16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 1511

Registration Code: S-R1464513002

FULL-SCALE STATIC LOADING TEST ON A FIVE STORY REINFORCED CONCRETE BUILDING (PART3: Pushover Analysis)

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Abstract

This paper presents the analytical model for 5 story full-scale RC moment frame with wing walls done at Building Research Institute's laboratory in 2014.To predict the backbone curve of this specimen, non-linear pushover analysis will be performed. In the analysis, effective width of slab and rigid zone length will be focused. The rigid zone length as analytical model is different for used spring model to predict the maximum strength. The backbone curve for each structural components will be calculated using recent proposal equations in Japan. Comparing the test result to calculation results using this analytical model, the validity of analytical model for RC frame with wall will be discussed.

Keywords: Effective width of slab, Rigid zone length, Non-linear Pushover analysis

1. Introduction

In order to evaluate the seismic performance of buildings, non-linear pushover analysis is mostly used in practical design. However, modeling method in non-linear analysis for column with walls and beam with walls has not enough described in current building standard or any guidelines. Therefore, recently, structural gaps surrounding walls are applied for convenience of modeling in practical design. Using those structural gaps, walls separated from surrounding moment resisting frame are expected not to have severe damage under earthquake. However, maximum strength of the building doesn't improve since those walls doesn't carry any shear force. Additionally, one of main damage patterns for RC structure in the 2011 Great East Japan Earthquake is damage of non-bearing RC walls constructed monolithically with structural frame (Pic.1). These buildings with the damaged walls are shown in Pic.1 The seismic safety performance of these buildings were still secured after the earthquake, these buildings couldn't be used continuously after the earthquake due to the damage of non-bearing RC walls. Non-bearing RC wall should be improved to mitigate the damage.

(a) Government office A[1] (b) Government office B[1] (c) Apartment building[2]

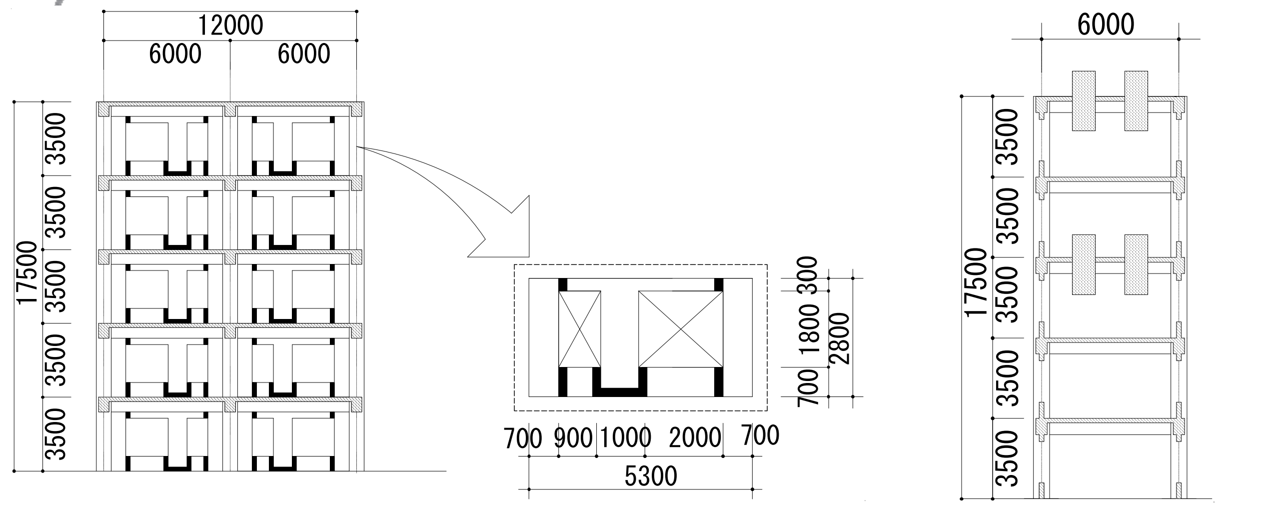
Pic.1 Damage of non-bearing walls observed in 2011 Great East Japan Earthquake

Based on above domestic background, BRI started the priority resarch program "Development on Seismic Design Method for Building with Post-Earthquake Functional Use" (2013～2015). In this project, i) allowable damage states of RC wall, ii) modeling of RC wall for damage evaluation, iii) modeling of RC structure with walls for frame analysis to evaluate behavior of whole structure. For the verification of above iii), non-linear pushover analysis is performed for full-scale five story RC specimen tested in 2014 at BRI, JAPAN and the validity of analytical model is discussed.

2. Loading test

2.1 Outline of the Specimen

To verify the structural performance and the allowable damage levels, the static loading test on full-scale reinforced concrete building is carried out [3]. Object structure of non-linear pushover analysis in this paper is a full-scale five story reinforced concrete building with 2 spans and 1 bay, which constructed in the laboratory of Building Research Institute in Tsukuba. The elevation of the specimen is shown in Fig.1. The story height is 3.5 m. The total height of the building is 18.7 m. The span length is 6.0 m in both directions. There are two types of the opening (2.0×1.8m, and 1.0m×1.8m) symmetrically provided on the walls along loading direction. There are structural gaps is provided at the end of the openings shown in Fig.1 (a). The vertical walls between openings are completely separated from the main frame by those gaps.



