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Study on seismic damage control of wall-type RC structure based on horizontal force loading test of a 1/2 scale 5-story 3D specimen

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Abstract

Wall-type reinforced concrete (hereinafter referred to as WRC) building are relatively inexpensive among reinforced concrete structures, and can be used in a spacious space because the column and beam protrusions do not come into the room. In addition, no significant damage has been reported even in the large earthquakes, and the damage prevention performance is recognized to be high (1). In the structural design, a simple calculation method called as an average shear stress method is applied, and there are following minimum structural requirements; the wall length (wall amount) per unit floor area in each direction, the wall thickness, the bending reinforcement set at the edge in accordance with the opening height, and the minimum wall reinforcement ratio. The average shear stress method is conducted as follows; 1) Average shear stress acting on the wall is obtained by dividing the story shear force with a shear coefficient of 0.2 by the horizontal cross-sectional wall area of the story. 2) The shear force carried by each wall is distributed according to wall area. 3) The moment at the wall end is obtained by setting the inflection point of each bearing wall to half the opening height of the bearing wall, and 4) The wall beam is designed by the moment form the wall.

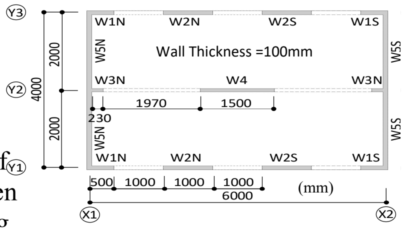
This study conducted a horizontal force loading test of a 1/2 scale 5-story WRC building designed in the method mentioned above, and quantitatively examined and evaluated the damage to the WRC building against a large earthquake. The horizontal forces are applied at the top FL and the 2nd FL, whose ratio is 7.3 : 1, so that the shear forces and the overturning moment at the 1st and the 2nd story are approximately equal to the prototype model. The weight of the specimen when calculating the base shear coefficient was defined as the story shear coefficient Co = 0.2 when the average shear stress of 0.45 N / mm^2 was generated in the 1st story bearing wall (total weight is 0.45x A1 / 0.2 = 1,881kN (A1: Total cross-sectional area of the first floor bearing wall in the loading direction (mm^2))). The horizontal strength is 1,394 kN, that is the base shear coefficient of 0.74.

Test specimen have a base shear coefficient of about 0.8 at an inter-story deformation angle of 1/200. Based on the load-deformation relationship and the hysteresis damping constant obtained from the experiment, the response of the test specimen for a large earthquake is estimated in less than 1/400, by equivalent linearization method (2). Considering the response deformation angle and the experimental results, it is considered that the WRC building targeted in this paper has sufficient damage prevention performance against large earthquakes.

Keywords: Wall-type reinforced concrete; Earthquake damage prevention; 3D large scale test; Earthquake response

References: 1) AIJ: AIJ Standard for Structural Design and Calculation of Reinforced Concrete Boxed Wall-Buildings, 2015, 2) NILIM, BRI: Technical manual for building standards on structure, 2015

Photo 1 Overview of test specimen after loading



The design standard strength of concrete is 24 Mpa, and the nominal yield strength of reinforcing bar is 295 Mpa.

Fig.1 Typical floor plan

1. Introduction

Wall-type reinforced concrete (hereinafter referred to as WRC) building are relatively inexpensive among reinforced concrete structures, and can be used in a spacious space because the column and beam protrusions do not come into the room. In addition, no significant damage has been reported even in the large earthquakes, and the damage prevention performance is recognized to be high, AIJ (2015), Teshigawara et al. (2017). In the structural design, a simple calculation method called as an average shear stress method is applied, and there are following minimum structural requirements; the wall length (wall amount) per unit floor area in each direction, the wall thickness, the bending reinforcement set at the edge in accordance with the opening height, and the minimum wall reinforcement.

The average shear stress method is conducted as follows;

1) Average shear stress acting on the wall is obtained by dividing the story shear force with a shear coefficient of 0.2 by the horizontal cross-sectional wall area at the story.

2) The shear force carried by the wall is obtained by multiplying the average shear stress by the cross-sectional area of the load bearing wall.

3) The moment at the end is obtained by setting the inflection point of each bearing wall to half the opening height of the bearing wall, and

4) The cross section of the wall beam is designed with a stress commensurate with the moment.

