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The Quantity Variations of the High-Strength Reinforcing Bars on the Underground Parking in a Rigid-Frame Building

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Abstract
It is dealt with the quantity variations of high-strength reinforcing bars in the underground parking spaces. The purpose of this study is to investigate the quantity variations of the high-strength reinforcing bars on the underground parking spaces in a rigid-structure building. Recently, constructing high-rise buildings and long-span structure in the architecture, engineering, and construction industry (AEC industry). However, there are a number of difficulties such as excessive reinforcing bars arrangement, failure of concrete quality management, unnecessary quantity take-off and so forth, when these types of structures and buildings are formed utilising normal strength reinforcing bars and concrete. As skyscrapers and long-span structures are getting more common in the AEC industry, it is widely applied high strength reinforcing bars, cement and supplementary materials to sustain durability and stability. The test results indicate that it would be possible to achieve the reduction of reinforcing bars arrangement and lowering the amount of bar arrangement when the high-strength rebars were applied to the underground parking spaces in a rigid-frame structure. Moreover, the reduced amount of bar arrangement will make it possible to improve workability and constructability of reinforced concrete structures.

INTRODUCTION

While it is popular to build skyscrapers and long-span structures in recent years, there might be a number of problems and difficulties such as deterioration of concrete placement quality, unnecessary quantity take-off on reinforcement and so forth to construct such buildings and structures using normal strength reinforcing bars and concrete. As high-rise buildings and long-span structures are getting more common in this field of work, it is popular to apply high-strength materials such as high-strength reinforcing bars, carbon fibre, and high-strength cement to sustain durability and stability. When such high-strength materials are utilised in large scale structures, it would be beneficial for contractors to lower the input of materials and to shorten the construction time. For example, it would be possible to reduce the quantity and size of arranging reinforcing bars and to simplify the details of connections, splice or development between them. As a result, it would be able to attain more durable structures and buildings with reduced construction time and more constructible methods.

Korea Concrete Institute (KCI) in South Korea regulates the usage of reinforcing bar strength as not exceeding 550MPa for the main reinforcement and 400MPa for the shear reinforcement bars. Based on these regulations, it is widespread to apply SD400 reinforcing bars to construct buildings and structures in South Korea. As it is getting common to build high-rise and long-span structures, it is required to consider implementing high-strength materials especially high-strength concrete and reinforcing bars. According to the revised Structural Concrete Design Code and Commentary (KCI, 2012) in South Korea, KCI revise the maximum tensile strength of reinforcing bars from 550MPa to 600MPa. Besides, SD500 and SD600 tensile strength rebars are recommended to apply in high-strength concrete by KCI. However, research regarding high-strength reinforcing bars in practice is rare and it is needed to investigate the usefulness and effectiveness. The main goal of this study is to verify the usefulness and effectiveness of SD500 and SD600 rebars in the underground parking spaces in a rigid-frame structure which are common to buildings in the town centre.

RESEARCH BACKGROUND

The purpose of this research is to investigate the quantity variations of high-strength rebars on underground parking spaces in rigid frame structures, which are popular to construct for offices, apartments and commercial buildings in South Korea. In this study, we explored the quantity variations (the pure quantity, development and splice) using high-strength rebars on beams, columns, walls and footings.

The reinforcing bars applied in the main reinforcement were SD400, SD500 and SD600, and the shear reinforcement rebars were also SD400, SD500 and SD600 of the tensile strength. As for the main reinforcement with SD600 rebars, the shear reinforcement was applied to SD500 reinforcing bars. This research also examined the effect of reinforcement bars' diameters. The size variables in this study were D10, D13 and D16 which are common to use high-rise buildings and long span structure in the AEC industry. Specifically, all the variables (D10, D13 and D16) was applied to SD400, SD500 and SD600 specimens. D13 and D16 were examined the specimens with SD400 rebars. Reinforcing bars over D16 were implemented SD400, SD500 and SD600 tests. Cases of D10 and D13 were examined with SD500 rebars, and over D16 reinforcing bars were combined with SD500 and SD600 samples. The tested members in this study are summarised in Table 1.

Table 1. The details of the tested model

Items	Slab		Beam and Girder		Column		Wall		Retaining wall		Footing	
Underground parking spaces	Main rebar	Shear rebar	Main rebar	Shear rebar	Main rebar	Shear rebar	Main rebar	Shear rebar	Main rebar	Shear rebar	Main rebar	Shear rebar
	o	X	o	o	o	o	o	x	o	x	o	x

Details of the structures

The summary of the studied model is summarised in Table 2. The floor plan of this research is also depicted in Figure 1.

Table 2 Structural summary of the studied model

Purpose	Number of stories (Ground/basement)	Structural type	Footing type	Concrete compressive strength (MPa)
Underground parking space	0 / 1	Rigid-frame	Bearing capacity of soil (Mat footing)	$f_{ck} = 24MPa$

