A STUDY OF STRUCTURAL MATERIAL QUANTITIES OF HIGH-RISE RESIDENTIAL BUILDINGS

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ABSTRACT

A major factor in the selection of the structural system for a high-rise building is the initial construction cost of candidate structural systems. This paper compares material quantities for representative building models up to 80 stories in height using both types of structural system. Based on a typical floor plan, six models are developed and the buildings are designed for gravity and lateral loading. Quantities of materials for each model are calculated and compared. The information presented can be used with appropriate cost data to compare construction costs for the two structural system types.

Keywords: Material quantity, Structural design, high-rise, Residential building, Structural system

1. INTRODUCTION

Most of the early high-rise buildings were built with composite steel and concrete structural systems. More recently concrete flat plate systems have been used. A major factor in the selection of the structural system for a particular project is the initial construction cost. However there is a lack of quantitative data to assist the engineer in making a selection. In this paper selected buildings that have been constructed in recent years are examined to determine typical floor plan arrangements and dimensions as well as typical span lengths and column spacing. Based on this exercise a representative floor plan is developed and structural designs are prepared for six models representing composite construction and concrete flat plate construction up to 80 stories in height. Material quantities are then calculated and compared. In future, these material quantities along with relevant cost data can be used compare overall construction cost for each system.

2. STRUCTURAL PLAN OF HIGH-RISE RESIDENTIAL BUILDINGS

2.1. Building models for analysis

Based on the study of existing buildings outlined, a typical building plan was developed as shown in Figure 1for both a composite steel framing system and a cast-in-place concrete slab system. The

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floor plan contains a central core along with columns on the exterior of the building. Overall plan width and depth are each 35 m and the central core is 14 m square. The distance between columns ranges from 8.0 m to 11.1 m. Details of the building models are summarized in Table 1 Three building heights are considered: 40, 60, and 80 stories. In each case the number of underground levels is fixed at 5 for underground parking and commercial use. Floors above ground are assumed to be residential.

Table 1: Building models for structural designs

Model	Stories		Height (m)	Plan dimension (m)	Frame material
	Above ground	Below ground			
S40	40	5	129.5	35× 35	composite
C40	40	5	129.5		concrete
S60	60	5	197.5		composite
C60	60	5	197.5		concrete
S80	80	5	265.5		composite
C80	80	5	265.5		concrete

3. STRUCTURAL DESIGNS FOR ANALYSIS

3.1. Structural scheme

The structures were designed according to the Korean building code requirements for structural concrete and commentary (KCI 2003), Korean standard minimum design loads for buildings and other structures (AIK 2002), and manual of steel structures: LRFD (Ministry of construction and transportation 1997). Computer programs MIDAS GENw, MIDAS SDSw, and MIDAS SET (MIDAS 2003) were used for structural analysis. Design loads, especially earthquake and wind loads are calculated assuming that the location is Seoul, Korea; i.e. exposure category is taken as B, and response modification factor is set to be 4.0 since both composite and concrete buildings have concrete structural walls. Damping ratios are assumed to be 2.5% for composite buildings and 3% for concrete buildings. Lateral displacement is limited to H/500, where H is the height of the building models (Taranath 1997). The floor where the outrigger system is constructed has a 6.4 m story height and the floor below has a 4 m story height.

3.2. Structural design

For detailed member design, construction sequences and stress variations due to installation of outrigger systems are considered. The following construction sequences for steel building models are assumed:

1. Composite columns, steel beams, and deck slabs are constructed consecutively after completion of three levels' shear walls.
2. After completion of frame construction, outrigger systems are constructed.
3. Apply finishing loads and live loads to the building.

Table 2: Design strengths for structural members

Material	Members	Design strength
Concrete	Column and wall	f_{ck} = 26 N/mm^2 - 59 N/mm^2
	Beam and slab	f_{ck} = 24 N/mm^2
	Foundation	f_{ck} = 34 N/mm^2
Reinforcement	Beam, column, wall and slab	KS SD40 (f_y= 392 N/mm^2)
	Foundation	KS SD50 (f_y= 490 N/mm^2)
Steel	Column	SM490 (f_y= 325 N/mm^2)*, SM520 (f_y= 355 N/mm^2)
	Beam	SS400 (f_y= 235 N/mm^2)**, SM490 (f_y= 325 N/mm^2)*
*: if thickness exceeds 40 mm, f_y= 295 N/mm^2 **: if thickness exceeds 40 mm, f_y= 215 N/mm^2		

