Steel and Composite Structures, *Vol. 20, No. 5 (2016) 1133-1153*
DOI: http://dx.doi.org/10.12989/scs.2016.20.5.1133

Additive 2D and 3D performance ratio analysis for steel outrigger alternative design

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(*Received February 24, 2015, Revised December 14, 2015, Accepted January 15, 2016*)

Abstract. In this article, an additive performance ratio method using structural analysis of both 2D and 3D is introduced to mitigate the complexity of work evaluating structural performances of numerous steel outrigger alternatives in multi-story buildings, especially high-rise buildings. The combined structural analysis process enables to be the design of economic, safe, and as constructional demanding structures by exploiting the advantages of steel, namely: excellent energy dissipation and ductility. First the approach decides the alternative of numerous steel outriggers by a simple 2D analysis module and then the alternative is evaluated by 3D analysis module. Initial structural analyses of outrigger types are carried out through MIDAS Gen 2D modeling, approximately, and then the results appeal structural performance and lead to decide some alternative of outrigger types. ETABS 3D modeling is used with respect to realization and evaluation of exact structural behaviors. The approach reduces computational burden in compared to existing concepts such as full 3D analysis methods. The combined 2D and 3D tools are verified by cycle and displacement tests including comprehensive nonlinear dynamic simulations. The advantages and limitations of the Additive Performance Ratio Approach are highlighted in a case study on a high rise steel-composite building, which targets at designing the optimized alternative to the existing original outrigger for lateral load resisting system.

Keywords: additive performance ratio method; structural analysis; steel outrigger; high-rise building; alternative; lateral load resisting system

1. Introduction

Among the residential apartments in Korea, most high-rise apartments with heights ranging from 40~70 floors are mixed-use apartments. In multi-story buildings with such height, the outrigger system (Fatima *et al.* 2011, Ali and Moon 2007, Deason *et al.* 2001, Wu and Li 2003, Lee *et al.* 2015, Lee *et al.* 2012) is very frequently applied, which effectively controls the excessive drift to lateral load. Especially in high-rise buildings with 100 or more stories, the use of an outrigger system is essential and a hybrid system combined with mega columns is also often adopted to resist lateral loading of high-rise buildings recently. Thus, a construction plan where an outrigger will connect a core and a mega column has a significant effect on the overall construction period.

The construction ability for one floor of outrigger plays a crucial role in a critical path because

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http://www.techno-press.org/?journal=scs&subpage=6 ISSN: 1229-9367 (Print), 1598-6233 (Online)

outriggers are formed in at least one story and up to 5 stories and in 2-3 zones in high-rise buildings with 100 stories or more. The shape of an outrigger determines the number of members and joints - the determining factors in the construction period.

In this article, consequently, the structure and performance of Jamsil world tower (Cho and Chung 2011), the representative high-rise building in Korea, are assessed to analyze the shape of the outrigger, and the structure and performance of various shapes are evaluated and compared to the original plan of outrigger design. The structural performance evaluation is performed by the present additive performance - displacement to weight - ratio method using combined 2D and 3D structural analyses. First the present method leads to decide the alternative of numerous steel outriggers by a simple 2D analysis module and then the alternative is evaluated by 3D analysis module.

The approach reduces computational burden in compared to existing concepts such as full 3D structural analysis methods (Zeng and Wiberg 1989, Ahmed 2015) and finite discritization methods (Akhaveissy 2012, Li *et al*. 2008, Pekau *et al*. 1996) simplifying 3D building models which use a 3D model for overall analysis of tall buildings. MIDAS-Gen (MIDAS Industry Co. 2011, Yang *et al*. 2012) a domestic general program, is used in 2D simulation and ETABS (Computers and Structures 2013, Wilson 2002, Osgoei and Gerami 2012), a general program for Jamsil world tower, is used in 3D analysis.

The outline of this study is as follows: The overview of subject structure is presented in Section 2 including the applied structural system, i.e., a combined core wall-mega column-outrigger-belt truss. In Section 3, the formulation of performance ratio or stiffness contribution ratio is presented to evaluate structural performance of outrigger systems, including a flowchart of the present method. The outrigger shape applied to Jamsil world tower and other shapes are evaluated to find the one possessing the optimal performance in Section 4 by using the present additive performance ratio method using 2D and 3D structural analysis. Finally, Section 5 presents the conclusions of this study, respectively.

2. Overview of subject structure

The building to which this study aims to apply the study result is Lotte Jamsil world tower located in Jamsil, Seoul, Korea. The final design of this building that used to be called as Jamsil 2d Lotte World was determined after multiple design changes. In this study, performance evaluation is conducted with the design in Schematic Design (SD) 100% stage. Fig. 1 and Table 1 below show the overview of the building in SD 100% stage.

The lateral load resisting systems applied to high-rise buildings are a tube system, an outrigger

Table 1 Overview of building

Items	Description
Location	Sincheon-dong, Songpa-gu, Seoul, Korea
Height	555 m
Number of Ssories	123 stories above ground and 6 stories underground
Purpose	Hotel, office, officetel, retail, etc.
Structure	Core wall + Mega Column + Outrigger Belt Truss

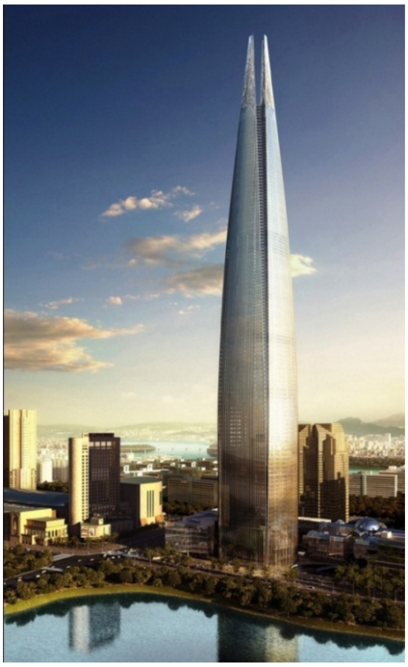


Fig. 1 Bird’s eye view of Jamsil world tower

& belt truss system, a brace system (Lee *et al*. 2016), etc. Recently, not one system but a hybrid system is applied as buildings become higher. Following the 911 terrorist attacks in the U.S., the tube system is no longer extensively used because of its vulnerability to progressive collapse (General Service Administration 2003, Kim and Lee 2010, Kim and Park 2008).