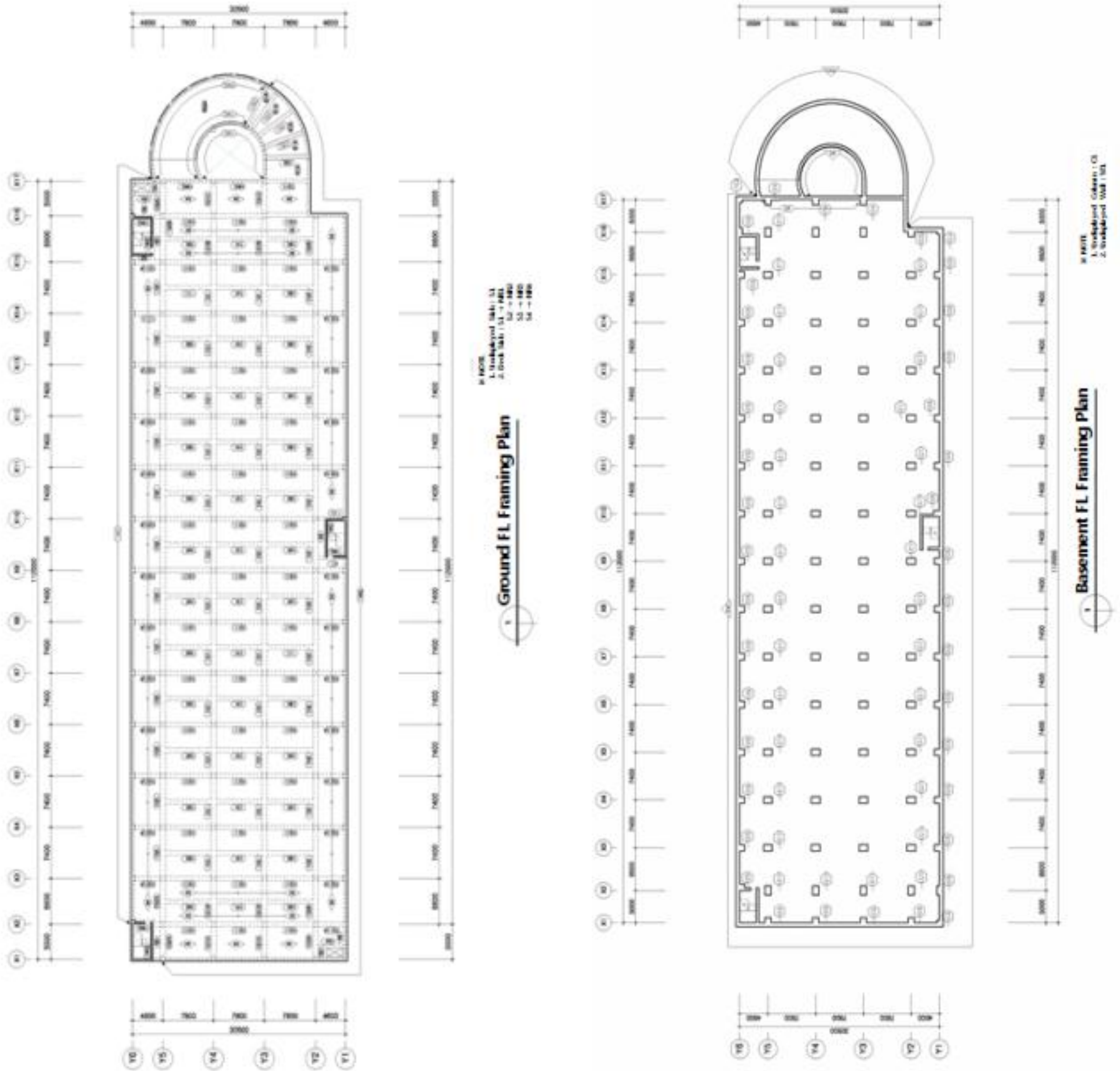

Figure 1. Floor plan of the underground parking (Left: ground floor, Right: basement floor)

APPLICATION OF THE DESIGN CODES

All the specimens in this research was designed in compliance with Structural Concrete Design Code and Commentary by Korea Concrete Institute (KCI,2012; KBC, 2009; AKI, 2009).

Analysis of the reference of codes

Main reinforcement

1. *Beams*
   1) Nominal flexural strength at section

      $M_n = \rho f_y b d^2 (1 - 0.59 \frac{\rho f_y}{0.85 f_{ck}})$

      M_n : Nominal flexural strength at section
      f_{ck}: Specified compressive strength of concrete, *MPa*
      f_y: Specified yield strength of reinforcement, *MPa*
      ρ: Tension reinforcement ratio
      b: Width of compression face of member, *mm*
      d: Effective depth, *mm*

   2) Minimum reinforcement ratio

      $$\rho_{min} = \frac{0.25\sqrt{f_{ck}}}{f_y}, f_{ck} > 30MPa$$

      $$\rho_{min} = \frac{1.4}{f_y}, f_{ck} \leq 30MPa$$

      SD400 is 0.35%, SD500 is 0.28% or lower than 20%, and SD600 is 0.23 % or lower than 33.3%

   3) Minimum allowable strain

      $f_y = 400MPa$ Minimum allowable strain: 0.004, Reinforcement ratio: $0.714\rho_b$
      $f_y = 500MPa$ Minimum allowable strain: 0.005 ($2\epsilon_y$), Reinforcement ratio: $0.688\rho_b$
      $f_y = 600MPa$ Minimum allowable strain: 0.005 ($2\epsilon_y$), Reinforcement ratio: $0.667\rho_b$

   4) Designing beam components
      - Design of non-seismic structures as single beam reinforced concrete, and composite reinforcing bars should be applied to two for minimum bar arrangement
      - Design of composite parts in seismic structures should be considered the lateral loads.

   5) Consideration of space for cracks control

2. *Slabs*
   1) Shrinkage and temperature reinforcement

      $When\ f_y \leq 400MPa \rightarrow 0.002$

      $When\ f_y > 400MPa \rightarrow 0.002 \times \frac{400}{f_y}$

      $f_y = 400MPa: 0.02, f_y = 500MPa: 0.0016, f_y = 600MPa: 0.0013 \rightarrow 0.0014$

      Maximum bar space: 3 times of slab depth or less than 450mm

   2) Limit of space for cracks control (1 way slabs)
   3) Bars arrangement for horizontal load

3. *Columns: calculating the amount of reinforcement for compression members*
   a) $P_{n,max} = 0.8 \times [0.85 f_{ck}(A_g - A_{st}) + f_y A_{st}]$

      $A_g: Gross\ area\ of\ concrete\ section, mm^2$

      $A_{st}: Total\ area\ of\ nonprestressed\ longitudinal\ reinforcement,, mm^2$

   b) Minimum and maximum reinforcement ratio $0.01 \leq \rho \leq 0.08$
   c) If a structure is high-rise and the section of the column is same in all floors, the dominant reinforcement ration is minimum reinforcement under certain conditions.
   d) When high strength reinforcing bars are used, it would be required to adjust the section of the column if we want to reduce the input of reinforcing bars.

