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Improvement of a Requirement for Providing Special Boundary Element Considering Feature of Domestic High-rise Shear Walls

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Abstract The reinforced concrete shear walls are being widely used in the domestic high-rise residential complex buildings. If designed by current codes, the special boundary element is needed in almost all high-rise shear wall buildings. This is because the equation for determining the provision of the special boundary element in the current codes cannot reflect the characteristics of the domestic high-rise shear walls with high axial load ratio and high proportion of elastic displacement to total displacement. In this study, a new equation to be able to reflect the characteristics is proposed. By using the equation, the special boundary element may not be necessary in certain cases so that structural engineers can relieve the burden of installing the special boundary element in every high-rise shear wall.

Keywords: High-rise Shear Wall, Special Shear Wall, Special Boundary Element, Axial Load, Yield Displacement

1. INTRODUCTION

The proportion of reinforced concrete (RC) shear walls in the seismic load resisting system of the domestic high-rise buildings is currently very high. The structural system of high-rise residential complex or office buildings is mainly a combination of RC core wall and steel-frame Steel frame, RC moment frame, or flat plate floor system. The former resists most lateral load caused by an earthquake as the seismic load resisting system, while the latter resists most of gravity load as the gravity load resisting system. From the late 1990s to present, many domestic high-rise residential complex buildings were built or during the construction. The seismic design of the shear wall is an important topic that domestic structural engineers meet more often than foreign engineers do.

Korean Building Code (KBC) 2009 (AIK 2009) and International Building Code (IBC) 2012 (ICC 2012) designate 'seismic design category (SDC)' for seismic resistant design of buildings. The seismic design category is determined by a seismic rating (risk category in ASCE 7 (2010)) and the design spectral acceleration. The category is assigned from A to D in the KBC 2009, and from A to F in the IBC 2012. Transition from A to F implies the increase of seismic risk. The seismic rating is related to building use, and the design spectral acceleration is dependent of peak ground acceleration and soil profile at the location of the building. The former KBC 2005 (AIK 2005) classified residential buildings with more than 15 stories as 'special' grade, which is equivalent to risk category IV in ASCE 7. As a result, most of the high-rise residential complex buildings belong to SDC D so that they should satisfy additional regulations such as deformation compatibility.

By the needs of the industry to mitigate the regulation, they are graded down to seismic rating I in the KBC 2009, but they still belong to the SDC D, depending on the soil conditions. Especially, almost all of them belong to SDC D in the regions such as coast and landfills where the site class is S_D. High-rise buildings in domestic region is usually dominated by the wind loads in the structural design, but there are many cases where the design is governed by the earthquake in relatively poor soil conditions. In the KBC 2009, even if a site class is S_C, it could belong to the SDC D depending on the hazard level. The ASCE 7 (2010) is similar to the KBC 2009 so the buildings belong to SDC D regardless of the use, if seismic hazard is similar to domestic and the site class is worse than S_C.

The KBC 2005 had been newly revised in 2009, which is the KBC 2009. One of the key revisions including the seismic rating is that the KBC 2009 provides various seismic load resisting systems as compared to the former KBC 2005. In particular, the special details that did not exist in the KBC 2005 are introduced in the KBC 2009. The seismic load resisting systems are restricted by height limit based on the SDC. The RC ordinary shear walls of the building frame system have a height limit of 60m when they belong to SDC D in the KBC 2009. Most of the residential complex buildings exceed 60m and belong to SDC D so that their structural system of RC shear walls should be designed to be special RC shear walls, not to be the RC ordinary shear walls.

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Special details such as the RC special shear walls should satisfy very strict criteria in order to maintain a very high level of ductility. It is because special details should possess relatively high deformation capacity instead of allowing the reduction of the design lateral force. For the high deformation capacity, special boundary element (SBE) is provided at the end of the special shear wall section. The design methodology of the SBE specified in the KBC 2009 and ACI 318 (2011) yields various problems when applied to the domestic high-rise shear wall buildings. In accordance with current standards, the SBE is required in most cases and it should be installed in a wide range of the wall section both horizontally and vertically.

Even though the weakness exists, to use the RC special shear walls is due to needs of the construction industry to increase economic efficiency by reduction of the volume. Therefore, practical application of the RC special shear walls is not viable without solving the weakness. To remedy this situation, this study was aimed at adjusting the requirement of providing the SBE by considering the characteristics of the domestic high-rise shear wall buildings. The design and construction of the SBE are difficult at home and abroad. However, this phenomenon appears particularly in the domestic high-rise shear wall buildings. To resolve this problem would be a valuable help for the domestic shear wall building system to be used globally.

2. CURRENT CODE REQUIREMENT

The design of the RC special shear walls is specified in '0520 Special considerations in seismic design' of the KBC 2009 and chapter 21 of the ACI 318. There is no difference between these standards for the design of special shear walls. One can say that the design of the SBE at the ends of the wall section is all about in the design of the special shear walls. The special shear walls can be secured in ductility by the SBE so that they can earn resistance to excessive deformation due to earthquakes. The standards stipulate that the SBE must be installed when the following conditions are true:

$$c \geq c_{lim} = \frac{l_w}{600(\delta_u/h_w)} \tag{1}$$

where δ_u/h_w should be equal to or higher than 0.007. Wallace and Orakcal (2002) presented equation (1), which is a requirement for providing the SBE. The basis of this criterion for the SBE can be found in Wallace (1994, 1995a, 1995b, 1996, 1998). The left-hand side of the equation represents the neutral axis depth of the shear wall cross-section when the section reaches its ultimate moment strength. The right-hand side of the equation is related to concrete compressive strain in wall section when the top of the shear wall reaches the design displacement. That the equation is true means the compressive strain of concrete in the wall section exceeds 0.003 so the SBE is necessary.

In the current design practices of the domestic high-rise shear wall buildings, structural engineers do not hesitate to bear gravity loads to the shear walls even though it is inevitable considering the shape of the floor plan. Along with this practical cause, the lower-story shear walls must bear very large axial load due to the building height. As the axial load in the wall section increases, the neutral axis depth in the left-hand side of equation (1) increases. The right-hand side of the equation is basically induced by an assumption that the axial load in the wall section is very small so it can be negligible, which is not compatible with characteristics of the domestic shear wall buildings. In addition to this, when the neutral axis depth at the level of design displacement is calculated in the equation, the plastic deformation is only considered without including the elastic deformation until yielding, which is also not compatible with the characteristics of domestic shear wall buildings where the elastic deformation possesses a high portion of the total deformation due to high aspect ratio (Kang & Kim 2010). Consequently, if equation (1) is applied to the domestic high-rise shear walls, the left-hand side has a very large value. On the other hand, the right- hand side has a relatively small. This results in the SBE being necessary in most of the domestic high-rise shear walls. Among key assumptions used to induce equation (1), the items that are not fit for the characteristics of the domestic high-rise shear walls are investigated below.