Jamsil world tower, the structure evaluated in this study, has a hybrid system where core walls, mega columns and outriggers & belt trusses are combined. The core walls and mega columns are RC structures and outrigger & belt truss are steel structures (Lee and Shin 2014, Lee *et al*. 2014).

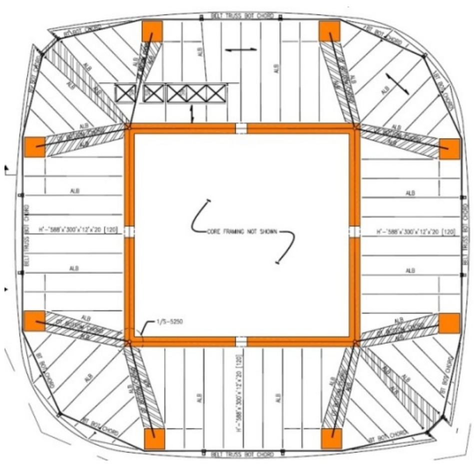
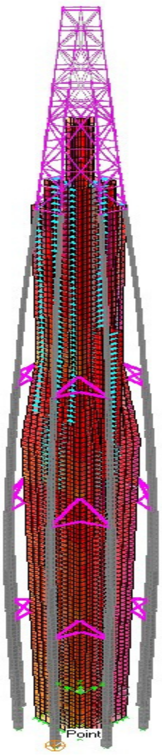
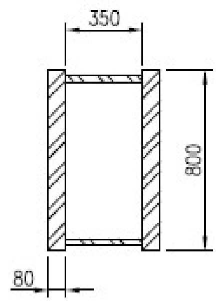


Fig. 2 Outrigger + core + mega column





Shape : Box type
Flange : 20 mm
Web : 80 mm
Offset : 40 mm
Steel type : SM490

(a) Outriggers in an analysis modeling (b) Example of a section of an outrigger member

Fig. 3 Outrigger system

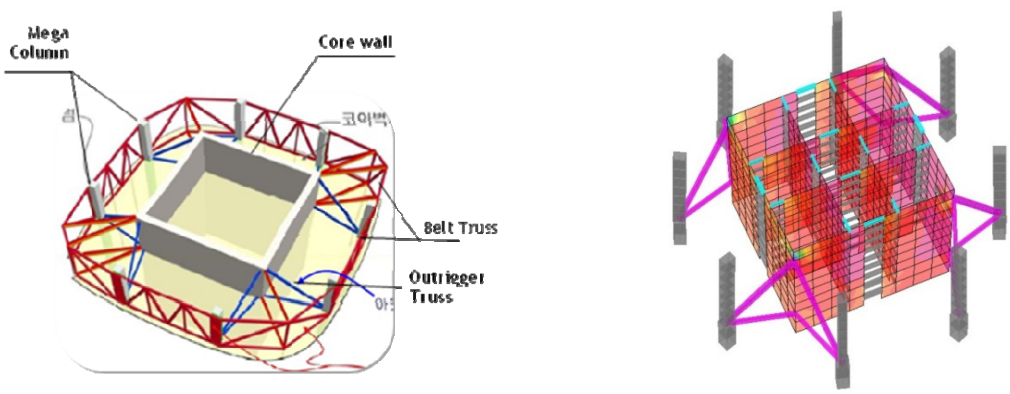
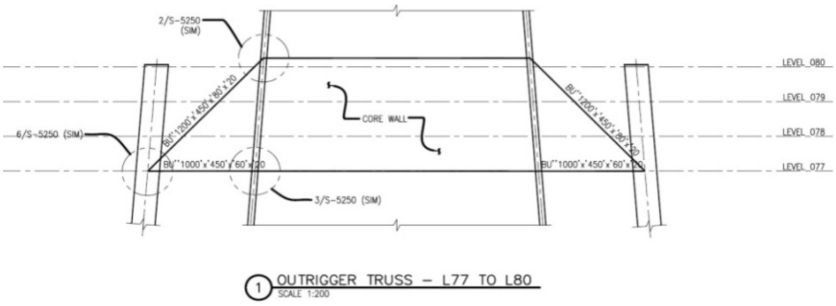
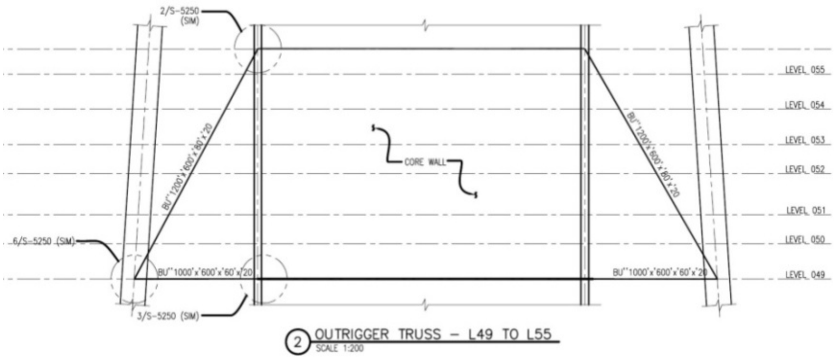
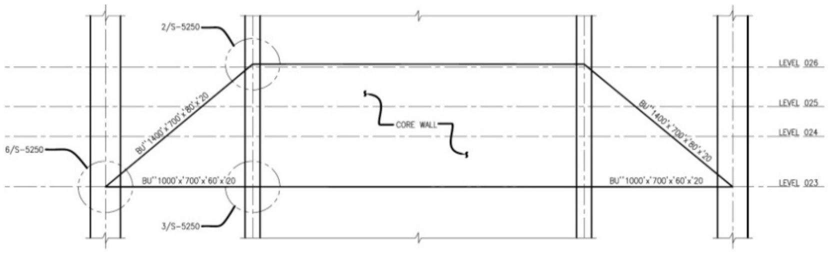


Fig. 4 Lateral load resisting system

As a representative lateral load resisting system, the core system is used widely in general buildings. In a world high-rise building, however, a core system alone is insufficient to resist lateral loads. Thus, a core connected to external mega columns is used to resist, as shown in Fig. 2, and outriggers and belt trusses are additionally installed in 3 zones (see Fig. 3).