4. *Walls: core walls*
   1) Horizontal reinforcement: the regulation is equal spacing (No reinforcing bars in section)
   2) Vertical reinforcement

      Under D16: 0.12% Exceeding D16: 0.15%

      Horizontal reinforcement

      Under D16: 0.2% Exceeding D16: 0.25%

      Limitation

      Vertical reinforcement: horizontal length of the wall/5, three times of the depth, or 450mm

      Horizontal reinforcement: horizontal length of the wall/3, three times of the depth, or 450mm
   3) There is no regulation in terms of reinforcement in wall regardless of f_y. Thus, the amount of high-strength reinforcing bars is same as the amount of SD400. Moreover, the efficiency would be lowered if the amount of minimum reinforcement would be increased.
5. *Footings*
   1) Design of footings should comply with the code of flexural members.

      $When\ f_y \leq 400MPa\ is\ 0.002$

      $When\ f_y > 400MPa\ is\ 0.002 \times \frac{400}{f_y}$

      $$f_y = 400MPa: 0.002, f_y = 500MPa: 0.0016, f_y = 600MPa: 0.00133 \rightarrow 0.0014$$
   2) When SD500 is used, f_y would be reduced 20 %, and when SD600 is applied, f_y would be deducted to 33.3 %.
   3) The type of footing is soil bearing capacity of mat foundations.
6. *Deflection*

   There are none of variables affecting deflection, when we use high strength reinforcing bars. However, the deflection would be slightly increased when the high strength reinforcing bars are used, since the cracked moment of inertia is decreased. In this study, each specimen was designed in consideration of deflection and the value was relatively small and negligible.
7. *Cracks*
   1) Reinforcement space of controlling cracks

      $S = 375\left(\frac{210}{f_s}\right) - 2.5C_c, S = 300\left(\frac{210}{f_s}\right), but\ f_s = (2/3)f_y$

      $C_c: Clear\ cover\ of\ reinforcement, mm$

      $f_s: Calculated\ tensile\ stress\ in\ reinforcement\ at\ service\ loads, MPa$
   2) If the section of beams is large, especially the width of beam is large, the tests were carried out in consideration of reducing the diameter of the reinforcing bars.
   3) Intervals of controlling cracks on slabs

      When SD400 is used, it is 235mm

      $$min\left[375 \times \frac{210}{266.66}\right] - 2.5 \times 20 = 245.31mm, 300 \times \frac{210}{266.66} = 236.26mm$$

      When SD500 is used, it is 186mm

      $$min\left[375 \times \frac{210}{333.33}\right] - 2.5 \times 20 = 186.25mm, 300 \times \frac{210}{333.33} = 195.3mm$$

      When SD600 is used, it is 146mm

      $$min\left[375 \times \frac{210}{400}\right] - 2.5 \times 20 = 146.87mm, 300 \times \frac{210}{400} = 157.5$$
   4) Intervals of controlling cracks on beams

      When SD400 is used, it is 170mm

      $min\left[375 \times \frac{210}{266.66}\right] - 2.5 \times 50 = 170.31mm, 300 \times \frac{210}{266.66} = 236.55mm$

      When SD500 is used, it is 136mm

      $min\left[375 \times \frac{210}{333.33}\right] - 2.5 \times 50 = 111.25mm, 300 \times \frac{210}{333.33} = 189.00mm$

      When SD600 is used, it is 71mm

$$min\left[375\times\frac{210}{400}\right]-2.5\times 20=71.875mm, 300\times\frac{210}{400}=157.5mm$$

8. *Development and splice*
   1) The development length
      a) Development length for deformed bars in compression: $l_{db}=\frac{0.25d_b f_y}{\lambda\sqrt{f_{ck}}}$
      b) Development length for deformed bars in tension: $l_{db}=\frac{0.90d_b f_y}{\lambda\sqrt{f_{ck}}}\frac{\alpha\beta\gamma}{\left(\frac{c+K_{tr}}{d_b}\right)}$
      c) Development length for standard hooks in tension: $l_{hb}=\frac{0.24\beta d_b f_y}{\lambda\sqrt{f_{ck}}}$

$d_b: Nominal\ diameter\ of\ bar, mm$
$\alpha: Reinforcement\ location\ factor$
$\beta: Coating\ factor$
$\lambda: Light-weight\ aggregate\ concrete\ factor$
$\gamma: Reinforcement\ size\ factor$
$c: Spacing\ or\ cover\ dimension$
$K_{tr}: Transverse\ reinforcement\ index$

   2) Beams: Applied to the general design codes
   3) Vertical members: Applied seismic resistance design
   4) Slabs: Applied 1 way slab design code
   5) Footings: Applied codes in accordance with the design code of beams

Shear reinforcement

1. *Beams*
   1) The strength of concrete with shear and flexural moment

$V_c=\frac{1}{6}\sqrt{f_{ck}}b_w d$

   2) Space of shear reinforcement
      a) $V_u<\frac{\emptyset V_c}{2}: Shear\ reinforcement\ is\ not\ required$
      b) $\frac{\emptyset V_c}{2}<V_u\le\emptyset V_c: Shear\ reinforcement\ is\ required$

$When\ shear\ reinforcement\ is\ requred, min\left[600,\frac{d}{2}, or\ s=\frac{A_v f_y}{0.35b_w}\right]$

      c) $\emptyset V_c<V_u\le\emptyset V_c+\emptyset\frac{1}{3}\sqrt{f_{ck}}b_w d: Shear\ reinforcement\ is\ required$

$When\ shear\ reinforcement\ is\ required,$
$min\left[600,\frac{d}{2}, s=\frac{A_v f_y}{0.35b_w}, or\ S=\frac{\emptyset A_v f_y d}{\emptyset V_s}\right]$

      d) $\emptyset V_c+\emptyset\frac{1}{3}\sqrt{f_{ck}}b_w d<V_u\le\emptyset V_c++\emptyset\frac{2}{3}\sqrt{f_{ck}}b_w d$

$: Shear\ reinforcement\ is\ required$
$When\ shear\ reinforcement\ is\ required,$
$min\left[300,\frac{d}{4}, or\ S=\frac{\emptyset A_v f_y d}{\emptyset V_s}\right]$
Then, $V_s=\frac{A_v f_y d}{s}$

   3) Minimum shear reinforcement

All the flexural members (The factored shear strength (V_u) is not exceeded a half of the minimum shear strength) should place shear reinforcement.