(a) Composite model **(b) Concrete model**

Figure 1 Typical plans for structural design

Table 3: Lateral resistance systems of building models

Model	Structural system	
	Lateral force resisting system	Outrigger system
S40	composite column + concrete shear wall	N/A
C40	concrete column + concrete shear wall	N/A
S60	composite column + concrete shear wall + outrigger and belt truss system	Installed in 31st floor.
C60	concrete column + concrete shear wall + outrigger and belt wall system	Installed in 31st floor.
S80	composite column + concrete shear wall + outrigger and belt truss system	Installed in 20th, 40th and 60th floor.
C80	concrete column + concrete shear wall + outrigger and belt wall system	Installed in 27th and 54th floor.

Table 4: Design results of outrigger and belt truss systems of composite models

Member		Design result	
		composite60	composite80
Outrigger	Brace(CFT)	□-700×700×30	□-1200×1200×70
	Upper/lower chord	50BH-600×600×30×40	50BH-600×600×30×40
Belt truss	Brace	H-300×300×10×15	H-300×300×10×15
	Upper/lower chord	H-588×300×12×20	H-588×300×12×20
- BH = Built-up wide flange steel beam			

Table 5: Design results of outrigger and belt wall systems of concrete models

Member		Design result	
		concrete60	concrete80
Outrigger	Brace (CFT)	□-500×500×30	□-1200×1200×70
	Upper/lower chord	900 mm × 900 mm	900 mm × 900 mm
Belt wall	Thickness	300mm	300 mm
	Upper/lower chord	1500 mm × 600 mm	1500 mm × 600 mm

Table 6: Design results of columns of concrete models

	C40		C60		C80	
	RC1	RC2	RC1	RC2	RC1	RC2
Levels below ground	1700× 1700	1500× 1500	1800× 1800	1600× 1600	2200× 2200	1800× 1800
1st level above ground	1600× 1600	1400× 1400	1700× 1700	1500× 1500	2200× 2200	1800× 1800
Top level above ground	800× 800	700× 700	900× 900	800× 800	1200× 1200	1000× 1000

Table 7: Design results of shear walls

Model		Wall thickness (mm)			
		W1,W2,W3,W4	W5,W6	W7	W8
S40		400	300	200	200
C40		500	300	200	200
S60		600	400	250	200
C60		600	400	250	200
S80		1200	800	300	300
C80	5th level below ground – 28th level above ground	1200	800	300	300
	29th – 54th level above ground	900	600	300	300
	55th – 80th level above ground	600	400	300	300

Table 8: Design results of columns of composite models

	S40		S60		S80	
	RSC1	RSC2	RSC1	RSC2	RSC1	RSC2
Levels below ground	900× 900	800× 800	1000× 1000	900× 900	1200× 1200	1000× 1000
1st level above ground	900× 900	800× 800	900× 900	800× 800	1200× 1200	1000× 1000
Top level above ground	700× 700	700× 700	700× 700	700× 700	800× 800	700× 700

4. QUANTITIES OF STRUCTURAL MATERIALS

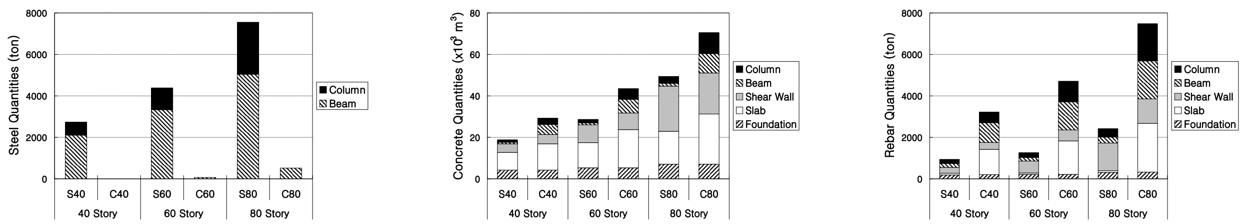
Quantities of structural materials were calculated from the structural design results in order to analyze the variation of material quantities by structural system and number of floor levels. The material quantities included weights of steel and concrete, volume of concrete, and areas of form and deck plate, the main contributors to initial construction cost. Comparisons of quantities in terms of structural members such as column, beam and slab are also presented.

Calculated quantities of materials are summarized in Table 9 in terms of total quantity, quantity per unit area, and ratio of quantities in concrete frame to quantities in composite frame. The quantities are presented graphically in Figure 4 to illustrate trends related to both structural system and number of stories.