(a) loading direction (b) loading transverse direction

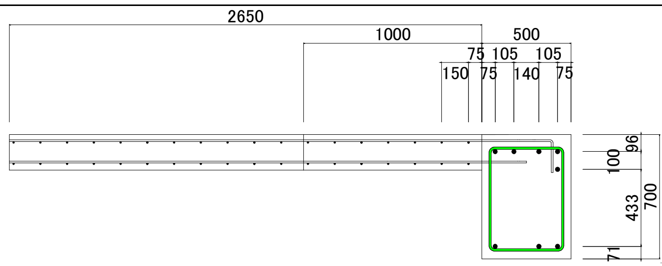
Fig. 1 – Elevation of specimen

2.2 Section and arrangement of reinforcement for Structural Components

Fig.2 and 3 show section of the beam with slab at 2, 3, 4 floor and column with wing walls at 1st floor. The section of beams is 500×700 mm section with eight D25 rebars (from 2nd to 4th floor), and with six D25 rebars (5th floor and top beam) as longitudinal reinforcement. Stirrup is D13 rebar at 100 mm interval. The slab thickness is 200 mm. The top and bottom of the reinforcement are basically D10 rebar at 150 mm intervals, but D13 is arranged alternatively with D10 rebar for top reinforcement in loading transverse direction. The lap splice of the reinforcement is provided in middle of the span, and the end of top reinforcement is anchored to the transverse beams with 90 degree hook. The anchorage length of the bottom reinforcement is 250 mm from side surface of the transverse beam. On the other hands, columns are 700 mm square section with sixteen D25 rebars as longitudinal reinforcement. The hoop is double D13 rebar at 100 mm interval (1st and 2nd story) and D13 rebar at 100 mm interval (from 3rd to 5th story). Steel type of longitudinal reinforcing rebar upgrade to SD390 for columns on upper story. Steel type of rebar is SD295, which diameter is smaller than 13 mm.

The length of wing wall is 700 mm, and thickness is 200 mm. The end of the wing wall section is specially arranged by six D16 longitudinal bars and confined by hoops to prevent the buckling of the longitudinal bars. The vertical reinforcement in the wall section is D10 rebar with double layer at 200 mm intervals, which is confined by the spreader bar (D10). The horizontal reinforcement (D10 rebar) in the wall section is anchored into the column section, and by 180 degree hook in the wing wall section. The intervals of those horizontal reinforcement is 100 mm for 1st story, and 200 mm for other stories.

Table 1 shows the material test result of concrete and reinforcement used in this specimen.

Beam with slab at 2,3,4 Floor Section Arrangement of reinforcment	
Longitudinal bar of beam	8-D25(SD345)

Stirrup of beam	2-D13(SD295A)@100
Slab reinforcement (loading direction)	2-D10(SD295A)@150
Slab reinforcement (loading transverse direction)	2-D10(SD295A)@150 ※top reinforcment is D10 & D13, and arranged alternatively

Fig. 2 – Section and reinforcement of beam with slab

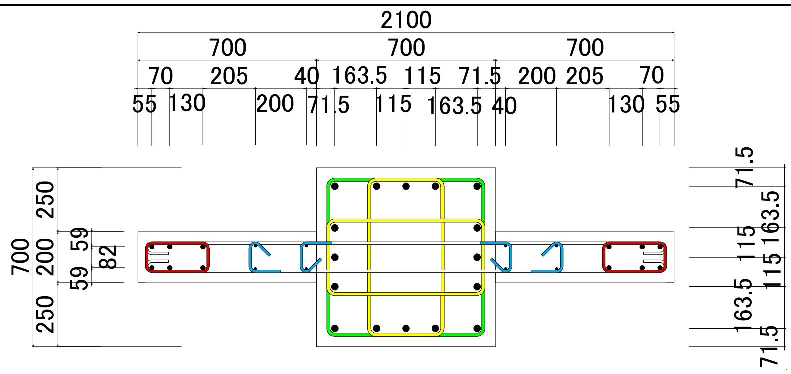
Column with wing walls at 1st floor Section Arrangement of reinforcement	
Longitudinal bar of Column	16-D25(SD345)
Hoop of Column	4-D13(SD295A)@100
Vertical reinforcement of wing wall	2-D10(SD295A)@200
Horizontal reinforcement of wing wall	2-D10(SD295A)@100
Longitudinal bar at wall edge	6-D16(SD345)
Confined reinforcement in wing wall	D10(SD295A)@100

Fig. 3 – Section and reinforcement of column with wing walls at 1st floor

Table 1 –Material test results

(a) steel

			Yield strength N/mm^2	Tensile strength N/mm^2
Main bar of column at 2nd~5th Floor	D25	SD390	449	628
Main bar of column at 1st floor and beam	D25	SD345	383	568
Shear reinforcement of beam and column	D13	SD295A	340	498
Wall and slab reinforcement	D10	SD295A	352	482
longitudinal bar at wall edge	D16	SD345	384	552

(b) concrete

	Compressive strength (N/mm^2)	Young's modulus (N/mm^2)
1F	34.9	2.86×10^4
2F	33.0	2.61×10^4
3F	37.7	2.85×10^4
4F	33.6	2.62×10^4
5F	31.3	2.47×10^4