$A_{v,min}=0.625\sqrt{f_{ck}}\frac{b_w s}{f_{yt}}$

However, the minimum shear reinforcement V_s should not exceed $0.35b_w\ s/f_{yt}$

   4) Maximum shear strength V_s should lower than $\left(2\sqrt{f_{ck}}/3\right)b_w d$

2. *Columns*
   1) The strength of compressive axial force members
      $$V_c = \frac{1}{6}\left(1 + \frac{N_u}{14A_g}\right)\sqrt{f_{ck}}b_w d$$
   2) Space of shear reinforcement
      a) $V_u < \emptyset V_c$: Shear reinforcement is not required
      b) $V_u > \emptyset V_c$: Shear reinforcement is required
      c) Shear reinforcement
         - Structures where locate in non-seismic areas
           $$min[main\ reinforcement\ \times\ 16, hoop \times\ 48, or\ half\ of\ the\ minimum\ of\ b\ or\ h]$$
         - Structures where locate in seismic area
           $$min[main\ reinforcement\ \times 16, hoop \times\ \ 24, minimum\ of\ b\ or\ h, or\ 300]$$
   3) Maximum shear strength V_s should be lower than $2\left(2\sqrt{f_{ck}}/3\right)b_w d$
3. *Walls*

   Generally, shear reinforcement in walls is similar to the design of shear reinforcement design in beams. However, there is slight difference of the arrangement in the vertical shear reinforcement, when the space of vertical and horizontal shear reinforcement, and the ration of shear span is very small.
   1) Shear strength V_c would be selected minimum value,
      $$V_c = 0.28\lambda\sqrt{f_{ck}}hd + \frac{N_u d}{4l_w} \text{ or}$$
      $$V_c = \left[0.05\lambda\sqrt{f_{ck}} + \frac{l_w\left(0.10\lambda\sqrt{f_{ck}} + 0.2\frac{N_u}{l_w h}\right)}{\frac{M_u}{V_u} - \frac{l_w}{2}}\right]hd$$
      λ : Light-weight aggregate concrete factor
      h : Overall thickness or height of member, mm
      d : Distance from extreme compression fibre to centroid of longitudinal tension reinforcement, mm
      N_u : Factored axial force normal to cross section occurring simultaneously with V_u or T_u is to be taken as positive for compression and negative for tension, kN
      l_w : Length of entire wall or length of segment of wall considered in direction of shear force, mm
   2) When $V_u > \emptyset V_c$, the arrangement of horizontal shear reinforcement is,
      $$V_s = \frac{A_{vh} f_y d}{S_h}$$
      A_{vh}: Area of shear reinforcement parallel to flexural tension reinforcement within spacing, mm
      S_h : Centre-to-centre spacing of longitudinal shear or torsion reinforcement, mm
   3) Minimum area of reinforcement and spacing
      $V_u \leq \emptyset\, V_c/2$: Comply with a) ~d), or reinforcement of walls
      $V_u > \emptyset\, V_c/2$: Comply with a) ~ d)
      a) $\rho_h = 0.0025$
      b) Reinforcement of horizontal shear force: Lower than $S_h = l_w/5$, $3h$, or $450mm$
      c) $\rho_l = 0.0025 + 0.5\left(2.5 - \frac{h_w}{l_w}\right)(\rho_h - 0.0025)$
      d) Reinforcement of vertical shear force: Lower than $S_v = l_w$, $3h$, or $450mm$

First of all, the splice and pure quantity of reinforcing bars were analysed in order to comprehend the relationships between the different sizes and the strength of the rebars. The used reinforcing bars in this study were applied differently for the parts of the underground parking space. SD400 and SD500 with D10 and D13 diameter reinforcing bars were applied to slabs. When it comes to beams, SD400 with D25, SD500 with D22, and SD600 with D19 were used. The yield strength of the main reinforcement in columns was SD400, SD500 and SD600. All the specimen was manufactured with D22 rebars in columns. The hoops in columns were applied D10 with SD400 and SD500. As for the walls in the basement, the vertical reinforcement was SD400, SD500 and SD600 which D13 and D16 rebars were applied. For the horizontal reinforcing bars, SD400 and SD500 yield strength with D10 and D13 rebars were put in the basement concrete. For footings, D16, D19 and D22 reinforcing bars were used for SD400 and SD500, and D13, D16, and D19 rebars were applied to SD600 specimens. In addition, the relationships between the strength of reinforcing bars and the quantity of them were also considered to corroborate the influence of high-strength rebars on the quantity of reinforcement arrangement. The quantity of reinforcement was examined both the increment of slice and development, and the decrease of reinforcement by member force. The tests were firstly carried out SD400, SD500 and SD600 for all the reinforcing bars. The following tests were conduceted D10 and D13 rebars with SD400 and SD500. Then, SD500 and SD600 tensile strength reinforcing bars were applied to rebars which were more than D16 diameter. Finally, D10 and D13 reinforcing bars were used on SD500 tensile strength reinforcing bars, and SD500 and SD600 rebars were tested with more than D16 diameter reinforcing bars. The test results of this research show in the following section.

The relationships between size and strength of the reinforcing bars

Slabs

The test result indicates that the pure quantity of reinforcing bars in slabs is reduced as the strength of the rebars grows in general. Table 3. The quantity of reinforcement in slabs (Unit: Ton) summarises the quantity of rebars of the pure quantity, splice and development on slabs. As the yield strength of the reinforcing bars was increased, the amount of reinforcing bars on SD500 and SD600 was reduced 20.7 per cent and 30.2 per cent respectively comparing with SD400 rebars.