The section and location of an outrigger system for each zone are shown in Table 2.

Table 2 Section and size for each outrigger zone

Section	Location and Size
	Location: 77~80 stories (LO77-80) Height: 10.8 m Width: 12.0 m
	Location: 49~55 stories (LO49-55) Height: 21.6 m Width: 14.0 m
	Location: 23~26 stories (LO23-26) Height: 13.5 m Width: 15.0 m

		L023-L026	L049-L055	L077-L080
Geometry (mm, Degree)	Height	13,500	21,600	10,800
	Length	15,000	14,000	12,000
	Diagonal	20,180	25,740	16,144
	Angle	42°	57°	42°
Core wall thickness		1,500	800	600
Member size	Diagonal	BU-1,400×550×80×20	BU-1,200×440×80×20	BU-1,200×290×80×20
	Chord	BU-1000×580×60×20	BU-1,000×480×60×20	BU-1,000×330×60×20
Forces (P_u, kN)`	Diagonal	46,344	44,530	39,156
	Chord	34,448	24,220	29,112

3. Formulation of performance ratio for evaluating outrigger alternative

The high-rise building examined in this study is not the building with one kind of structural system but a hybrid system. Therefore it is significant to quantitatively investigate how each structural system affects stiffness of the given building. In this study, contribution of bearing lateral forces is as follows:

A representative value of stiffness on each structural system is obtained by that of displacement as shown in Eq. (1), and is written in Eq. (2). The representative value of stiffness on each structural system is divided by weight of i-th story which consists of outriggers, and then the so-called performance ratio or stiffness contribution ratio is written into Eq. (3). Fig. 5 shows flowchart of the additive performance ratio method.

- Representative value of displacement

$$X_i = \sqrt{\frac{\sum \Phi_i^2}{N}} \tag{1}$$

where Φ_i : displacement of i-th story, N : the number of story

- Representative value of stiffness

$$I_i = \frac{1}{X_i} \tag{2}$$

- Performance ratio

$$P_i = \frac{I_i}{W_i} \tag{3}$$

where W_i : weight of i-th story, here outrigger stories

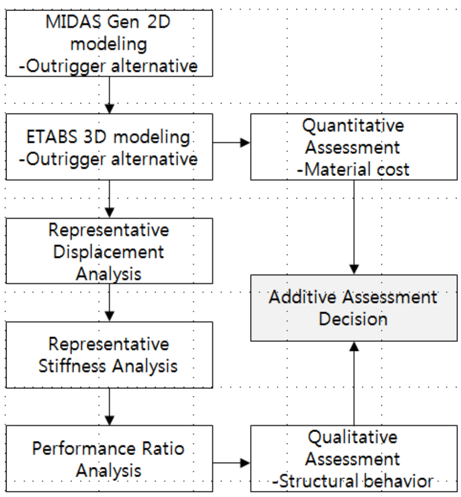


Fig. 5 Flowchart of the additive performance method

4. Structural performance analysis of alternative design of outrigger

In Section 4, the outrigger shape applied to Jamsil world tower and other shapes are evaluated to find the one possessing the optimal performance. Here the present additive performance ratio - vertical displacement to weight or volume ratio - method using 2D and 3D structural analysis is provided for effective structural performance evaluation, which enables to reduce computational burden. Outrigger shapes (Raj Kiran Nanduri *et al*. 2013, El-Leithy *et al*. 2011, Gerasimidis *et al*. 2009) are separated and 2D analyses using MIDAS-Gen are conducted to evaluate performance of various outrigger types. For those found to have the same or better structural performance than the original plan after the 2D analysis, a 3D analysis is conducted with ETABS.

4.1 Additive performance ratio method of outrigger alternative for 2D analysis

A 2D analysis is conducted on 6 outrigger shapes to evaluate their structural performance. The results are shown in Fig. 6. Six shapes are evaluated, including the original plan (type 1).

The modeling for each type in MIDAS-Gen is as shown in Fig. 7, with additional modeling conducted from the reverse direction of type 1, but the result is the same.

The evaluation of structural performance is conducted by applying vertical loads on mega columns upwards and downwards as shown in Fig. 8 and evaluating the size of vertical displacement. A vertical load of 26,200 kN (= 39,156 × sin42°) - the vertical component of 39,156 kN that worked on diagonal members - is applied.