Table 9: Structural material quantities of structural models

Material	Quantity	40 story model		60 story model		80 story model	
		S40	C40	S60	C60	S80	C80
Steel	Quantity (ton)	2,736	0	4,386	65	7,551	519
	Quantity per unit area (kg/m^2)	49.63	0	55.08	0.82	72.52	4.98
	Quantity comparison (concrete frame/composite frame)	-	0.0	-	0.015	-	0.069
Reinforcement	Quantity (ton)	1,055	3,587	1,409	5,262	2,786	8,450
	Quantity per unit area (kg/m^2)	19.14	65.07	17.70	66.09	26.76	81.15
	Quantity comparison (concrete frame/composite frame)	-	3.40	-	3.74	-	3.03
Concrete	Quantity (m^3)	18,820	29,254	28,680	43,512	49,354	70,527
	Quantity per unit area (m^3/m^2)	0.34	0.53	0.36	0.55	0.47	0.68
	Quantity comparison (concrete frame/composite frame)	-	1.55	-	1.52	-	1.43
Form	Quantity (m^2)	40,277	96,142	54,088	137,215	72,295	188,644
	Quantity per unit area (m^2/m^2)	0.73	1.74	0.68	1.72	0.69	1.81
	Quantity comparison (concrete frame/composite frame)	-	2.39	-	2.54	-	2.61
Deck plate	Quantity (m^2)	49,000	0	73,500	0	98,000	0
	Quantity per unit area (m^2/m^2)	0.89	0	0.92	0	0.94	0

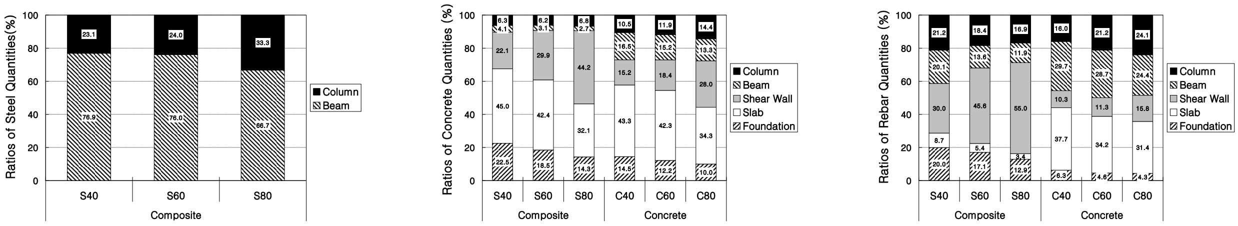
Structural steel is a major component of the composite system as indicated in figure 4 (a). On the other hand, for the cast-in-place concrete system, structural steel is only required for concrete-filled tubes used for the outrigger systems and represents a relatively small contribution to overall cost. As indicated in Figure 4 (b) the amount of concrete required for structural walls increases relative to the amount of concrete in slabs as the building height increases. As shown in Figure 4 (c) the amount of reinforcement required in the concrete system increases rapidly with building height and less so for the composite system. The concrete structure requires more formwork than the composite structure as expected but the quantity of formwork per unit of floor area remains fairly constant as the number of stories increases as indicated in Table 9. Similarly the deck plate per unit area for the composite system remains approximately constant as the number of stories increases.



(a) Steel quantity (b) Concrete quantity (c) Reinforcement quantity

Figure 4: Structural material quantities of high-rise buildings

The distribution of material quantities among the various structural members is presented in Figure 5. For the composite system the amount of steel in columns relative beams increases with building height as shown in Figure 5 (a). Similarly the relative amount of concrete in structural walls increases with height for both systems as expected due to increasing gravity and lateral loads as the building height increases. On the other hand the relative amount of concrete in the foundation decreases as the building height increases. Similar trends are seen in reinforcement quantities as shown in Figure 5 (c).



(a) Steel (b) Concrete (c) Reinforcement

Figure 5: Ratios of structural material quantities of high-rise buildings

5. SUMMARY AND CONCLUSIONS

This study has provided data on the relative amounts of materials required for high-rise residential buildings up to 80 stories in height using both composite construction and cast-in-place concrete construction. The study indicated that structural walls are adequate for lateral resistance in buildings up to 40 stories. For buildings of 60 and 80 stories outrigger systems were used to provide additional lateral stiffness to satisfy drift limitations. The data developed on material quantities are presented in both tabular and graphical form and various trends have been noted. Using appropriate unit cost values comparative estimates of initial construction costs can be obtained.

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