Table 3. The quantity of reinforcement in slabs (Unit: Ton)

Yield strength	**Diameter**	**Pure quantity**	**Development / splice**	**Total**
SD400	D10	0.93	0.66	0.99
	D13	57.29	4.77	62.06
	D16	7.29	0.79	8.08
	Subtotal	65.5 (100%)	5.6 (100%)	71.1 (100%)
SD500	D10	18.07	1.30	19.37
	D13	29.30	2.96	32.26
	D16	3.02	0.49	3.51
	Subtotal	51.69 (78.9%)	4.75 (84.5%)	56.44 (79.3%)
SD600	D10	26.60	1.97	28.57
	D13	18.66	2.39	21.05
	Subtotal	45.26 (69.1%)	4.36 (77.6%)	49.62 (69.8%)

Beams

The quantity of reinforcement on beams was analysed in three folds. Main reinforcement and shear reinforcement were analysed separately and then the combined amount (the sum of main and shear reinforcement) was examined in the end. The following section displays the analysed data of beams.

Main reinforcement

The overall quantity variations of the main reinforcement on beams were reduced as the yield strength of the reinforcing bars was increased. As seen in Table 4, the pure quantity of reinforcement with SD500 was reduced 21.0 per cent comparing with SD400. When the development and splice were considered, the total quantity was decreased 20.0 per cent. SD600 rebars were also reduced 33.5 per cent of the pure quantity and 26.5 per cent of the total quantity.

Table 4. The quantity of main reinforcement on beams and girders

Yield strength	**Diameter**	**Pure quantity**	**Development / splice**	**Total**
SD400	D25	81.18 (100%)	13.7 (100%)	94.88 (100%)
SD500	D22	64.10 (79.0%)	11.82 (86.3%)	75.92 (80.0%)
SD600	D19	54.02 (66.5%)	7.89 (57.6%)	61.91 (65.3%)

Shear reinforcement

The test results of shear reinforcement on beams were similar to the effect of the high-strength main reinforcement on beams. The quantity of reinforcement, development and splice was reduced as the strength of the reinforcing bars was increased. As seen in Table 5, the pure quantity of reinforcement was lowered as the strength of the reinforcing bars was increased. In addition, the development and splice were reduced when the high-strength rebars were implemented.

Table 5. The quantity of shear reinforcement on beams and girders (Unit: Ton)

Yield strength	**Diameter**	**Pure quantity**
SD400	D13	31.79 (100%)
SD500	D13	25.35 (79.7%)

Combination of the main and shear reinforcement

The combined quantity of the main and shear reinforcement was reduced in all aspects. The total quantity of reinforcement was reduced 20.1 per cent on SD500 and 31.1 per cent on SD600. The test results summarise in Table 6.

Table 6. The combined quantity of main and shear reinforcement on beams and girders (Unit: Ton)

Yield strength	**Main rebar**			**Shear rebar**	**Total**
	Pure quantity	**Development /Splice**	**Subtotal**		
SD400	81.18 (100%)	13.7 (100%)	94.88 (100%)	31.79 (100%)	126.67 (100%)
SD500	64.10 (79.0%)	11.82 (86.3%)	75.92 (80.0%)	25.35 (79.7%)	101.27 (79.9%)
SD600	54.02 (66.5%)	7.89 (57.6%)	61.91 (65.3%)	25.35 (79.7%)	87.26 (68.9%)

Columns

While the pure quantity of reinforcing bars on columns was decreased on SD500 and SD600 comparing with SD400, the amount of reinforcing bars on development and splice was increased. However, the total quantity of rebars on columns indicates reduced tendency since the increment of the pure quantity was slightly larger than the development and splice. As shown in Table 7, the total quantity considering pure quantity of reinforcement, development, splice and hoops were reduced 3.0 per cent on SD500 and 7.2 per cent on SD600 comparing with SD400 reinforcing bars.

Table 7. The quantity of reinforcement in walls (Unit: Ton)

Yield strength	Main rebar			Shear rebar	Total
	Pure quantity	Development /Splice	Subtotal		
SD400	15.79 (100%)	7.36 (100%)	23.15 (100%)	2.54 (100%)	25.69 (100%)
SD500	14.16 (89.7%)	8.23 (111.8%)	23.39 (96.7%)	2.54 (100%)	24.93 (97%)
SD600	12.54 (79.4%)	8.75 (118.9%)	21.29 (92.0%)	2.54 (100%)	23.83 (92.8%)

Walls

The quantity of reinforcing bars on walls is summarised in Table 8. The arrangement of rebars on walls was considered both vertical and horizontal reinforcement. Both horizontal and vertical reinforcement indicate the lowering of the material input even though the quantity of development and splice were increased. SD500 rebars would be able to lower the quantity for 3.8 per cent comparing with SD400 and SD600 was 7.3 per cent lower than SD400 reinforcing bars.

Table 8. The quantity of reinforcement in walls (Unit: Ton)

Yield strength	Vertical rebar			Horizontal rebar			Total
	Pure quantity	Development/ Splice	Subtotal	Pure quantity	Development/ Splice	Subtotal	
SD400	19.74 (100%)	3.85 (100%)	23.59 (100%)	9.28 (100%)	0.48 (100%)	9.76 (100%)	33.35 (100%)
SD500	17.83 (90.3%)	4.37 (113.5%)	22.20 (94.1%)	9.28 (100%)	0.6 (125.0%)	9.88 (101.2%)	33.08 (96.2%)
SD600	16.98 (86.0%)	4.07 (105.7%)	21.05 (89.2%)	9.28 (100%)	0.6 (125.0%)	9.88 (101.2%)	30.93 (92.7%)

Footings

The pure quantity, development, splice and total quantity of reinforcing bars on footings are summarised in Table 9. The test results indicate that 14.4 per cent reduction on SD500 and 27.2 per cent decrease on SD600 comparing with SD400.