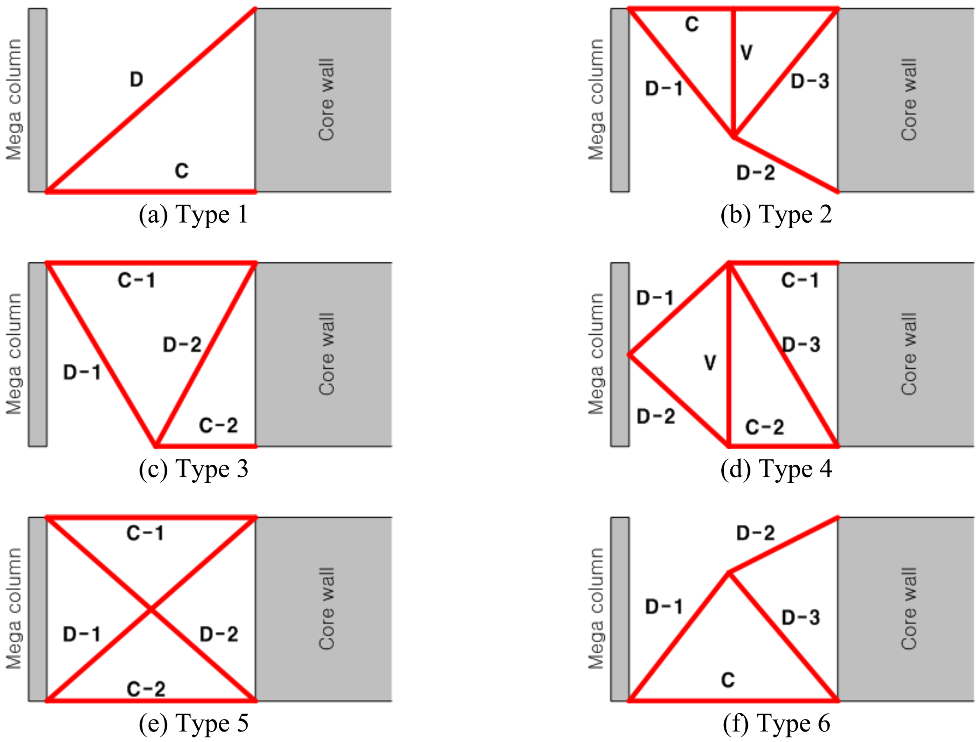


Fig. 6 Shape by types

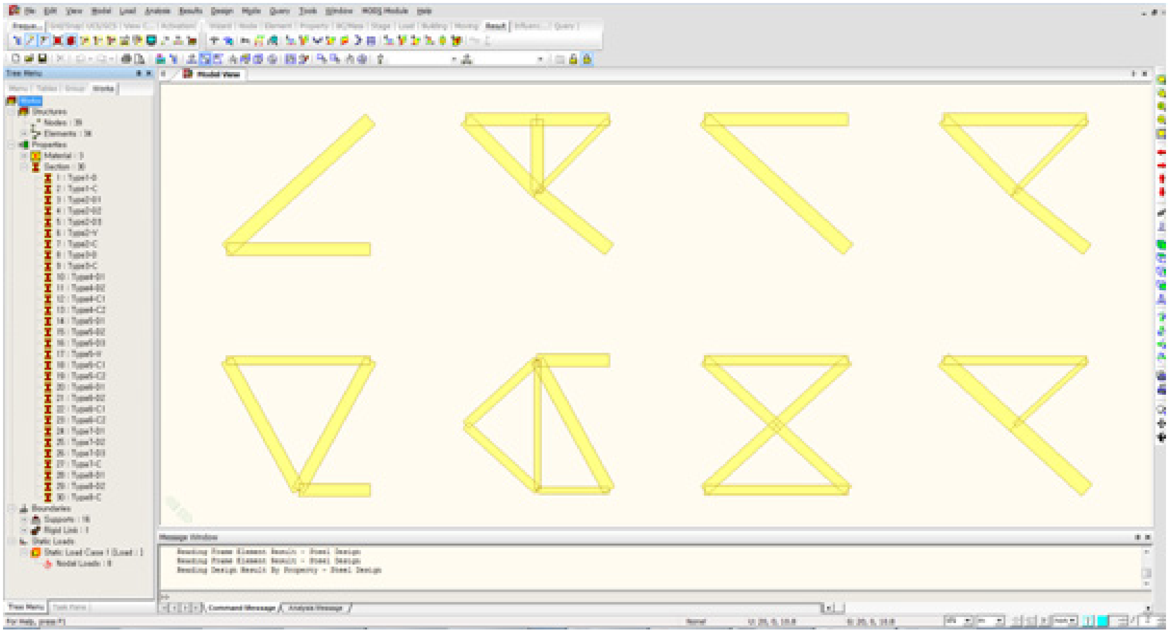


Fig. 7 MIDAS-Gen modeling by types

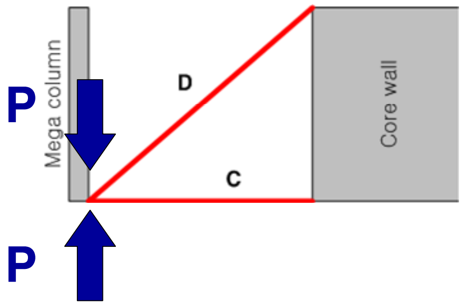


Fig. 8 Direction of load action in 2D analysis

Table 3 Size of members by types (high stories)

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B+2T_w$	
Type-1	Diagonal	1,200	290	80	20	450	4.885
	Chord	1,000	330	60	20	450	
Type-2	Diagonal-1	1,150	310	70	20	450	4.897 (100.24%)
	Diagonal-2	1,150	310	70	20	450	
	Diagonal-3	500	390	30	20	450	
	Vertical	1,000	370	40	20	450	
	Chord	1,000	370	40	20	450	

Table 3 Continued

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B + 2T_w$	
Type-3	Diagonal-1	1,050	330	60	20	450	4.930 (100.92%)
	Diagonal-2	1,050	330	60	20	450	
	Chord-1	700	390	30	20	450	
	Chord-2	1,000	330	60	20	450	
Type-4	Diagonal-1	750	350	50	20	450	4.900 (100.31%)
	Diagonal-2	750	350	50	20	450	
	Diagonal-3	1,050	330	60	20	450	
	Vertical	500	370	40	20	450	
	Chord-1	1,000	330	60	20	450	
	Chord-2	550	370	40	20	450	
Type-5	Diagonal-1	900	350	50	20	450	4.884 (99.98%)
	Diagonal-2	900	350	50	20	450	
	Chord-1	800	390	30	20	450	
	Chord-2	800	390	30	20	450	
Type-6	Diagonal-1	1,050	290	80	20	450	4.889 (100.08%)
	Diagonal-2	1,050	290	80	20	450	
	Diagonal-3	500	390	30	20	450	
	Chord	1,000	330	60	20	450	

The outrigger system in high stories (77~80th stories) is first selected and the quantities of types 2~6 are adjusted to the original plan to evaluate structural performance by shapes. The size of members is as shown in Table 3 above.

As can be seen in Table 4, according to the analysis result, the type with similar or better vertical displacement than the original plan is type 5 and type 6.