2.3 Loading and Measurement Plan

Fig.4. shows the attachment of the actuators on the top floor. Eight actuators are used in the loading test, and a series of 4 actuators located on the roof level and 4th floor level in each and the maximum capacity of the actuator is ±1000 kN within ±500 mm. The load of each actuators is measured by load cell. Two actuators on the top of the specimen is controlled by horizontal displacement at top floor and other actuators follows the load of those two actuators. Loading history is cyclic loading toward each target value of whole drift angle which horizontal displacement at top floor divided by total height. The cyclic number for 0.0625% and 0.125% of the drift angle is one, and the number for 0.25%, 0.50%, 1.00%, 1.50% and 2.00% is two. Story drift angle are measured by displacement transducers. The local displacement such as moment curvature and shear deformation is measured for 1st story column and 2nd floor beams and drift angle of those members is obtained. The strain of reinforcement for beam, slab, column, wing wall is measured by strain gauges. Crack width of structural components are also measured by crack scale.

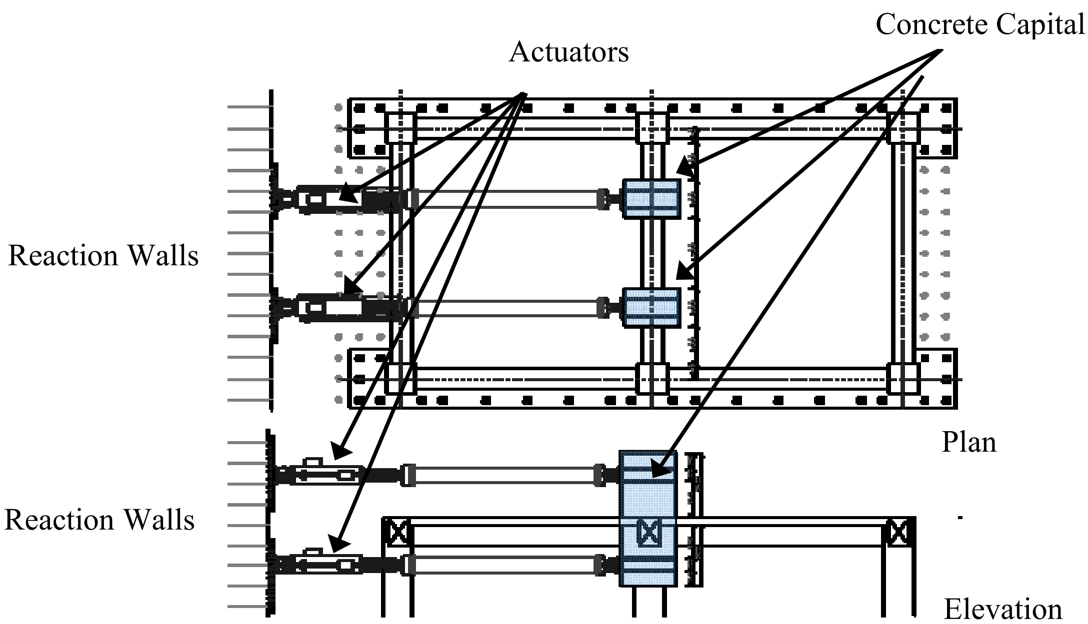


Fig. 4 – Loading set up on the roof level

3. Analytical model for non-linear pushover analysis

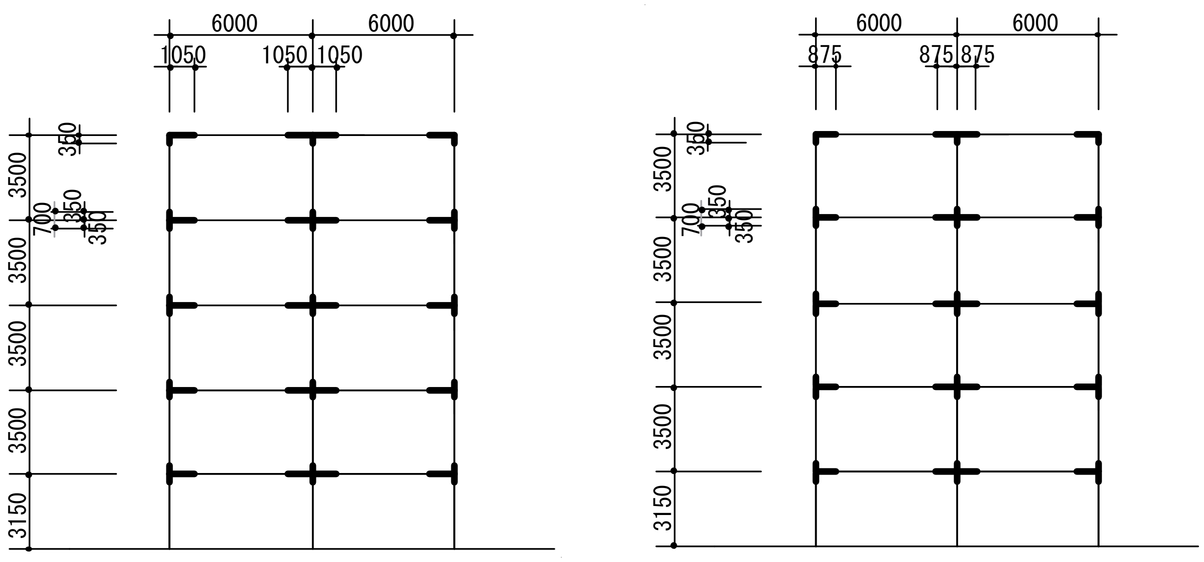
3.1 Modeling of global system

Fig.5. shows the analytical model of global system in loading direction. The joints between beams and column with wing walls are modeled as rigid zone shown in Fig.5 (a). Once the rigid zone length is determined, a critical section of each structural element is set to the edge of rigid zone. According to the current standard in Japan, the length from node to "face of walls – D/4 (D is total depth of a structural element)" is applied in practical design. In this paper, the rigid zone length of beams are shorten from the face of wing wall shown in Fig.5 (b). The length used in analysis is one of variable parameters (see Table 2). The lateral loading points are top floor and 4th floor, the distribution ratio is 1 to 2 same as loading test.