Table 9. Quantity of reinforcement in footings (Unit: Ton)

Yield strength	Diameter	Pure quantity	Development / splice	Total
SD400	D16	64.58	14.15	78.73
	D19	27.62	4.35	31.97
	D22	47.92	17.11	65.03
	Subtotal	14012 (100%)	35.61 (100%)	175.73 (100%)
SD500	D16	53.06	13.21	66.27
	D19	23.39	4.63	28.02
	D22	40.27	15.82	56.09
	Subtotal	116.72 (82.8%)	33.66 (94.5%)	150.38 (85.6%)
SD600	D13	16.94	4.17	21.11
	D16	46.21	11.33	57.54
	D19	36.18	13.06	49.24
	Subtotal	99.33 (70.9%)	28.56 (80.2%)	127.89 (72.8%)

Comparisons of the total quantity of reinforcing bars by yield strength

1. As shown in Table 10 and Figure 2, the total quantity of reinforcement was reduced 15.6 per cent on SD500 and 26.1 per cent on SD600 comparing with SD400, when SD500 and SD600 were applied to slabs, beams or girders, columns, walls, and footings.

Table 10. The quantity of reinforcement by yield strength (Unit: Ton)

Member		Slabs	Beams / Girders	Columns	Walls	Footings	Total
SD 400	Pure quantity	65.61	112.97	18.33	29.02	140.12	365.95 (100%)
	Development / Splice	5.62	13.7	7.36	4.33	35.61	66.62 (100%)
	Subtotal	71.13 (100%)	126.67 (100%)	25.69 (100%)	33.35 (100%)	175.73 (100%)	432.57 (100%)
SD 500	Pure quantity	51.69	89.45	16.70	27.11	116.72	301.67 (82.4%)
	Development / Splice	4.75	11.82	8.23	4.97	33.66	63.43 (95.2%)
	Subtotal	56.44 (79.3%)	101.27 (79.9%)	24.93 (97.0%)	32.08 (96.2%)	150.38 (85.6%)	365.10 (84.4%)
SD 600	Pure quantity	45.26	79.37	15.08	26.26	99.33	265.3 (72.5%)
	Development / Splice	4.36	7.89	8.75	4.67	28.56	54.23 (81.4%)
	Subtotal	49.62 (69.8%)	87.26 (69.9%)	23.83 (92.7%)	30.93 (92.7%)	127.89 (72.8%)	319.53 (73.9%)
Note: All the reinforcing bars was applied SD400, SD500 and SD600							

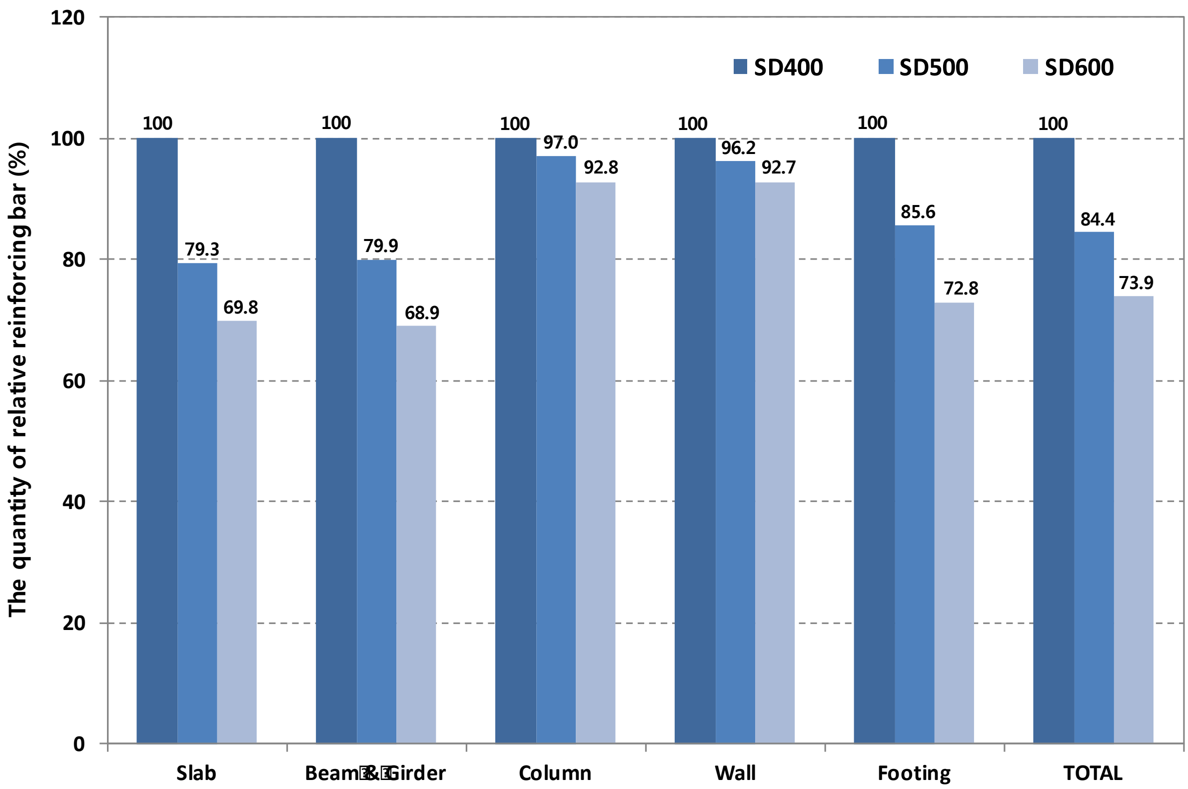

Figure 2. The quantity of main reinforcement by yield strength variables 1

2. The test results in Table 11 indicate SD400 reinforcing bars with D10 and D13 in diameter, and SD400, SD500 and SD600 using over D16 rebars. As shown in Table 11 and Figure 3, the total quantity of reinforcement was reduced 11.1 per cent on SD500 rebars comparing with SD400. Besides, it would be possible to lower the input amount of reinforcing bars up to 20.6 per cent, when SD600 rebars were applied comparing with SD400 ones.