2.1 Ignoring the role of the elastic deformation

As follows are taking a closer look at the process of inducing equation (1). First, the design displacement δ_u can be expressed as the following equation (2).

$$\delta_u = \frac{11}{40}\phi_y h_w^2 + (\phi_u - \phi_y) l_p \left(h_w - \frac{l_p}{2}\right) \tag{2}$$

where ϕ_u: ultimate curvature in design displacement (δ_u); ϕ_y: yield curvature ($0.003/l_w$, l_w: wall length); l_p: plastic hinge length ($l_w/2$); h_w: wall height. The front part of the right-hand side of equation (2), $11/40\,\phi_y h_w^2$ indicates the yield displacement (δ_y) and the remaining part indicates the plastic displacement. Wallace and Orakcal (2002) assumed that the yield displacement, the front part of equation (2), is negligible and the design displacement can be represented by only the plastic displacement as the following equation (3):

$$\delta_u = \theta_p h_w = (\phi_u l_p) h_w \tag{3}$$

where θ_P: plastic rotation at base. To simplify equation (2) like equation (3) is based on the assumption that the elastic displacement is relatively small as compared to the plastic displacement after yielding. Of course, the center of the plastic hinge moves to top of the base so discrepancy due to the neglect of the elastic displacement can be alleviated. However, one will not be able to accurately evaluate the curvature of the wall section at the level of the design displacement if the ratio of the elastic displacement to total displacement is high.

The displacement-based design approach in the current standards is derived for the wall aspect ratio (wall height/wall length) that is equal to or less than 3.0. But Kang & Kim (2010) presented that the yield displacement is approximately 50% of the total when axial force and the aspect ratio is high. In equation (2), the yield displacement is proportional to the square of the height while the plastic displacement is proportional to the height. Therefore, the ratio of the yield displacement to the total displacement increases as the height increases.

Domestic shear walls are usually constructed in high-rise buildings and should be provided with the SBE since the KBC 2009 specifies the SBE for the buildings more than 60m. Therefore, if neglecting the role of the elastic displacement in the design of the domestic high-rise shear wall buildings, the actual behavior can be seriously distorted so the elastic displacement should be included in the calculation of the design displacement. Kang & Kim (2010) insisted that the equation in the current codes may underestimate the actual displacement ability when the aspect ratio is greater than 1.5, and proposed an equation revising equation (1):

$$c \geq c_{\text{lim}} = \frac{l_w}{600\,(C_d\text{-}1)\delta_e/h_w} \tag{4}$$

where C_d: displacement amplification factor defined in codes; δ_e : elastic displacement for design lateral force. The analysis for this equation will be provided later in this paper.

2.2 Not considering the influence of the axial load

In the United States, the shear walls are generally located between the columns of moment frames and as a result, work to be boundary elements of the walls. In this case, it is assumed that the shear walls do not support the gravity loads so they are designed for only shear forces and moments due to the lateral force. However, in the case of the domestic high-rise shear wall buildings, shear walls are not placed between the columns and designed to resist a large amount of gravity load as well. Furthermore, the axial load level of the shear walls is very high because it is mainly constructed in high-rise.

The high axial load has a large impact on yield curvature but a relatively small impact on ultimate curvature. Wallace and Orakcal (2002) suggested the yield curvature is $0.003/l_w$. Cho (2002) suggested it is approximately $2\varepsilon_y/l_w$ (ε_y: yield curvature of reinforcement) though it may vary depending on the conditions. For the reinforcement with the yield strength of 400MPa, the yield strain is 0.002 so that the yield curvature becomes $0.004/l_w$. Wu et al (2004) proposed that if the axial load of the wall is large, the tensile rebars do not yield until the wall section yields and the yielding of the wall section can be defined when the concrete compressive strength reaches its maximum value. Assuming that the maximum value of concrete strain is 0.002, the yield curvature will be $0.002/l_w$. This value is a half of that from Cho (2002) and two thirds of that from Wallace and Orakcal (2002).

The above-mentioned two issues exist when determining whether the SBE will be provided or not for the domestic high-rise shear walls using the current codes. Therefore, it needs to improve equation (2) to fit for the characteristics of the domestic high-rise shear walls. In this study, a new equation to determine the provision of the SBE was proposed by considering the issues described above.

3. DESIGN OF EXAMPLE BUILDINGS

A typical type of the residential complex shear wall buildings generally constructed in domestic was used in order to more accurately reflect the actual design process. A plan for example buildings was adopted from that in AIK (2008), which is shown in Figure 1. The structural system of the plan consists of the RC core wall in the center as the seismic load resisting system, and perimeter columns and the flat plate floor system as the gravity load resisting system. Among the RC core walls, walls with a large thickness located at perimeter are only studied in this study.

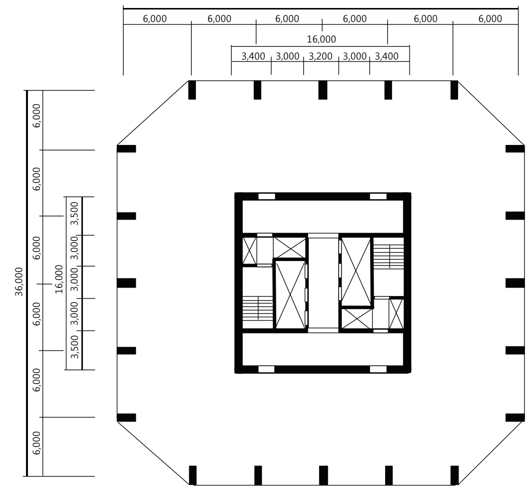


Figure 1. Plan view of example buildings

A total of 34 buildings were designed for AIK (2008) by varying the wall thickness for different stories (20, 30, and 40) and different soil conditions (SC and SD). A horizontal wall (Wx) and a vertical wall (Wy) were designed for each direction and each building, so total 68 shear walls were designed and utilized for investigating their behavior. Dead and Live load are presented in Table 1 regardless of the number of stories in the example buildings. Slab thickness is 250mm for every floor. Compressive strength of concrete (f_c') is 30 MPa for 20 and 30 story buildings, and 40 MPa for 40 story buildings. Yield strength of reinforcing steel (f_y) is 400 MPa.