Table 4 Performance ratio by types and vertical displacement (high stories)

Category		Total volume (m^3)	Performance ratio	Vertical displacement (cm)
Type-1	Diagonal	4.885	0.896	3.686
	Chord		0.823	
Type-2	Diagonal-1	4.897 (100.24%)	0.914	4.074 (110.53%)
	Diagonal-2		0.899	
	Diagonal-3		0.357	
	Vertical		0.000	
	Chord		0.945	

Table 4 Continued

Category		Total volume (m^3)	Performance ratio	Vertical displacement (cm)
Type-3	Diagonal-1	4.930 (100.92%)	0.912	4.051 (109.90%)
	Diagonal-2		0.912	
	Chord-1		0.864	
	Chord-2		0.823	
Type-4	Diagonal-1	4.900 (100.31%)	0.927	4.523 (122.71%)
	Diagonal-2		0.927	
	Diagonal-3		0.912	
	Vertical		0.915	
	Chord-1		0.823	
	Chord-2		0.846	
Type-5	Diagonal-1	4.884 (99.98%)	0.792	3.705 (100.52%)
	Diagonal-2		0.792	
	Chord-1		0.782	
	Chord-2		0.782	
Type-6	Diagonal-1	4.889 (100.08%)	0.888	3.525 (95.63%)
	Diagonal-2		0.872	
	Diagonal-3		0.357	
	Chord		0.741	

Although type 2 is similar to type 6, its brace quantity is reduced because of the presence of vertical members (V), and consequently, its vertical displacement increases.

For the case of type 3, the size of C-2 members is increased because the location of joints where horizontal members and braces of C-2 met is disadvantageous to transfer loads, which resulted in an increase in the vertical displacement due to the reduction in the size of brace members.

Type 4 had a relatively large number of members considering the structural role of its outriggers, which caused a decrease in the size of each member, although its overall quantity is the same. It had the largest vertical displacement among all types, which means the lowest structural performance.

Type 5, a typical truss form, is the same as installing the originally planned forms twice. Although its section is reduced as a result, the overall structural performance is similar to that of the original plan.

In type 6, brace members (D-3) are added to the original plan, which resulted in better overall vertical displacement performance compared to the original plan by reducing the working loads on brace members (D-1 and D-2) and horizontal members (C).

However, it is estimated that there will be additional loads on the joints with core walls in type 6 due to the added braces. Therefore, the structural performance of core walls in terms of additional loads shall be reviewed.

Moreover, types 5 and 6 generally have better performance ratios than the original plan, which suggests the possibility of reduction in quantity. Therefore, the performance ratios of type 1 plan, type 5 and type 6 are standardized to be approximately 0.9 and their quantity and vertical displacement are evaluated.

Fig. 9 indicates the modeling analyzed by standardizing the performance ratios of type 1 plan,

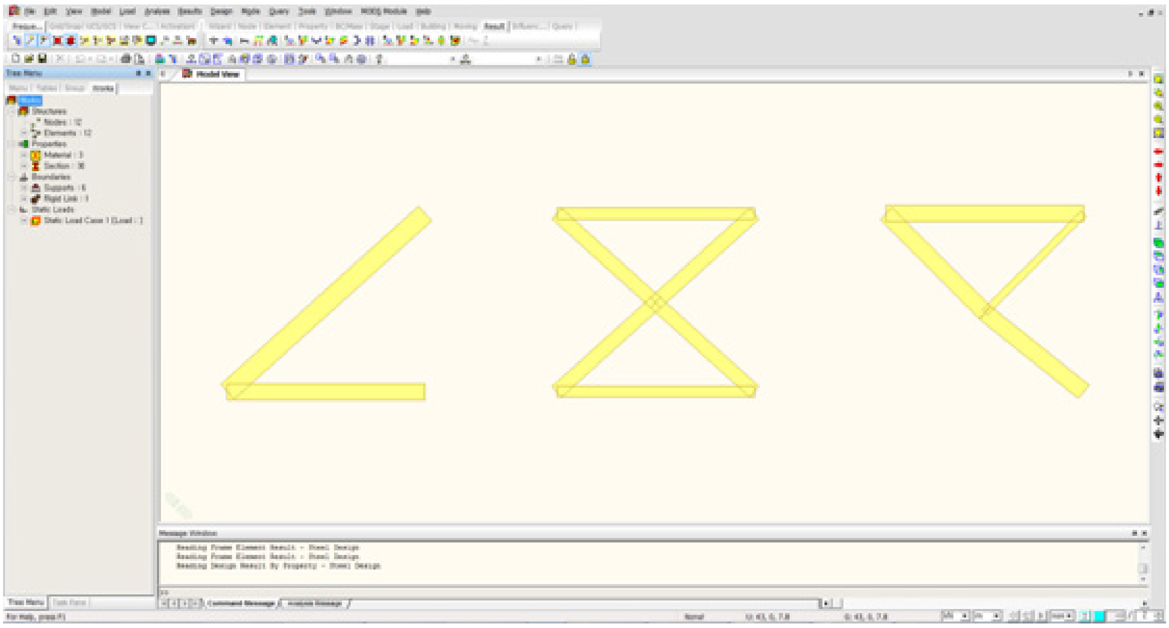


Fig. 9 MIDAS-Gen modeling (performance ratio standardized)

Table 5 Size of members according to equation of performance ratios of type 1, type 5 & type 6 (high stories)

Category		Size of Section					Total volume (m^3)	Performance ratio
		D	B	T_w	T_f	$B+2T_w$		
Type-1	Diagonal	1,200	290	80	20	450	4.885	0.896
	Chord	1,000	330	60	20	450		0.823
Type-1’	Diagonal	1,200	290	80	20	450	4.770 (97.64%)	0.896
	Chord	1,000	340	55	20	450		0.889
Type-5	Diagonal-1	860	360	45	20	450	4.318 (88.38%)	0.896
	Diagonal-2	860	360	45	20	450		0.896
	Chord-1	680	390	30	20	450		0.884
	Chord-2	680	390	30	20	450		0.884
Type-6	Diagonal-1	1,030	290	80	20	450	4.488 (91.87%)	0.904
	Diagonal-2	1,030	290	80	20	450		0.888
	Diagonal-3	450	410	20	20	450		0.479
	Chord	980	350	50	20	450		0.883

type 5 and type 6.