Table 11. The quantity of reinforcement with combined reinforcing bars 1 (Unit: Ton)

Member		Slabs	Beams / Girders	Columns	Walls	Footings	Total
SD 400	Pure quantity	65.51	112.97	18.33	29.02	140.12	365.98 (100%)
	Development / Splice	5.62	13.7	7.36	4.33	35.61	66.62 (100%)
	Subtotal	71.13 (100%)	126.67 (100%)	25.69 (100%)	33.35 (100%)	175.73 (100%)	432.57 (100%)
SD400 + SD500	Pure quantity	64.05	95.89	16.70	28.04	116.72	321.40 (87.8%)
	Development / Splice	5.46	11.82	8.23	4.14	33.66	63.31 (95.0%)
	Subtotal	69.51 (97.7%)	107.71 (85.0%)	24.93 (97.0%)	32.18 (96.5%)	150.38 (85.6%)	384.71 (88.9%)
SD400 + SD600	Pure quantity	61.22	85.81	15.08	27.55	99.33	288.99 (79.0%)
	Development / Splice	5.08	7.89	8.75	4.04	28.56	54.32 (81.5%)
	Subtotal	66.3 (93.2%)	93.70 (74.0%)	23.83 (92.8%)	31.59 (94.7%)	127.89 (72.8%)	343.31 (79.4%)
Note: D10 and D13 were applied SD400, D16 or more was applied SD400, SD500 and SD600.							

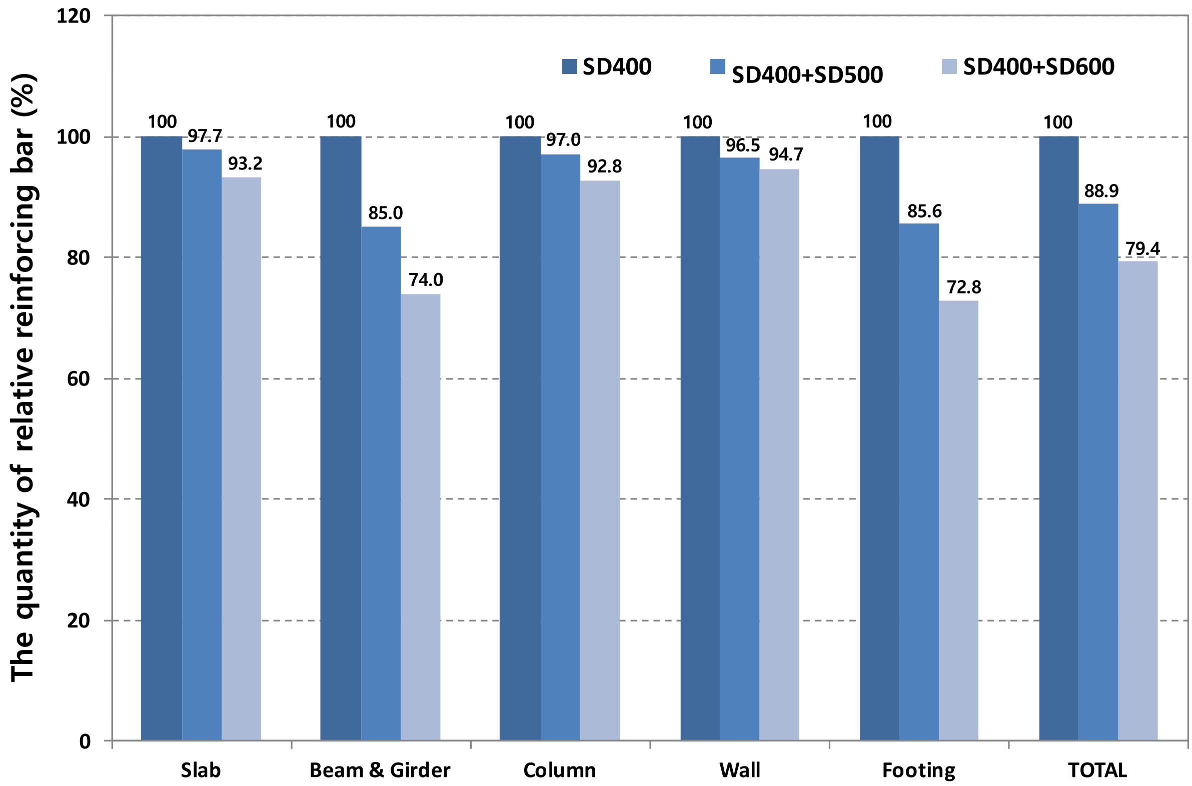

Figure 3. The quantity of main reinforcement by the yield strength variables 2 (Unit: Ton)

3. The data show in Table 12 that it would be possible to gain 15.6 per cent reduced quantity of reinforcement on SD500 with D10 and D13 reinforcing bars comparing with SD400. In addition, the test result indicates that 25.6 per cent reduction of rebars, when the combination of SD500 and SD600 reinforcing bars were used in the specimens. In general, high-strength reinforcing bars would be more beneficial and efficient to lower the total quantity of reinforcement comparing with lower yield strength materials (See Figure 4).

Table 12. The quantity of reinforcement with combined reinforcing bars 2 (Unit: Ton)

Member		Slabs	Beams / Girders	Columns	Walls	Footings	Total
SD 400	Pure quantity	65.51	112.97	18.33	29.02	140.12	365.95 (100%)
	Development / Splice	5.62	13.7	7.36	4.33	35.61	66.62 (100%)
	Subtotal	71.13 (100%)	126.67 (100%)	25.69 (100%)	33.35 (100%)	175.73 (100%)	432.57 (100%)
SD400 + SD500	Pure quantity	51.69	89.45	16.70	27.11	116.72	301.67 (82.4%)
	Development / Splice	4.75	11.82	8.23	4.97	33.66	63.43 (95.2%)
	Subtotal	56.44 (79.4%)	101.27 (80.0%)	24.93 (97.0%)	32.08 (96.2%)	150.38 (85.6%)	365.10 (84.4%)
SD400 + SD600	Pure quantity	47.67	79.37	15.08	26.26	99.33	267.71 (73.1%)
	Development / Splice	4.31	7.89	8.75	4.75	28.56	54.26 (81.4%)
	Subtotal	51.98 (73.1%)	87.26 (68.9%)	23.83 (92.8%)	31.01 (93.0%)	127.89 (72.8%)	321.97 (74.4%)
Note: D10 and D13 were applied SD500, D16 or more was applied SD500 and SD600.							