While the other conditions were kept same, the wall thickness varied along with the reinforcement ratio. The minimum wall thickness was selected to be a possible size with reasonable placement of reinforcement when design story drift is closest to allowable story drift. The reinforcement ratio decreases with the increase of the wall thickness so the maximum wall thickness was selected to be a value when the ratio is closest to the minimum reinforcement ratio for the wall, 0.25%. It is noted that the reinforcement ratio no longer decreases below a certain level even though the wall thickness is kept increasing. This phenomenon is because the increase in the wall thickness resulted in increase of the wall weight and increase of seismic loads as well. The vertical reinforcement was assumed to be placed by double layer. The diameters of the reinforcement were between 13mm and 25mm. The horizontal spaces between vertical reinforcement were between 150mm and 400mm. The diameters and horizontal spaces are selected to fit for practice in construction.

Dimensions and properties of the designed walls are summarized in Table 2. In the nomenclature of the Wall ID, the first two digits indicate the number of story, the next character indicates the site class and the wall direction, and the last three digits indicate the wall thickness. The wall lengths to the horizontal and vertical direction are fixed at 8m and 16m, respectively. The wall thicknesses range from 200mm to 700mm. The ratios of the vertical reinforcement (ρ_v) range from 0.29% to 1.77%. The aspect ratios (h_w/l_w) are observed in 4.4 to 16.7. The axial load ratios ($p = P/t_w \ell_w f'_c$, P: design axial load) range from 0.2 to 0.5. The design drift ratios are observed in 0.0028 to 0.0117.

Table 1. Design load (kN/m^2)

Story	Usage	Dead Load	Live load
1~5	Commercial	9.5 or 10.0	4.0
Typical	Residential	9.5 or 10.0	2.0
Roof	Roof	7	2.0

Table 2. Dimensions and properties of shear walls

Wall ID	l_w (m)	Vertical Reinf.	ρ_v	p	h_w/l_w	δ_u/h_w	SBE
20ScWx250	8	D25@300	0.0135	0.49	8.8	0.0056	O
20ScWy250	16	D19@200	0.0115	0.51	4.4	0.0037	O
20SdWx200	8	D25@300	0.0177	0.34	8.8	0.0078	O
20SdWx250	8	D25@400	0.0106	0.30	8.8	0.0068	X
20SdWx300	8	D25@200	0.0169	0.46	8.8	0.0060	O
20SdWx300	8	D19@200	0.0098	0.27	8.8	0.0061	X
20SdWx350	8	D16@200	0.0057	0.42	8.8	0.0053	O
20SdWx350	8	D22@250	0.0091	0.24	8.8	0.0056	X
20SdWx400	8	D25@300	0.0089	0.22	8.8	0.0051	X
20SdWx450	8	D19@150	0.0086	0.21	8.8	0.0048	X
20SdWx500	8	D25@250	0.0084	0.20	8.8	0.0045	X
20SdWy200	16	D22@300	0.0131	0.38	4.4	0.0050	O
20SdWy250	16	D25@400	0.0104	0.34	4.4	0.0044	O
20SdWy300	16	D25@300	0.0113	0.50	4.4	0.0040	O
20SdWy300	16	D19@200	0.0097	0.31	4.4	0.0039	O
20SdWy350	16	D19@300	0.0055	0.46	4.4	0.0036	O
20SdWy350	16	D22@250	0.0090	0.28	4.4	0.0035	O
20SdWy400	16	D25@300	0.0086	0.26	4.4	0.0032	O
20SdWy450	16	D25@300	0.0076	0.24	4.4	0.0030	O
20SdWy500	16	D19@150	0.0077	0.23	4.4	0.0028	O
30ScWx300	8	D16@200	0.0066	0.46	12.7	0.0083	O
30ScWx350	8	D16@300	0.0038	0.41	12.7	0.0076	X
30ScWy300	16	D19@150	0.0127	0.50	6.4	0.0064	O
30ScWy350	16	D13@250	0.0029	0.45	6.4	0.0058	O
30SdWx250	8	D25@400	0.0106	0.43	12.7	0.0109	O
30SdWx300	8	D25@400	0.0089	0.38	12.7	0.0097	O
30SdWx350	8	D22@300	0.0074	0.43	12.7	0.0094	O
30SdWx350	8	D19@200	0.0084	0.35	12.7	0.0088	X
30SdWx400	8	D13@200	0.0032	0.40	12.7	0.0086	O
30SdWx400	8	D25@300	0.0089	0.23	12.7	0.0081	X
30SdWx450	8	D25@300	0.0079	0.30	12.7	0.0075	X
30SdWx500	8	D19@150	0.0077	0.28	12.7	0.0070	X
30SdWx550	8	D16@100	0.0072	0.27	12.7	0.0067	X
30SdWy250	16	D25@400	0.0106	0.49	6.4	0.0084	O
30SdWy300	16	D19@200	0.0087	0.44	6.4	0.0075	O
30SdWy350	16	D25@300	0.0097	0.48	6.4	0.0072	O
30SdWy350	16	D25@300	0.0098	0.41	6.4	0.0067	O
30SdWy400	16	D16@300	0.0033	0.44	6.4	0.0066	O
30SdWy400	16	D25@300	0.0086	0.38	6.4	0.0062	O
30SdWy450	16	D25@300	0.0076	0.35	6.4	0.0057	O
30SdWy500	16	D19@150	0.0077	0.33	6.4	0.0053	O
30SdWy550	16	D19@150	0.0070	0.31	6.4	0.0050	O
40ScWx450	8	D22@200	0.0086	0.47	16.7	0.0093	X
40ScWx500	8	D16@200	0.0040	0.44	16.7	0.0087	X
40ScWx550	8	D16@200	0.0036	0.41	16.7	0.0082	X
40ScWy450	16	D25@150	0.0150	0.51	8.3	0.0084	O
40ScWy500	16	D25@300	0.0068	0.47	8.3	0.0077	O
40ScWy550	16	D16@250	0.0029	0.44	8.3	0.0072	O
40SdWx400	8	D22@300	0.0068	0.44	16.7	0.0117	O
40SdWx450	8	D22@300	0.0060	0.41	16.7	0.0108	O
40SdWx500	8	D22@150	0.0103	0.46	16.7	0.0108	O
40SdWx500	8	D22@300	0.0054	0.38	16.7	0.0101	X
40SdWx550	8	D16@200	0.0036	0.44	16.7	0.0101	X
40SdWx550	8	D25@350	0.0055	0.36	16.7	0.0095	X
40SdWx600	8	D16@200	0.0033	0.41	16.7	0.0096	X
40SdWx600	8	D22@250	0.0053	0.34	16.7	0.0090	X
40SdWx650	8	D25@300	0.0055	0.33	16.7	0.0085	X
40SdWx700	8	D22@200	0.0057	0.31	16.7	0.0082	X
40SdWy400	16	D19@150	0.0096	0.48	8.3	0.0106	O
40SdWy450	16	D25@400	0.0058	0.45	8.3	0.0097	O
40SdWy500	16	D25@150	0.0135	0.51	8.3	0.0096	O
40SdWy500	16	D22@300	0.0052	0.43	8.3	0.0090	O
40SdWy550	16	D19@150	0.0069	0.47	8.3	0.0090	O
40SdWy550	16	D19@200	0.0053	0.40	8.3	0.0084	O
40SdWy600	16	D16@200	0.0033	0.44	8.3	0.0085	O
40SdWy600	16	D22@250	0.0052	0.38	8.3	0.0079	O
40SdWy650	16	D25@300	0.0053	0.37	8.3	0.0075	O
40SdWy700	16	D25@300	0.0049	0.35	8.3	0.0071	O

4. ANALYSIS OF BEHAVIOR OF DESIGNED SHEAR WALLS AND PROPOSITION OF A NEW EQUATION

For the designed walls, factors and their weight affecting the decision of provision of the SBE is investigated. Then, a new equation for the decision is proposed.