Table 5 shows size of members by standardizing the performance ratios of type 1 plan, type 5 and type 6.

In Fig. 4, type 1 - highlighted in yellow - is the original plan and type 1’ below shows members where the performance ratio of horizontal members is changed to about 0.9. The resulting evaluation of vertical displacement of the remaining types based on the vertical displacement of type 1’ is shown in Table 6.

For the case of type 5, the quantity decreases by about 11.6% compared to the original plan, but the vertical displacement increases by 10.4% compared to type 1’ when performance ratios are standardized.

Although the quantity decreases by 8.2%, type 6 has very similar vertical displacement to type 1’, when performance ratios are standardized. Thus the structural performance according to shapes is in the order of type 6 > type 1 > type 5.

In addition, the superior performances of type 5 and type 6 in high-story buildings are compared to the result of type 1 to evaluate the shape of outriggers in the middle stories (49~55 stories) using the same analysis method. For the effect of vertical loads on mega columns, however, 37,346 kN - the load that worked on the middle stories - is applied. The size of members and vertical displacement in middle stories are shown in Table 7 and 8 by outrigger types.

Table 6 Vertical displacement of type 1, type 5 & type 6 with performance ratios standardized (high stories)

Category	Vertical displacement (cm)
Type-1	3.686 (97.10%)
Type-1’	3.796 (100.0%)
Type-5	4.190 (110.38%)
Type-6	3.804 (100.21%)

Table 7 Size of members by types (middle stories)

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B + 2T_w$	
Type-1	Diagonal	1,200	440	80	20	600	7.344
	Chord	1,000	480	60	20	600	
Type-5	Diagonal-1	900	500	50	20	600	7.360 (99.21%)
	Diagonal-2	900	500	50	20	600	
	Chord-1	650	540	30	20	600	
	Chord-2	650	540	30	20	600	
Type-6	Diagonal-1	1,200	450	75	20	600	7.359 (100.21%)
	Diagonal-2	1,200	450	75	20	600	
	Diagonal-3	500	540	30	20	600	
	Chord	900	500	50	20	600	

Table 8 Performance ratio and vertical displacement by types (middle stories)

Category		Total volume (m^3)	Performance ratio	Vertical displacement (cm)
Type-1	Diagonal	7.344	0.937	3.947
	Chord		0.656	
Type-5	Diagonal-1	7.360 (99.21%)	0.888	3.911 (99.09%)
	Diagonal-2		0.888	
	Chord-1		0.684	
	Chord-2		0.684	
Type-6	Diagonal-1	7.359 (100.21%)	0.962	3.906 (98.96%)
	Diagonal-2		0.893	
	Diagonal-3		0.433	
	Chord		0.747	

When the quantity is standardized, the analysis results of the performance ratio and vertical displacement are generally similar to those of high stories. But a slight difference in vertical displacement is noted in type 6, possibly due to the concentration of axial force on the member that resists vertical loads because middle stories had greater height than width, while high stories had greater width than height.

The evaluation of quantity and vertical displacement when performance ratios of all types are standardized to 0.9 as in the high stories are shown in Tables 9 and 10.

When performance ratios are standardized, overall analysis is similar to that of the high stories. Type 6 spent less quantity than type 1 for the same performance in the high stories, while type 1

Table 9 Size of members of type 1, type 5 & type 6 with performance ratios standardized (middle stories)

Category		Size of section					Total volume (m^3)	Performance ratio
		D	B	T_w	T_f	$B+2T_w$		
Type-1	Diagonal	1,200	440	80	20	600	7.344	0.937
	Chord	1,000	480	60	20	600		0.656
Type-1’	Diagonal	1,200	440	80	20	600	6.815 (92.79%)	0.937
	Chord	900	510	45	20	600		0.901
Type-5	Diagonal-1	850	500	50	20	600	6.705 (91.29%)	0.932
	Diagonal-2	850	500	50	20	600		0.932
	Chord-1	600	560	20	20	600		0.893
	Chord-2	600	560	20	20	600		0.893
Type-6	Diagonal-1	1,200	450	75	20	600	7.006 (95.40%)	0.962
	Diagonal-2	1,200	450	75	20	600		0.893
	Diagonal-3	500	540	30	20	600		0.433
	Chord	800	520	40	20	600		0.879

Table 10 Vertical displacement of type 1, type 5 & type 6 with performance ratios standardized (middle stories)

Category	Vertical displacement (cm)
Type-1	3.947 (93.22%)
Type-1’	4.234 (100.0%)
Type-5	4.326 (102.17%)
Type-6	4.141 (97.80%)

Table 11 Size of members by types (low stories)

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B + 2T_w$	
Type-1	Diagonal	1,400	550	80	20	710	7.112
	Chord	1,000	580	60	20	700	
Type-5	Diagonal-1	1,000	610	50	20	710	7.139 (100.37%)
	Diagonal-2	1,000	610	50	20	710	
	Chord-1	750	640	30	20	700	
	Chord-2	750	640	30	20	700	
Type-6	Diagonal-1	1,350	560	75	20	710	7.139 (100.38%)
	Diagonal-2	1,350	560	75	20	710	
	Diagonal-3	500	640	30	20	700	
	Chord	1,000	590	55	20	700	

Table 12 Performance ratio and vertical displacement by types (low stories)

Category		Total volume (m^3)	Performance ratio	Vertical displacement (cm)
Type-1	Diagonal	7.112	0.927	4.729
	Chord		0.907	
Type-5	Diagonal-1	7.139 (100.37%)	0.886	4.698 (99.35%)
	Diagonal-2		0.886	
	Chord-1		0.925	
	Chord-2		0.925	
Type-6	Diagonal-1	7.139 (100.38%)	0.938	4.463 (94.38%)
	Diagonal-2		0.923	
	Diagonal-3		0.511	
	Chord		0.908	

spent less quantity than type 6 in the middle stories. These findings are thought to be caused by the considerable reduction in the size of horizontal members when the performance ratios are standardized (performance ratio of horizontal members increases only slightly from 0.823 to 0.889, in the high stories but increases significantly from 0.656 to 0.901, in the middle stories). In other words, the size of horizontal members in type 1' used as a standard decreases considerably because the effect on horizontal members is less in types 5 and 6 than in type 1, while one vertical member and one horizontal member each resist loads in type 1. Analysis of vertical displacement also revealed similar results as those found during analysis of quantity.