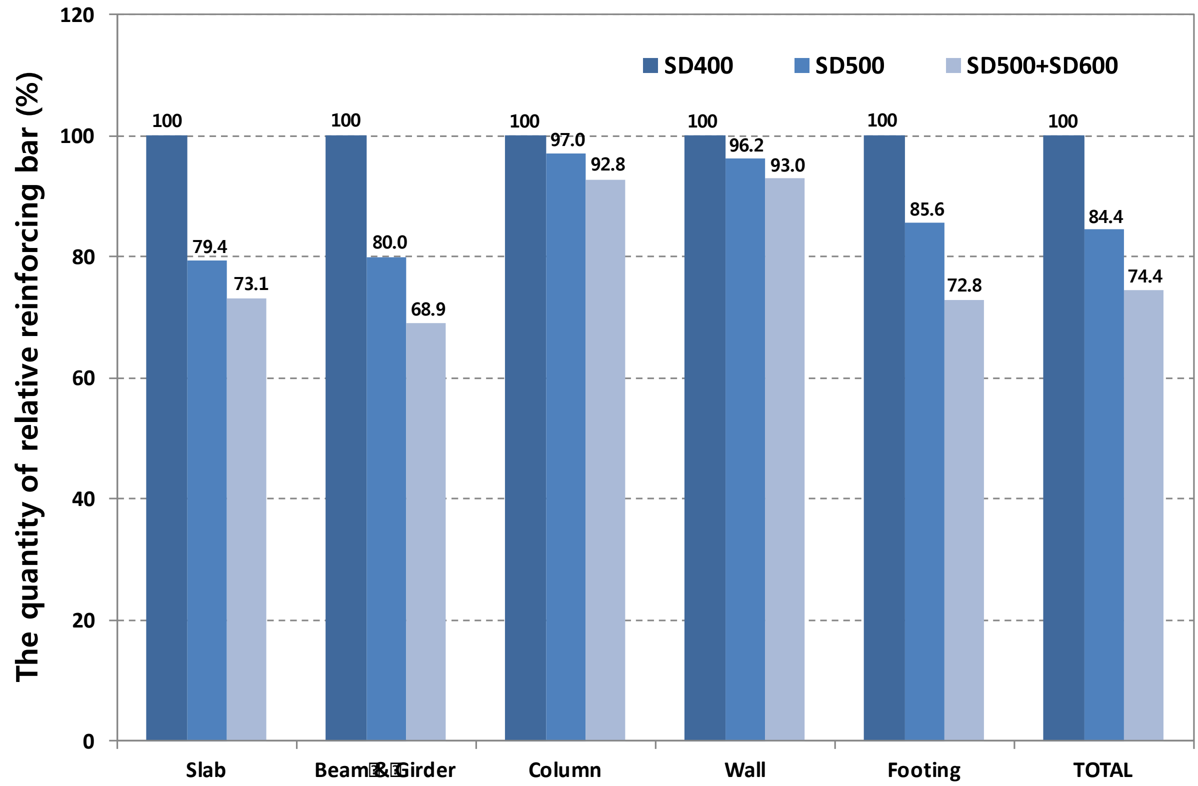

Figure 4. The quantity of main reinforcement by the yield strength variables 3 (Note: Application of D10 and D13 with SD500, and D16 or more with SD500 and SD600)

CONCLUSIONS

The main purpose of this research is to corroborate the effectiveness and practicality of the high-strength reinforcing bars in the underground parking space in a rigid-frame structure building (Rahmen structure) which is popular as well as resist vertical and lateral loads at the same time in concrete structures.

1. When SD500 and SD600 reinforcing bars were applied in the underground parking structures, the overall strength of the reinforcing bars would be increased 25 per cent and 50 per cent compared to SD400 rebars. When the structures on SD500 and SD600 were designed in compliance with KCI Design Codes, the quantity of reinforcing bars would be reduced approximately 20 per cent and 33 per cent respectively. In addition, the length of splice and development on SD500 and SD600 would be increased up to 25 per cent and 50 per cent
2. It was prominent for the underground structure buildings to reduce the amount of reinforcing bars, since the loads applied in the underground parking structures are heavier so the size of members such as slabs, beams and footings as well as the design of such members are designed by strength rather than the minimum reinforcement. Another cause of lowering the amount of reinforcing bars might be the length of splice and development was decreased as the quantity and the size of rebars were diminished. As a result of these factors, the overall amount of reinforcing bars shows reduced, when the high-strength reinforcing bars were applied to the specimen. On the other hand, for columns and walls, the length of splice and development was increased, and the hoops and horizontal rebars were not lowered. Therefore, the quantity of reinforcing bars was not reduced and the effect of reduction was marginal on columns and walls.
3. In general, it will be possible to lower the pure quantity of reinforcing bars arrangement in all aspects. The test result shows that we would be able to reduce 17.6 per cent on SD500 compared with SD400 rebars. For SD600, the amount of reinforcing bars would be lowered 27.5 per cent compared with SD400. When the length of splice and development was considered, the quantity of reinforcing bars on SD500 and SD600 were 15.6 per cent and 26.1 per cent respectively compared with SD400 rebars. In this aspect, it was negligible that the rate of increased amount of reinforcing bars on the splice and development was 1.4 ~ 2.0 per cent. The reason for this result is that the reduced amount of pure reinforcement is far greater than the quantity of the splice and development when the high-strength reinforcing bars were applied in the specimens.
4. The most effective method to reduce the amount of reinforcing bars arrangement was using SD600 on all the reinforcement. However, when we apply all the reinforcement with SD600 rebars, there is a restriction to use the shear reinforcement only with SD500. In this case, there would be a difficulty to adopt this method in practice, since the size of rebars is increased and there would be a possibility of causing segregation and placing of concrete.
5. As a result, it would be possible to attain the reduction of reinforcing bars arrangement and lowering the amount of work on site. Moreover, the decreased amount of bar arrangement will lead to reduce the reinforcement work as well as to improve the constructability in concrete structures. The reduced amount of resources in concrete structures would be able to achieve lean construction as well as sustainability in the AEC industry. Ultimately, it would be possible to attain the improved quality and efficiency of reinforced concrete structures.

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