3.2 Modeling of local system

Beam with slab and column with wing wall are modeled as structural elements in this analysis. Beam with slab is modeled by uniaxial spring (US model) as line element considering flexural deformation and shear deformation. The contribution of slab width to ultimate flexural strength for beam is one of variable parameters (see Table 2) in this paper. Generally 1.0m of the effective width of slab is used in Japanese practical design. Column with wing wall is modeled by uniaxial spring as line element considering flexural, shear and axial deformation, and multi axial spring (MS model) which can represent the interaction among bending moment and axial load. The plastic hinge zone length is determined to be consistent with the theoretical value of initial stiffness. The backbone curve of structural elements are tri-linear type for flexural and shear deformation component shown in Fig.6 (a, b). Regarding the backbone curve of axial spring, axial stiffness model (see Fig.6(c)) which can represent compression and tension behavior of RC is used. On the other hand, the backbone curve of axial spring for MS model is shown in Fig.6 (d, e). Regarding the post-peak compression behavior of concrete, negative stiffness of concrete is ignored in this paper.

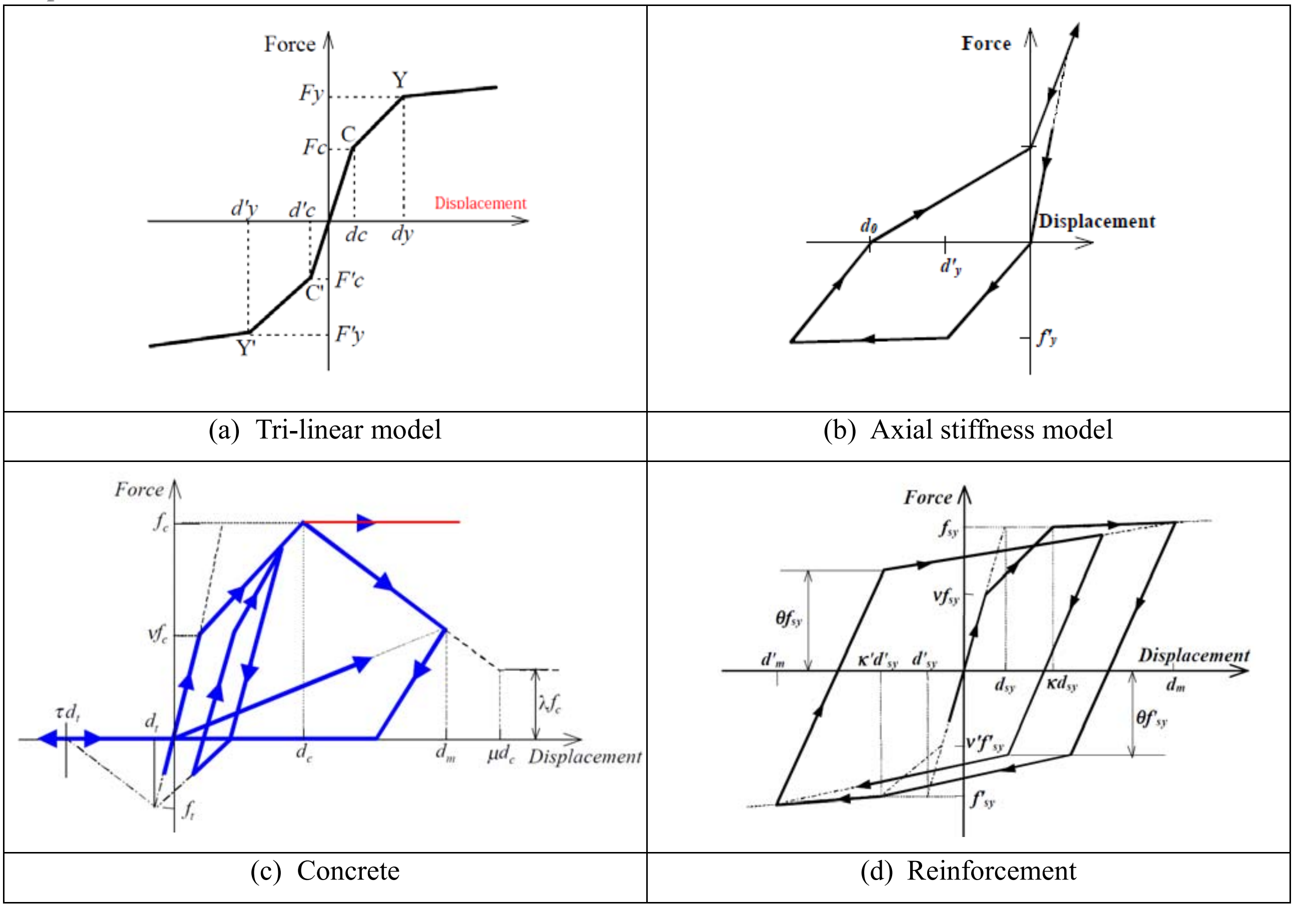
The research [4,5] on an evaluation method for yielding stiffness and ultimate shear strength for column with wing walls are carried out recently in Japan, the evaluation method is applied for modeling of column with wing walls in this paper. Additionally, ultimate flexural strength for structural elements is calculated by section analysis based on equivalent rectangular compressive stress distribution method.