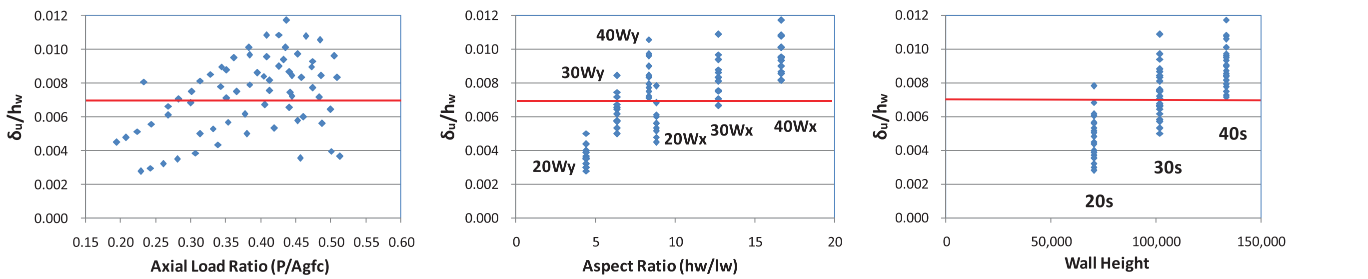
4.1 Displacement of shear walls

First of all, the effect of the axial load ratio, the aspect ratio, and the wall height to the design displacement (or drift ratio) was investigated. Figure 2 shows plots of the design drift ratios for the parameters. There is not clear correlation between the reinforcement ratio and the design drift ratio. As the axial load ratio increases, the design drift ratio increases but it was not shown remarkable tendency (Figure 2(a)). On the other hand, the design drift ratio tends to be affected more by the aspect ratio and the wall height than by the axial load ratio (Figure 2(b), (c)). This is because the design drift ratio is highly affected by the wall height and the axial load ratio is just increased as the wall height increases. However, the minimum design drift ratio is more important than the parameters described above.

In Figure 2, the horizontal red line represents the minimum design drift ratio of 0.007 in equation (1). The lateral displacement of shear wall buildings further increases as the height increases unlike moment resisting frame buildings because the deformed shape is in the form of cantilever. As the result, the design drift ratios of the 40 story buildings exceed the minimum design drift ratio regardless of the aspect ratio. On the other hand, those of the relatively low 20 story buildings are less than the minimum ratio. Those of the 30 story buildings show a mixed result, which are less or more than the minimum ratio for low or high aspect ratio, respectively (Figure 2(b)). If the number of story is below thirty and the aspect ratio is less than 8, the minimum ratio of 0.007 governs equation (1) since the design drift ratio is less than the minimum ratio. In this case, the SBE is not required for the actual design displacement, but should be provided if the minimum ratio is applied.

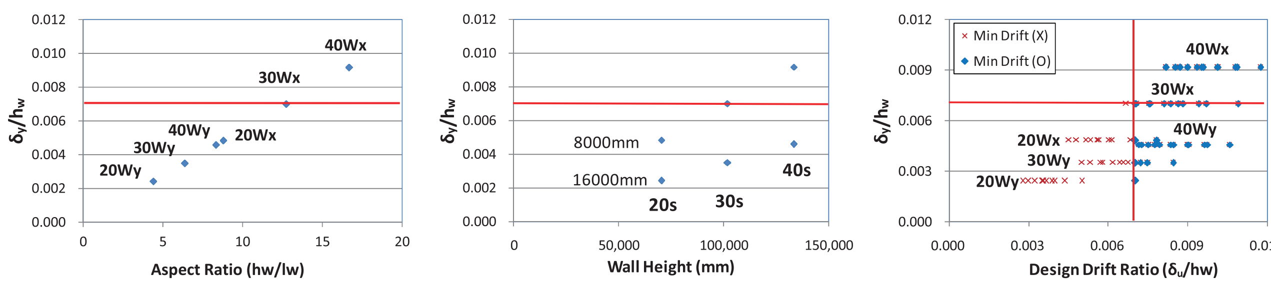
Following is about the effect of the parameters to the yield displacement (or drift ratio). As mentioned above, tensile rebars do not yield until the yield point when the axial load ratio is high. Of the three yield curvature calculation methods, the smallest one (Wu et al 2004) was used in this study. It is because the yield displacement could be over-estimated if the other methods are used. For instance, the yield curvature of Cho (2002) is about double that of Wu et al (2004), and the yield displacement is as well. It can be seen later that the yield displacement is greater than the design displacement using that of Cho (2002), which may rather overestimate the ability of the wall. For this reason, the method to earn the smallest value was selected to estimate the yield displacement. Figure 3 shows the yield drift ratios for three e variables, which are the axial load ratio, aspect ratio, and wall height. As can be seen from equation (2), the yield displacement is proportional to the wall height and the square of the curvature. The yield curvature is of course inversely proportional to the length of the wall, so it is after all proportional to the height and aspect ratio of the wall. Figure 3(a) and Figure 3(b) show this trend well.

In order to investigate the relationship between the design and yield displacements, the design drift ratio along the horizontal axis and the yield drift ratio along the vertical axis are plotted in Figure 3(c). There are two plots in Figure 3(c), one of which is when applying the minimum drift ratio of 0.007 and the other of which is when does not. The horizontal and vertical red lines represent the minimum drift. If not applying the minimum drift ratio, the yield drift ratios exceed the design drift ratios in many cases. If applying it, however, the design drift ratios unconditionally exceed the yield drift ratios especially for the walls (Wy) in the 20 and 30 story buildings, which have relatively low aspect ratios. On the other hand, the design drift ratios are less than the yield drift ratios in more than half the walls (Wx) of the 40 story buildings, which have the largest aspect ratio, regardless of the minimum drift ratio. Therefore, if the aspect ratio is very large, the walls are likely to stay in the elastic region until the level of the design displacement.



