,105	1,105
		Steel of column & beam	-	8,994	8,994
	Form work	Outer form of ext. wall	8,176	-	- 8,176
		Form for int. wall	11,221	-	- 11,221
		Form for slab	10,733	-	- 10,733
		Shoring work	3,163	-	- 3,163
		Joint form	-	517	517
		Steel form	-	1,771	1,771
		Deck plate	-	11,862	11,862
	[Subtotal]		**73,100**	**42,960**	**-30,140**
Additional quantity	Finish work	Surface treatment (ext. wall)	1,187	-	- 1,187
		Surface treatment (int. wall)	1,048	-	- 1,048
		Dry-wall (ext. wall)	-	17,055	17,055
		Dry-wall (int. wall)	-	11,839	11,839
	PC installation		-	2,089	2,089
	Tower crane		3,332	3,487	155
	[Subtotal]		**5,567**	**34,469**	**28,903**
	[Total]		**78,667**	**77,430**	**- 1,237**

5. Conclusion

To practically apply a new method like GF to an actual site, economics should be verified and secured through cost analysis. Therefore, a comparative analysis should be performed of the construction costs for the bearing-wall structure and GF, after calculating each unit cost applied. The findings of this study are as follows.

First, work types were identified according to the characteristics of each structural type. The additionally considered items were defined to perform an equivalent comparison due to the replacement of the cast-in-place concrete wall with dry walls.

Second, a case project was selected to calculate the quantity of structural materials needed for each structural type. The structural work of GF has good constructability and requires less material to complete compared to the bearing-wall structure.

Third, construction costs were calculated and compared between GF and the bearing-wall structure through a quantity analysis. Through this comparison, it was found that the construction cost of GF was 1.57% lower compared to the bearing-wall structure. Even assuming that a 1.57% reduction in cost is within the possible tolerance error, GF can be constructed with a construction cost equivalent to that of building a bearing-wall structure. On the other hand, if the flat plate structure currently in wide use to secure the flexibility of apartment units is used, the construction cost tends to increase by 5.6~28.6% compared to that required a bearing-wall structure[12]. For this reason, GF is more appropriate for application to apartment building construction for two reasons: it offers better flexibility than the flat plate structure and can be constructed at an equivalent construction cost to a bearing–wall structure. It is expected that this research can be utilized as fundamental data in improving structural types, to reduce costs and develop elemental technologies in the future.

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