(a) Rigid zone length 01
From node to face of wall for beam

(b) Rigid zone length 02
From node to "face of wall -D/4" for beam

Fig. 5 – Analytical model of global system (Loading direction)



(a) Tri-linear model

(b) Axial stiffness model

(c) Concrete

(d) Reinforcement

Fig. 6– Backbone curve of each spring

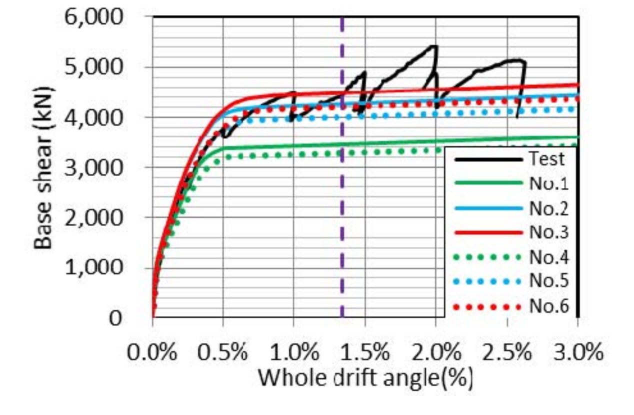
Table 2 –Variable parameters of analysis

No.	Rigid zone length see Fig. 5	Effective width of slab	Modeling of column
1	01	0m	Uniaxial
2	01	1m	Uniaxial
3	01	all length(2.65m)	Uniaxial
4	02	0m	Uniaxial
5	02	1m	Uniaxial
6	02	all length(2.65m)	Uniaxial
7	01	0m	Multi-Axial
8	01	1m	Multi-Axial
9	01	all length(2.65m)	Multi-Axial
10	02	0m	Multi-Axial
11	02	1m	Multi-Axial
12	02	all length(2.65m)	Multi-Axial

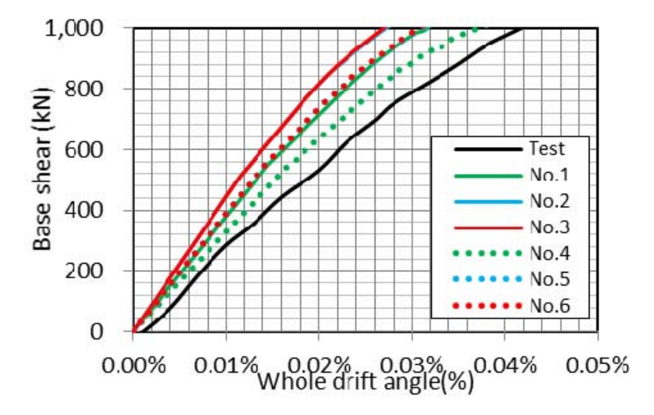
4. Comparison between analytical results and test results

4.1 Base shear – Whole drift angle

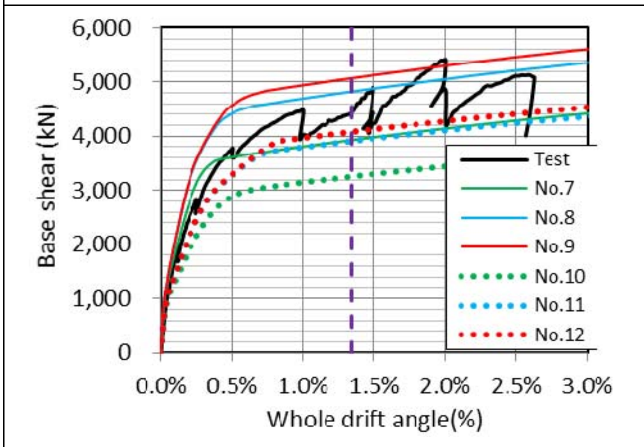
Fig.7 shows the relationship between base shear and whole drift angle to compare analytical result and test result. The vertical dotted line shows the point which bottom of vertical hanging wall firstly hit against standing wall on the beam. Once the wall hit, the wall carries shear force and measured story shear force increases. However the analytical model doesn't consider this phenomena. The result of analysis after "the wall hit point" is shown as reference. Fig.7 (a), (b) shows the analytical result using the US model. The base shear of No.1 and No.4 are apparently lower than test result, since the effect of effective width of slab doesn't consider in the analysis. The result of No.3 has good agreement to the base shear measured at the wall hit point. However the reinforcements in effective width of slab in loading direction don't yield at this point shown in Fig.8. Therefore, the result of No.2, which effective width of slab is 1.0m and critical section position for beams is at face of wing wall, has good agreement with test result in terms of maximum base shear. Fig.7 (b) shows to compare an initial stiffness of both results. No.1 and No.2, No.4 and No.5 are same results, respectively. No.4 which ignore the effective width of slab and consider shorten rigid zone length shown in Fig.5 (b), have good agreement with test result in terms of initial stiffness. Fig.7 (c), (d) shows the analytical result using the MS model. No.8, which effective width of slab is 1.0m, overestimates the base shear at the point. It implies the rigid zone length in the analysis using MS model should be shorten properly.