(a) (b) (c)

Figure 2. Design drift ratio



(a) (b) (c)

Figure 3. Yield drift ratio

4.2 Neutral axis depth of shear wall section

In the current standards, the neutral axis depth in the wall cross section is the most important variable in determining whether the SBE will be provided or not. It is also important to investigate the characteristics of the domestic high-rise shear walls. In order to calculate the neutral axis depth, section analysis must be performed but it is time consuming. Kang and Park (2002) proposed the following equation for the neutral axis depth of the wall section, which includes the effect of the axial load.

$$c = l_w\left(\frac{\rho_v f_y + P/A_g}{\alpha\beta\, f_c' + 2\rho_v f_y}\right) \tag{5}$$

where A_g: gross sectional area of wall ($t_w l_w$); α,β: coefficients for equivalent rectangular stress block of unconfined concrete. The ratios of the neutral axis depth to the wall length for several parameters are shown in Figure 4. The neutral axis depth does not show distinct correlation with the reinforcement ratio (Figure 4(a)). The aspect ratio has a little more effect on the neutral axis depth than the reinforcement ratio (Figure 4(c)), but less effect than the axial load ratio. The neutral axis depth increases almost linearly as the axial load ratio increases (Figure 4(b)). Using equation (5), the neutral axis depth is about 0.3 to 0.7 times of the wall length. When the axial load ratio is 0.35, it is approximately 0.5, i. e., half the wall length. This large depth implies that the strain of tensile reinforcement is not large when the concrete compressive strain reaches 0.003 at the end of the wall section.

In order to verify the reliability of equation (5), the neutral axis depth was also calculated using the section analysis. The section analysis determines the neutral axis depth by dividing the wall section into numerous layers of concrete and using the actual amount and location of the rebars. Figure 5 shows the ratio of the neutral axis depth from the section analysis to that from the equation. When the reinforcement ratio exceeds 0.01 or the axial load ratio exceeds 0.4, the neutral axis depth from the section analysis is greater than that from the equation. The difference increases with the axial load ratio increases. There is no apparent relevance to the aspect ratio. When the reinforcement ratio is less than 0.01, the section analysis produces the smaller depth than the equation in many cases. When the axial load ratio is 0.4 or less, the section analysis is likely to produce the smaller depth than that from the equation.

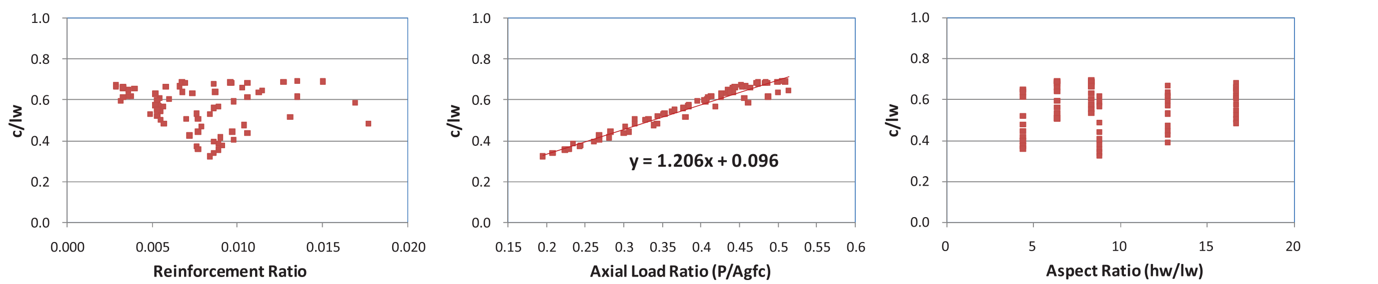
This phenomenon can be attributed to an assumption that all of the rebars yield across the wall cross section in the course of the derivation of the equation. In fact, all of the rebars do not yield even if the axial load does not exist. If the axial load exists, even some rebars in the tensile side do not yield. This is why the neutral axis depths from the section analysis and the equation do not match.

Therefore, the difference between two approaches increases as the reinforcement and axial load ratios increase.

If the neutral axis depth is calculated using the equation (2) and is larger than that from section analysis, it is not a problem at all since the ability of the wall is conservatively estimated. If it is smaller, on the contrary, it should be calibrated since the ability of the wall is estimated larger than the actual ability. Analyzing the plots in Figure 4 and Figure 5, an equation of the neutral axis depth for the axial load ratio (p) is proposed in equation (6) when the ratio less than 0.4. When the ratio is equal to or larger than 0.4, the equation is multiplied by the axial load ratio (p) plus 0.6 like equation (7). Both equation (6) and (7) could be effectively utilized during the preliminary design process of the RC special shear walls.

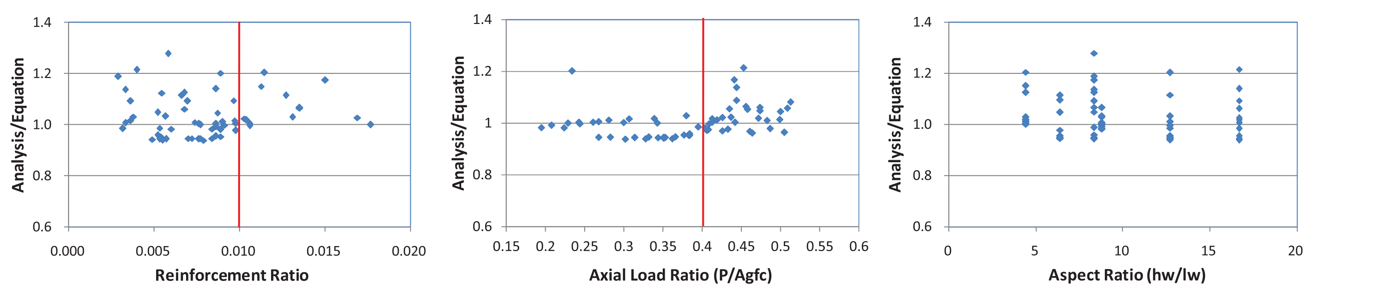
$$c=(1.2p+0.1)l_w,\ p<0.4 \tag{6}$$

$$c=(p+0.6)(1.2p+0.1)l_w,\ p\geq 0.4 \tag{7}$$



(a) (b) (c)

Figure 4. Neutral axis depth/wall length by equation (before refinement)



(a) (b) (c)

Figure 5. Ratio of neutral axis depth by analysis to that by equation

4.3 Proposition of a new equation for special boundary elements

The determination of the provision of the SBE using the neutral axis depth depends on the right-hand side of equation (1), i. e., the neutral axis depth limit (c_{lim}). As mentioned above, the right-hand side of equation (1) is derived by neglecting the elastic displacement. If the equation (1) is applied to the domestic high-rise shear walls where the design displacement (demand) is not so large, the neutral axis depth corresponding to the design displacement is estimated to be very small, which means that the demand gets estimated to abnormally high on the contrary. As the result, most of the domestic high-rise shear walls are needed to install the SBE. In order to solve this problem, the neutral axis depth limit was recalculated by using equation (2). At this time, the front part of equation (2), which is the yield displacement (δ_y), is included unlike Wallace and Orakcal (2002). The ultimate curvature can be expressed by rearranging equation (2) as

$$\phi_u = \frac{\delta_u-\delta_y}{l_p\left(h_w-0.5l_p\right)} + \phi_y \tag{8}$$