Finally, an analysis is conducted using the same method as before to evaluate the shape of outriggers in lower stories (23~26 stories). For the vertical load's effect on mega columns, however, 31,010 kN – the load that worked on the low stories – is applied. The size of members and vertical displacement in low stories by outrigger types are shown in Tables 11 and 12.

When quantity is standardized, the analysis results of performance ratios and vertical displacements are generally similar to those from the high stories, possibly because of similarities in the ratio of height to width in high stories and low stories. Performance ratios of all types are originally planned to be standardized to 0.9 to evaluate quantity and vertical displacement, but the performance ratio of type 1 is chosen as a standard because it is close to 0.9. The results are shown in Tables 13 and 14.

When the performance ratio is standardized, the overall results are similar to those of the high stories and the middle stories. Type 6 displayed better performance than type 1 and type 5.

Table 13 Size of members of type 1, type 5 & type 6 with performance ratios standardized (low stories)

Category		Size of section					Total volume (m^3)	Performance ratio
		D	B	T_w	T_f	$B + 2T_w$		
Type-1	Diagonal	1,400	550	80	20	710	7.112	0.927
	Chord	1,000	580	60	20	700		0.907
Type-1'	Diagonal	1,400	550	80	20	710	7.112 (100.00%)	0.927
	Chord	1,000	580	60	20	700		0.907
Type-5	Diagonal-1	900	610	50	20	710	6.735 (94.70%)	0.925
	Diagonal-2	900	610	50	20	710		0.925
	Chord-1	750	640	30	20	700		0.914
	Chord-2	750	640	30	20	700		0.914
Type-6	Diagonal-1	1,350	560	75	20	710	7.139 (100.38%)	0.938
	Diagonal-2	1,350	560	75	20	710		0.923
	Diagonal-3	500	640	30	20	700		0.511
	Chord	1,000	590	55	20	700		0.908

Table 14 Vertical displacement of type 1, type 5 & type 6 with performance ratios standardized (low stories)

Category	Vertical displacement (cm)
Type-1	4.729 (100.0%)
Type-1'	4.729 (100.0%)
Type-5	4.942 (104.12%)
Type-6	4.463 (94.38%)

Table 15 Vertical displacement of type 1, type 5 & type 6 with quantity standardized

Category	High stories	Middle stories	Low stories
Type-1	100.0%	100.0%	100.0%
Type-5	100.52%	99.09%	99.35%
Type-6	95.63%	98.96%	94.38%

Table 16 Comparison of quantity and vertical displacement in type 1, type 5 & type 6 with performance ratios standardized

Category		High stories	Middle stories	Low stories
Comparison of Quantity	Type-1	100.0%	100.0%	100.0%
	Type-5	88.38%	91.29%	94.70%
	Type-6	91.87%	95.40%	100.38%
Comparison of Vertical Displacement	Type-1’	100.0%	100.0%	100.0%
	Type-5	110.38%	102.17%	104.12%
	Type-6	100.21%	97.80%	94.38%

Based on the results above, Table 15 displays the summarized results of vertical displacement in high stories, middle stories and low stories when quantity is standardized. As shown in the table below, type 6 displayed 5.6~1.0% better performance than the original plan with the same quantity, while type 1 and type 5 displayed similar performances.

Table 16 describes the results of quantity compared to the original plan and vertical displacement compared to type 1’ in high stories, middle stories and low stories when performance ratios are standardized. Although the quantity of type 5 decreases significantly as a whole, it cannot be considered as an efficient outrigger shape because its vertical displacement increases about 2.2~10.4%. In addition, type 5 has a disadvantage in construction because it has the largest number of joints.

In the case of type 6, vertical displacement is similar in high stories but a reduction in quantity is possible. The quantity is similar in low stories but vertical displacement decreases. In middle stories, the quantity and vertical displacement decreases from high stories and low stories by 4.6% and 2.2%, respectively.

In other words, type 6 is the most suitable shape for use as an outrigger among the shapes analyzed in this study, and it has better structural performance than the shape applied to Jamsil world tower.

4.2 Additive performance ratio method of outrigger alternative for 3D analysis

The 2D analysis results in Section 4.1 indicated that types 5 and 6 had similar structural performances to the original plan so 3D analysis is conducted with ETABS on them. The load in the original plan of Jamsil world tower is applied, while the shape of outriggers and the size of members are adjusted. Sizes of members are calculated separately by high stories, middle stories and low stories and applied as shown in Tables 17~19 to evaluate structural performance by types in the same quantity.