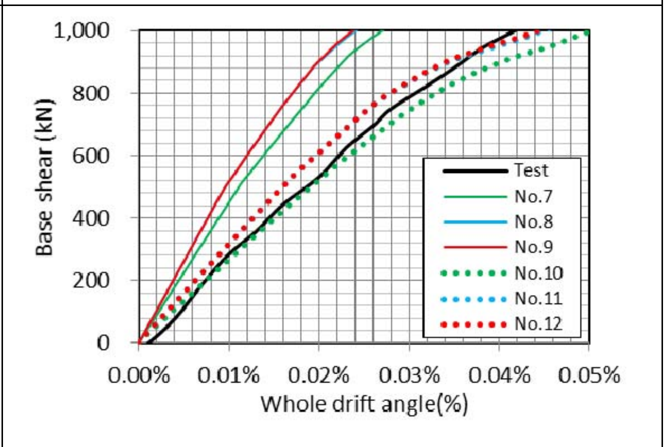
(a) No.1-No.6 (US Model)



(b) No.1-No.6 (US Model)



(c) No.7-No.12 (MS Model)



(d) No.7-No.12 (MS Model)

Fg.7 – Comparison of base shear vs. whole drift angle

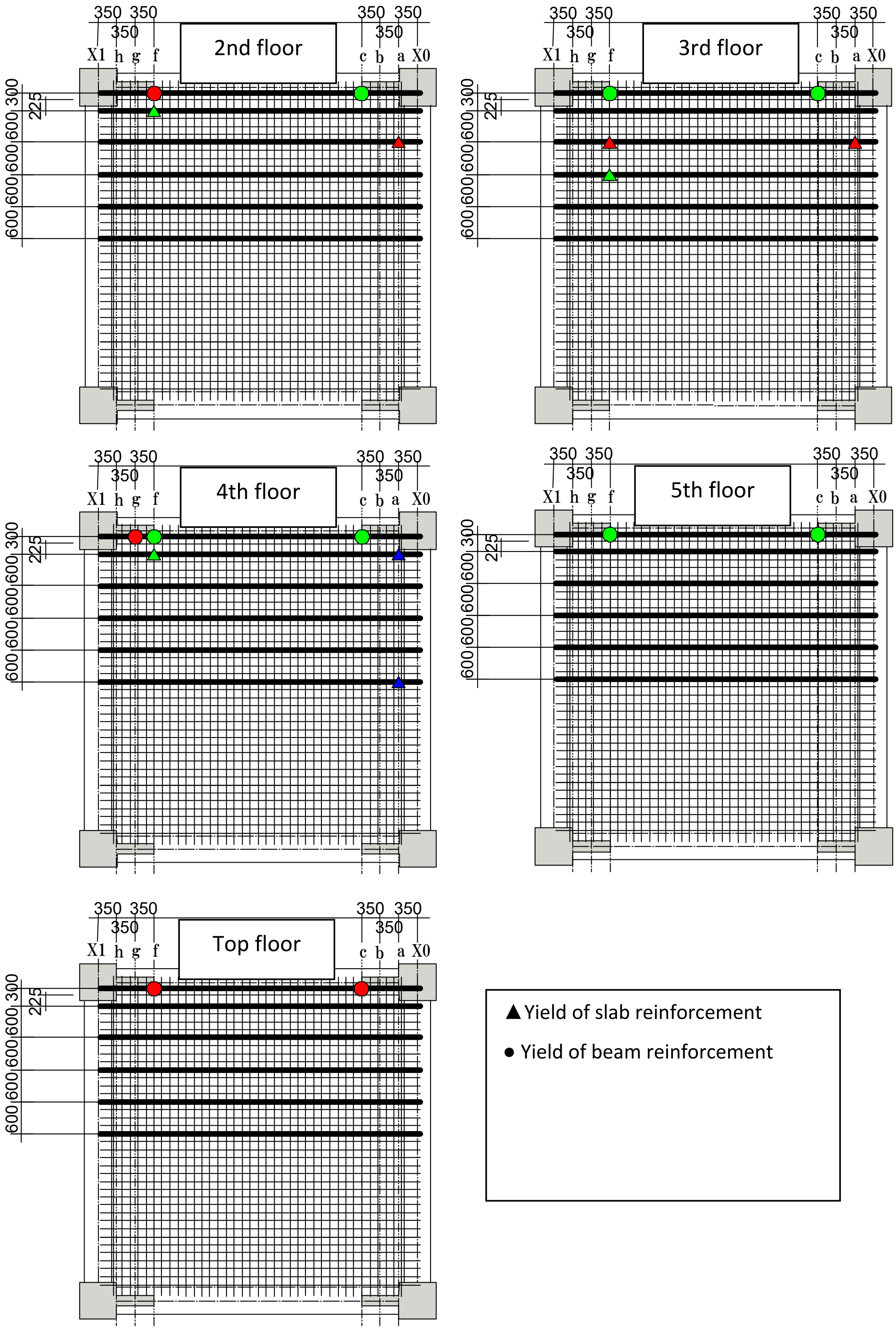
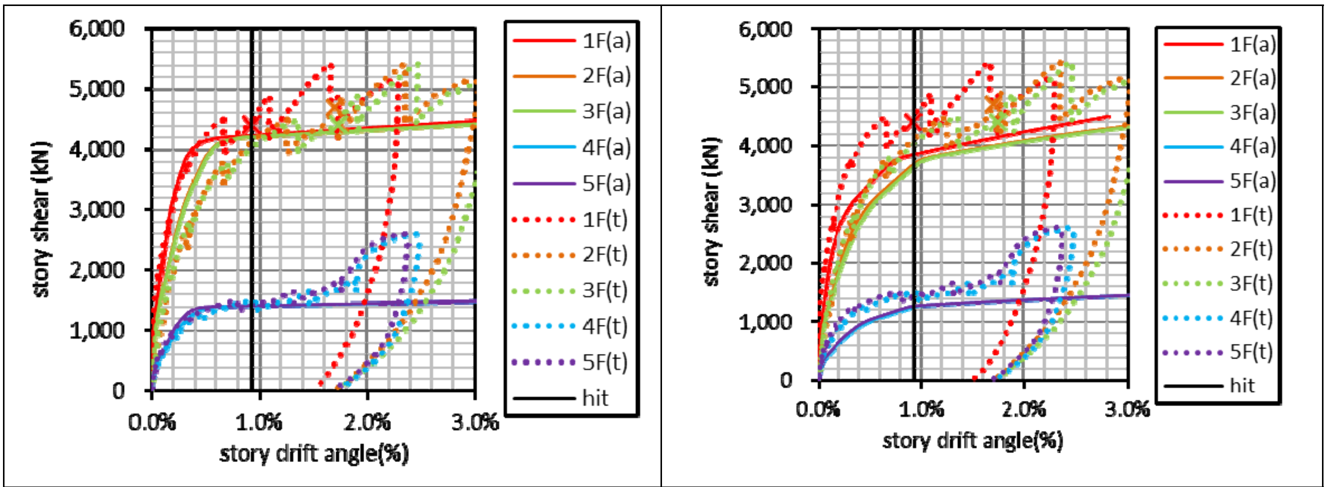