Then, substituting ϕ_u for $0.003/c$, $0.5l_w$ for l_p and $0.002/l_w$ for ϕ_y, equation (8) can be expressed as

$$\frac{0.003}{c} = \frac{2\left(\delta_u-\delta_y\right)}{l_w\left(h_w-0.25l_w\right)} + \frac{0.002}{l_w} \tag{9}$$

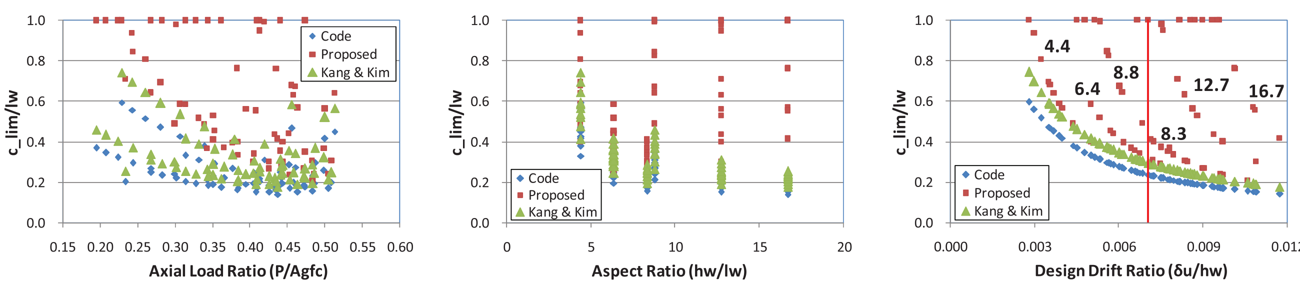
The left-hand side of equation (9) designates the capacity of the shear wall while the right-hand side does the demand. Therefore, if the right-hand side exceeds the left-hand side in equation (9), it implies the concrete compressive strain exceeds the limit strain, 0.003. Finally, substituting '≤' sign for '=' sign in equation (9) and rearranging it for c, the neutral axis depth, an equation for determining the provision of the SBE can be proposed as

$$c > c_{lim}=0.003l_w\left[\frac{2\left(\delta_u-\delta_y\right)}{\left(h_w-0.25l_w\right)}+0.002\right]^{-1} \tag{10}$$

Equation (10) is valid only when the design displacement (δ_u) exceeds the yield displacement (δ_y) and if not, c_{lim} is conservatively assumed to be l_w.

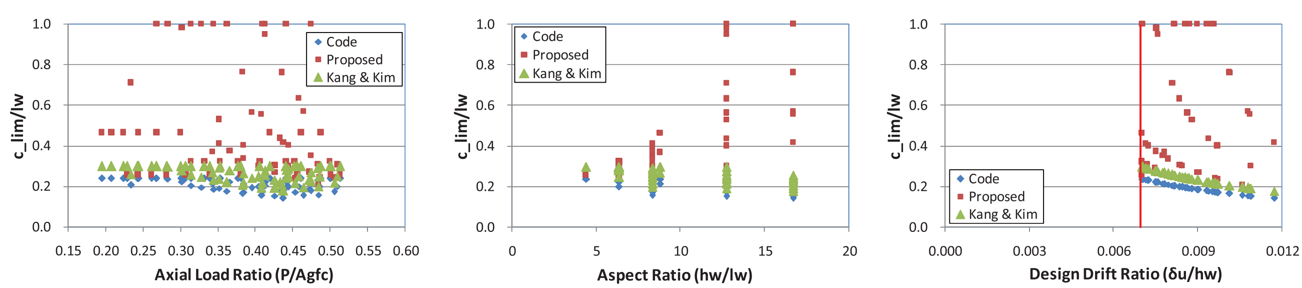
The c_{lim} from this proposed equation is compared that from the code and Kang & Kim. Firstly, the c_{lim} from the code and Kang & Kim shows the same trend, but that from Kang & Kim is slightly larger than that from the code regardless of applying the design drift limit or not (Figure 6 & Figure 7). This is because two equations from the code and Kang & Kim are same except the design displacement δ_u is multiplied by 0.8 in Kang & Kim. In both cases, the c_{lim} gradually decreases as the axial load ratio, aspect ratio, and design drift ratio increase. The decrease in the c_{lim} means that the demand increases so that the probability of the SBE being necessary increases. This is undoubted result since the demand in the code and Kang & Kim is directly proportional to the design drift ratio. As the height increases, both the design drift ratio and the aspect ratio increase. The axial load ratio increases as well even though it is affected relatively small by the increase of the height.

When the design drift limit is not applied, the c_{lim} exceeds 50% of the wall length for the code and Kang & Kim if the parameters have low values (Figure 6). In this value of c_{lim}, the SBE may not be necessary since the neutral axis depth c may be less than the value. If the design drift limit is applied, however, the c_{lim} is reduced to less than 0.3_w as shown in Figure 7. Comparing the c_{lim} of 0.3_w with those in Figure 4, the SBE is necessary in most of the shear walls. On the other hand, the c_{lim} from the proposed equation (8) is not directly related to the design drift ratio, so the c_{lim} is distributed in high axial load ratio, aspect ratio, and design drift ratio (Figure 7). As the result, the probability of not providing the SBE increases if using the proposed equation. This is due to inclusion of the yield displacement for derivation of equation (10). Since the maximum value of the c is about 0.7_w as shown in Figure 4, the SBE does not need to be installed when the c_{lim} is greater than 0.8_w.