Table 17 Size of members in high stories (77~80th stories)

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B+2T_w$	
Type-1	Diagonal	900	350	50	20	450	4.885
	Chord	900	350	50	20	450	
Type-5	Diagonal-1	800	390	30	20	450	4.884 (99.98%)
	Diagonal-2	800	390	30	20	450	
	Chord-1	1,050	290	80	20	450	
	Chord-2	1,050	290	80	20	450	
Type-6	Diagonal-1	500	390	30	20	450	4.889 (100.08%)
	Diagonal-2	1,000	330	60	20	450	
	Diagonal-3	900	350	50	20	450	
	Chord	900	350	50	20	450	

Table 18 Size of members in middle stories (49~55th stories)

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B+2T_w$	
Type-1	Diagonal	1,200	440	80	20	600	7.344
	Chord	1,000	480	60	20	600	
Type-5	Diagonal-1	900	500	50	20	600	7.360 (99.21%)
	Diagonal-2	900	500	50	20	600	
	Chord-1	650	540	30	20	600	
	Chord-2	650	540	30	20	600	
Type-6	Diagonal-1	1,200	450	75	20	600	7.359 (100.21%)
	Diagonal-2	1,200	450	75	20	600	
	Diagonal-3	500	540	30	20	600	
	Chord	900	500	50	20	600	

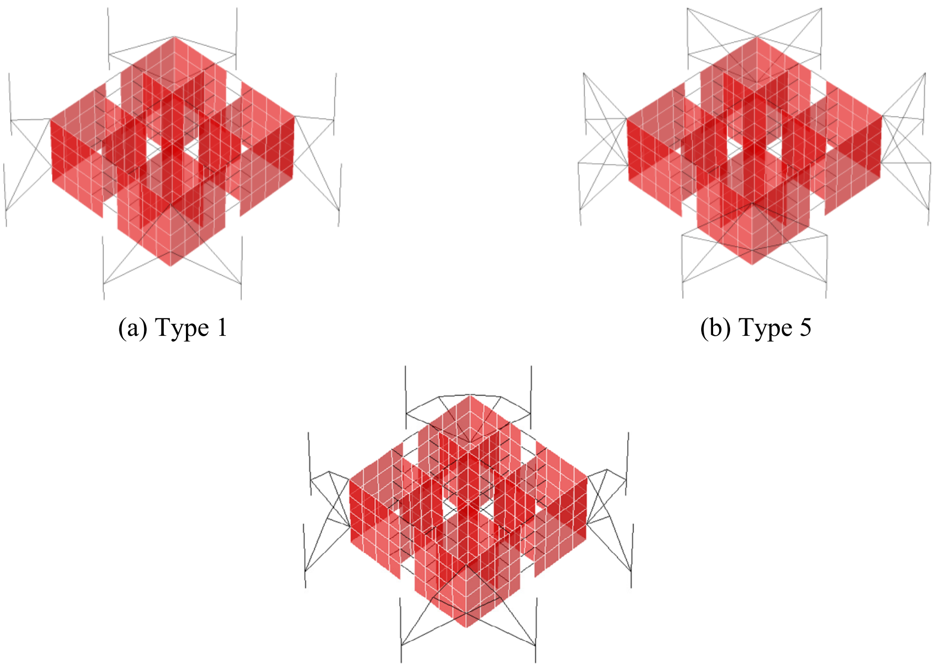
Table 19 Size of members in low stories (23~26th stories)

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B+2T_w$	
Type-1	Diagonal	1,400	550	80	20	710	7.112
	Chord	1,000	580	60	20	700	
Type-5	Diagonal-1	1,000	610	50	20	710	7.139 (100.37%)
	Diagonal-2	1,000	610	50	20	710	
	Chord-1	750	640	30	20	700	
	Chord-2	750	640	30	20	700	

Table 19 Continued

Category		Size of section					Total volume (m^3)
		D	B	T_w	T_f	$B+2T_w$	
Type-6	Diagonal-1	1,350	560	75	20	710	7.139 (100.38%)
	Diagonal-2	1,350	560	75	20	710	
	Diagonal-3	500	640	30	20	700	
	Chord	1,000	590	55	20	700	

Fig. 10 displays the changes made to outrigger shapes on ETABS. As can be seen, outrigger alternative combined with core walls (with red color) and mega columns may be easily and visually described with respect to connectivity and joint location of outrigger members from ETABS.



(a) Type 1

(b) Type 5

(c) Type 6

Fig. 10 ETABS model (low stories)

Table 20 3D Analysis

Category	Cycle (s)	Displacement in highest floor (cm)	Acceptable displacement (cm)
Type 1	8.737	90.26	111.0
Type 5	8.788 (Increased by 0.6%)	92.04 (Increased by 2.0%)	
Type 6	8.925 (Increased by 2.2%)	92.11 (Increased by 2.1%)	

Table 20 shows the 3D analysis of a cycle of buildings and displacement in the highest story.

It is estimated that cycles and the number of members increase in types 5 and 6 compared to type 1 resulting in decreasing the size of members' section to cause a reduction in the rigidity of the outrigger layer. Although the displacement in the highest story increases by about 2.0% due to the reduction in rigidity, it is still within acceptable displacement limits, which means it considered safe to use. However, additional review is necessary to determine usability in terms of acceleration and acceptable displacement since the building's occupants will include a hotel and officetel.

5. Conclusions

In this study, an additive performance ratio method combined to 2D and 3D analyses was developed using the MIDAS-GEN and ETABS software to account for the structural nonlinear behavior of outrigger–tall building interaction.

The additive performance ratio method to evaluate outrigger alternative has the following process: A representative value of stiffness on each structural system is obtained by that of displacement and then it is divided by weight of specific stories which consists of outriggers, and then finally the relationship is the so-called performance ratio or stiffness contribution ratio formulation.

In addition, alternatives to an existing outrigger are evaluated according to capacities of safe, economic, and constructional workability. Furthermore, the efficiency of outrigger alternatives for structural performance evaluation was estimated as the ratio of effective vertical displacement to weight or volume of steel obtained using a given structural deformation limitation criteria.

In this study, the outrigger shape of Jamsil world tower and its effectiveness compared to the original plan by evaluating the structural performance of various types are analyzed. The shape of type 6 is found to have similar structural performance but there is the possibility of a reduction in quantity compared to type 1, although type 6 had 4 joints, one more than original plan. Consequently, the constructability will be evaluated according to the connection method or the shape of joints where 3 braces met in type 6. Through such studies, i.e., the additive performance ratio method of 2D and 3D model for use in steel outrigger alternative design, the shape of an outrigger may be proposed and technical support provided for use in future high-rise buildings. As a suggestion for future studies, an experimental investigation should be carried out to verify the numerical results.

Acknowledgments

This research was supported by a grant (2013R1A1A2057502) from the National Research Foundation of Korea (NRF) funded by the Korea government.

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