Fig. 8 – Location of yielded reinforcement in slab at each floor

4.2 Story shear – Story drift angle

Fig.9 shows the relationship between story shear and story drift angle to compare analytical and test result. The vertical black line shows the wall hit point same as Fig.7. Before the point, maximum value of lower story shear is about 4400kN in test. Fig.9 (a), (b) show the result of No.2 and No.11 which have relatively good agreement in Fig.7 (a), (c). At the wall hit point, the upper story and lower story shear of No.2 has good agreement with test result. Comparing Fig.9 (a) to (b) at the point, the story shear of No.11 is less than value measured by test and underestimates the maximum story shear. There are rooms for further investigation for modeling of MS model to predict maximum story shear properly.



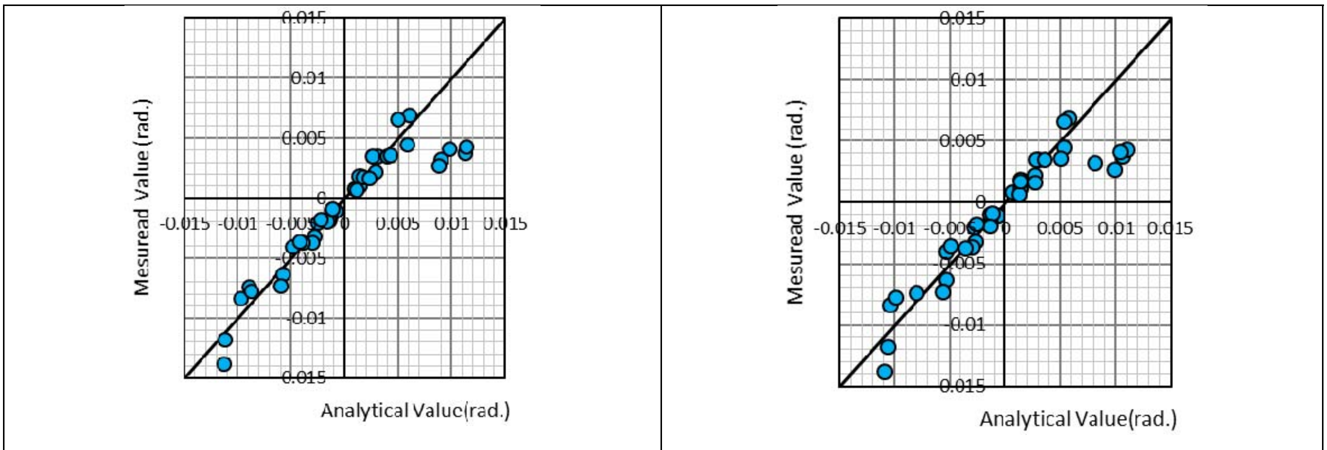
(a) No.2 (US Model)

(b) No.11 (MS Model)

Fig. 9 – Comparison of story shear vs. story drift angle

4.3 Story drift angle

Fig.10 shows the comparison result of story drift angle at each peak whole drift angle. The analytical value of both model can predict the measured value excluding the value in large story drift angle at both side.