(a) (b) (c)

Figure 6. Neutral axis depth limit w/o applying design drift limit



(a) (b) (c)

Figure 7. Neutral axis depth limit w/ applying design drift limit

Unlike the neutral axis depth and its limit, the curvature can be expressed as a curvature capacity (ϕ_{cap}) and a curvature demand (ϕ_{demand}) or requirement (ϕ_{req}). The curvature capacity is assigned to be the maximum concrete compressive strain of 0.003 divided by the neutral axis depth as presented in equation (11).

$$\phi_{cap} = 0.003/c \tag{11}$$

The curvature demand or requirement (ϕ_{req}) can be derived by substituting ϕ_{req} for ϕ_u in equation (8) and rearranging the right-hand side. It is expressed as

$$\phi_{req} = \frac{1}{l_w}\left[0.002 + \frac{2(\delta_u - \delta_y)}{(h_w - 0.25 l_w)}\right] \quad (\delta_u \geq \delta_y) \tag{12}$$

This is valid only when the design displacement exceeds the yield displacement. If not, the ϕ_{req} can be derived by using only the front part of the right-hand side of equation (2) and substituting ϕ_{req} for ϕ_y. When the design displacement is less than the yield displacement, the ϕ_{req} is expressed as

$$\phi_{req} = \frac{40}{11}\frac{\delta_u}{h_w^2} \quad (\delta_u < \delta_y) \tag{13}$$

The curvature capacity decreases as the axial load ratio, aspect ratio, and design drift ratio increase (Figure 8(a), (b), and (c)). This is because the curvature capacity is directly affected by the high axial load accompanied by the high design drift ratio. The curvature capacity also decreases as the aspect ratio increases, but the tendency is highly affected by the wall length. Even though the aspect ratios are similar, the curvature capacity for smaller wall length is larger than that for lager one (Figure 8(b)). The curvature demand shows the same trend as the neutral axis depth limit. For instance, the curvature demand does not show distinct correlation with the axial load ratio and the aspect ratio (Figure 8(d), (e)), on the other hand, it is proportional to the design drift ratio (Figure 8(f)) while the neutral axis depth limit is the inverse of the design drift ratio. This can be recognized by equation (8) and (9).

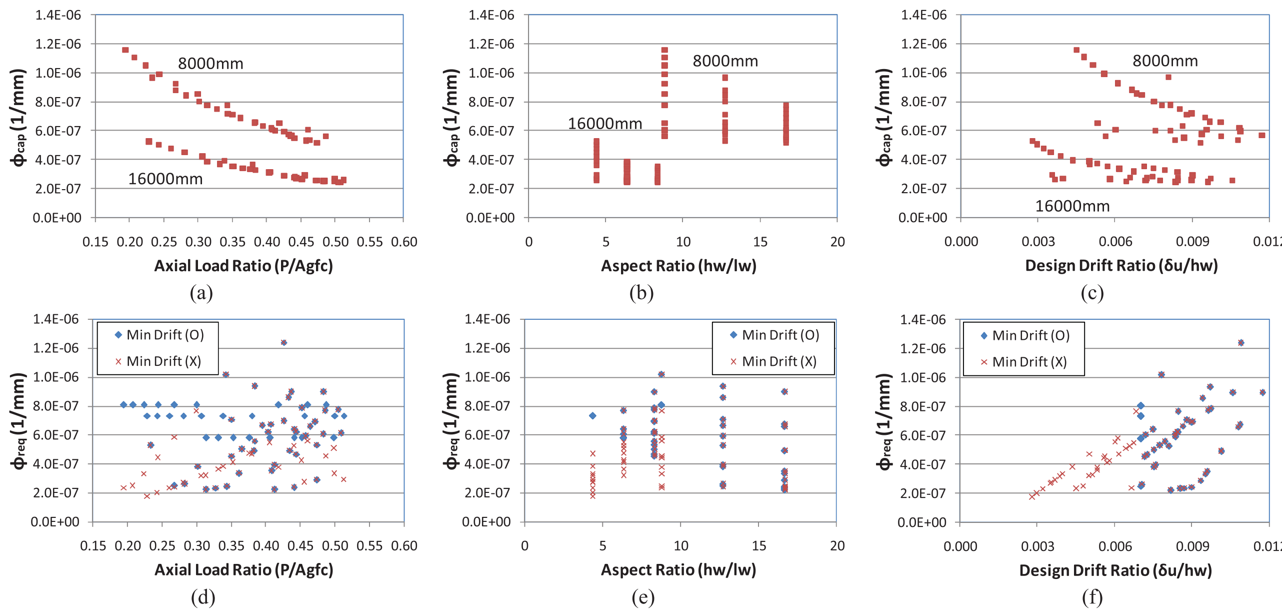


Figure 8. Curvature capacity and requirement

5. DISCUSSION

It is investigated the applicability of the proposed equation (10) to determine whether the SBE is necessary or not. The results of the proposed equation are compared with those of the current code and Kang & Kim (2010), which are shown in Figure 9. The ratios of the neutral axis depth to its limit (c/c_{lim}) are plotted for the three cases. It is noted that the SBE is necessary if this ratio is 1.0 or higher. The ratios are provided with and without applying the minimum design drift ratio. It can be seen that the values of the c/c_{lim} increase if applying the minimum ratio.

The results for the current code and Kang & Kim are firstly discussed. If using the current code, all of the shear walls need the SBE (Figure 9(a) through Figure 9(f)). The c/c_{lim} from Kang & Kim was slightly reduced compared to that from the current code, but those from both the code and Kang & Kim still exceed 1.0 in all of the shear walls. This is because the code specifies the minimum design drift ratio of 0.007. As matter of course, if you do not use the minimum design drift, the SBE is sometimes not necessary. As the axial load ratio increases, the c/c_{lim} increases, which means the probability of the SBE being necessary becomes greater (Figure 9(a), (d)). The probability also increases as the aspect ratio increases. As can be seen in Figure 9(b) and Figure 9(e), however, the size of the c/c_{lim} also depends on the absolute length of the wall. Even though the aspect ratio is same, the c/c_{lim} increases if the wall length is relatively large. As the design drift ratio increases, the c/c_{lim} increases since the c_{lim} is inversely proportional to the design drift ratio while the c is not affected by the design drift ratio (Figure 9(c), (f)).

If using the proposed method, there are some cases the SBE is not necessary even though the probability increases as the axial load ratio increases like the previous two methods. If you do not use the minimum design drift ratio, the proposed method showed the c/c_{lim} of less than 1.0 when the axial load ratio is less than 0.35. However, a number of the shear walls get to need the SBE among them when using the minimum design drift ratio (Figure 9(g), (h), and (i)). The difference between this proposed method and the previous two methods is that it is less sensitive to the aspect ratio and design drift ratio. This is because the design drift ratio is the strongest parameter to affect the c_{lim} in the previous two methods and it increases as the aspect ratio increases. Some of the shear walls did not need the SBE even when the aspect ratio is greater than 10 and the design drift ratio exceeds 0.007. In the proposed method, the elastic displacement is considered so that the SBE could be unnecessary even when both the aspect ratio and the design drift ratio are high. Therefore, some of the domestic high-rise shear walls might not need the SBE if the proposed method is applied, which is presented in Table 2.

The curvature mentioned above can be also used to determine the necessity of the SBE, but which got the same result as using the neutral axis depth. Even though both the curvature and neutral axis depth give us the same result, using the curvature has a remarkable strength since the capacity and demand is clearly distinctive and the ϕ_{req} can be provided in case that the design displacement is less than the yield displacement. As mentioned in the previous chapter, the SBE is necessary if the demand exceeds the capacity. There exists a merit for using the curvature, but it is still convenient to use the neutral axis depth, considering continuity with the existing standards.

The results of analyzing the characteristics of the walls are as follows, for which the SBE is not necessary when the proposed method is used. The number of story was not relevant, but the aspect ratio was more than 8.8. The wall length was only 8000mm; on the other hand, 16000mm walls must install the SBE regardless of the other parameters. This is because the demand in the wall cross section will be relatively large in long length walls even though the design displacement is the same. Therefore, in order to avoid installing the SBE, it will be better to design the shear wall with the aspect ratio as high as possible and the wall length as long as possible. Furthermore, the way to increase of the probability that the SBE is not necessary is that the axial load ratio is less than 0.35 (or at least 0.40) and the reinforcement ratio is 1.0% or less. That is to say, the probability increases when the reinforcement ratio decreases by increasing the wall thickness if the axial load ratio is high. An increase in the wall thickness is encouraged for reduction of the reinforcement ratio and the axial load ratio.

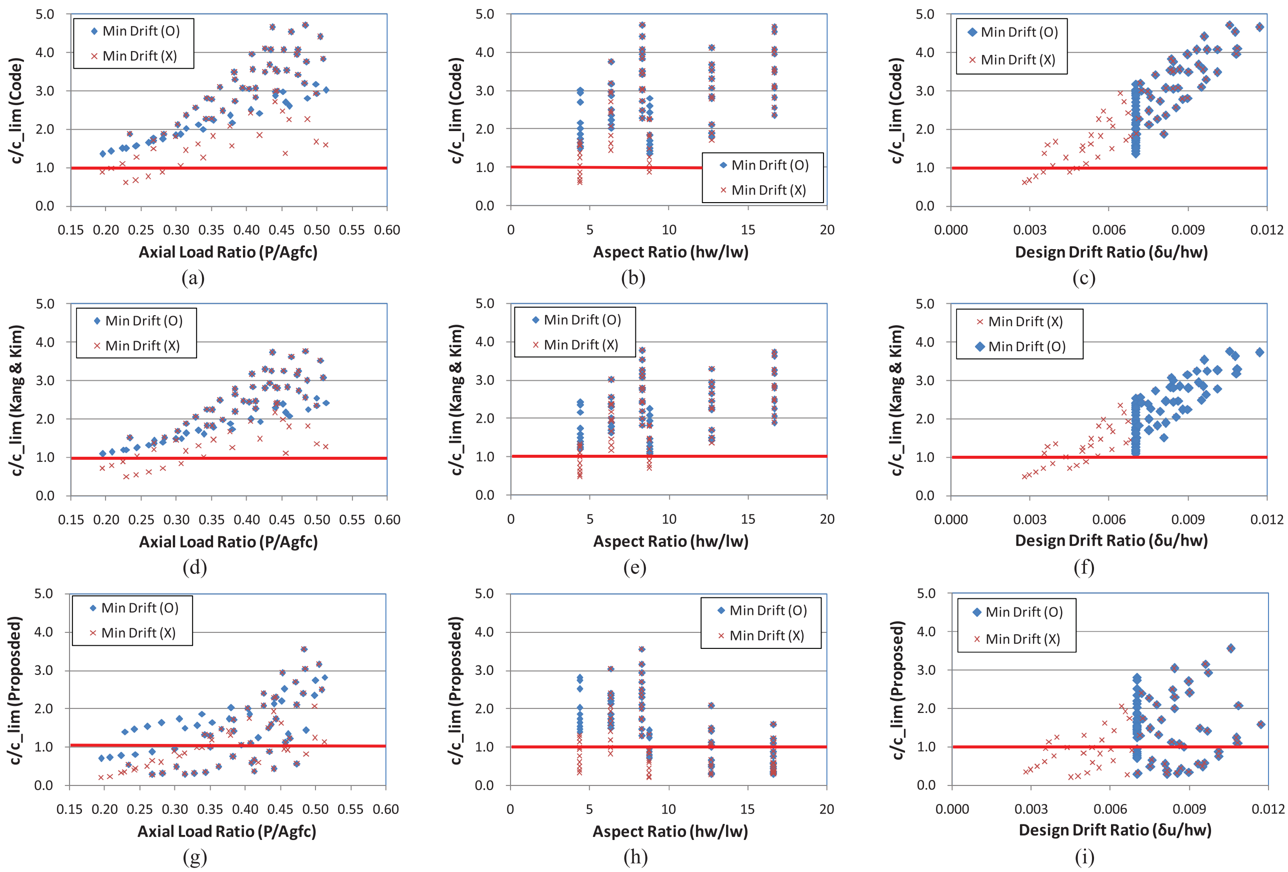


Figure 9. Ratio of neutral axis depth to neutral axis depth limit (code, Kang & Kim, proposed)

6. CONCLUSION

The equation in the current codes for determining the provision of the SBE in shear walls does not reflect the characteristics of the domestic high-rise shear walls, which are the high axial load ratio and high proportion of the elastic displacement to the total displacement. If applying the equation to the domestic high-rise shear walls, they need the SBE in almost all cases. To install the SBE in all of them is not economical, and not efficient in construction. In order to resolve this problem, a new equation reflecting the characteristics of the domestic high-rise shear walls was proposed. About a third of the example shear walls do not need to have the SBE if applying the proposed equation. As the result, using the proposed equation, the SBE may not be necessary in certain cases so that structural engineers can relieve the burden of installing the SBE in every shear wall.

For reducing the probability of providing the SBE when the proposed equation is used, the following conditions are recommended. The aspect ratio is 8.8 or higher regardless of the number of story. At this time, it is advantageous that the wall length is relatively small, the axial load ratio is less than 0.35 or 0.40, and the reinforcement ratio is less than 1.0%. The probability of not providing the SBE increases by increasing the wall thickness, which reduces both the reinforcement ratio and the axial load ratio.

In order to be able to use the proposed equation in codes, it is necessary to perform experiments that reflect the characteristics of the domestic high-rise shear walls. Especially, the experiments should be executed for walls with high axial load ratios and low design displacements. If the new equation can be verified through the experiments, it will be helpful when the type of the domestic high-rise shear walls is designed and constructed in low and mid seismic regions of the world.

In this study, the equation for determining the provision of the SBE is only dealt with. In addition to this, the proper size of the SBE and the amount of stirrups must be also studied. If following the current codes, more than half the neutral axis depth needs to be reinforced by the SBE. It should be also verified if such area is required to be reinforced in low and mid seismic regions like the domestic. As can be seen in this study, it might not be necessary to follow the size of the SBE and the amount of the stirrups required by the current codes because the demand of high-rise shear walls is not so large.

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