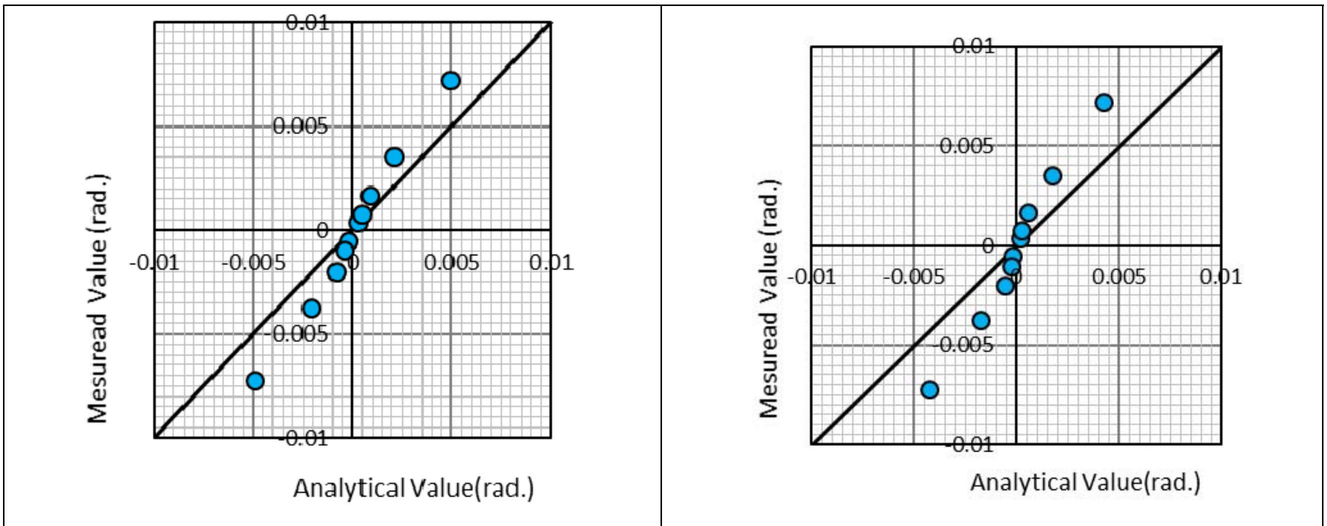
(a) No.2 (US Model)

(b) No.11 (MS Model)

Fig. 10 – Comparison of story drift angle

4.4 Drift angle of column with wing walls

Fig.11 shows the comparison results of drift angle of column with wing walls at 1st floor for both models. The value of vertical axis is obtained by the sum of flexural deformation and shear deformation measured by displacement transducers. The value of horizontal axis is calculated by the sum of flexural deformation of flexural spring and shear deformation of shear spring in analytical model. The analytical value underestimates measured value for both model, however, can predict the measured value roughly.



(a) No.2 (US Model) | (b) No.11 (MS Model)

Fig. 11 – Comparison of drift angle of column with wing walls at 1st floor

5. Concluding remarks

This paper shows the comparison of calculated value obtained from non-linear pushover analysis and measured value obtained from the static loading test on the full scale five story reinforced concrete building carried out at the Building Research Institute. The obtained results are shown as followings;

- The analytical model with US model, which rigid zone for beam is set as the length from node to face of wall and effective width of slab is 1.0m, can predict measured maximum story shear.
- The analytical model with MS model, which rigid zone for beam is set as the length from node to “face of wall –D/4” and effective width of slab is 1.0m, can relatively predict the maximum story shear among the analytical cases using MS model, however, underestimates test result comparing to the analytical result using US model. There are rooms for further investigation to predict maximum story shear.
- Regarding the initial stiffness, the result of analytical models, which the effect of slab is ignored and consider shorten rigid zone length, have good agreement wtih measured value.
- The above two models can roughly predict story drift angle at each story and drift angle of colmn with wing walls at 1st floor.

6. Acknowledgements

This study was carried out by a joint study of National Technology Development Project of MLIT "Development of function sustaining technologies for buildings used as Disaster Prevention Bases" (2013～2016) and Priority Research Program of BRI "Development on Seismic Design Method for Building with Post-Earthquake Functional Use" (2013～2015). The grand design of the test was planned by Technical WG (Chairman Prof. Teshigawara (Nagoya University)). The static loading test was carried out by Structural Engineers of Nishimatsu Construction Co. Ltd., Hazama Ando Corporation, Kumagai Gumi, Sato Kogyo Co. Ltd, Toda Corporation, Fujita Corporation, and Maeda Corporation. The efforts in measuring various damage of concrete for damage analysis by Tokyo Institute of technology, Tokyo University of Science and Tohoku University are gratefully acknowledged.

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