Even with complex wall arrangements, there is no difficulty in modeling the building, and there is no problem with modeling the bearing wall itself.

This study conducts a horizontal force loading test of a 1/2 scale 5-story WRC building designed in the method mentioned above, and quantitatively examined and evaluated the extent of damage to the WRC building against a large earthquake.

2. OUTLINES OF EXPERIMENT

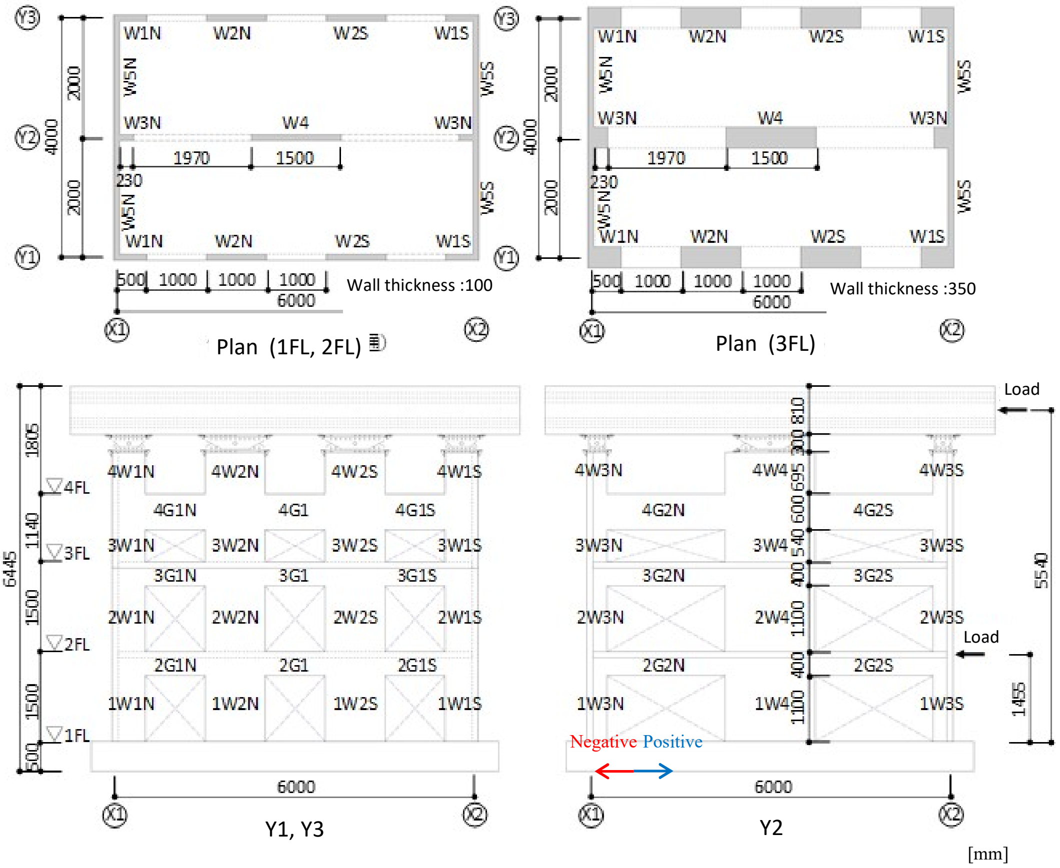
The test specimen used in this experiment is built so that the lower two stories of the five-story typical WRC building designed based on the WRC standard, AIJ (2015), are the same as the design, and the upper three stories are modeled for loading. Test specimen is reduced to 1/2 scale. The design policy is described 2.1.

2.1 Prototype of Test Specimen

Typical prototype five-story WRC building is designed so that the amount of wall and bar arrangement satisfy the minimum requirements of the WRC standard, AIJ (2015). The L-type and T-type load-bearing walls are determined so that the wall amount is about 1/3 of the total, and the wall amounts are equal in the orthogonal horizontal directions. The layout of the walls is the same on each floor. The vertical and horizontal bars of the wall are within the range that satisfies the allowable stress level design (approx. 0.5 to 0.9), and the amount of the standard shear reinforcement ratio specified by WRC standard 1). The beam reinforcement was also determined to satisfy the allowable stress design. The wall edge reinforcement is also equal to or greater than the minimum requirement of the WRC standard, AIJ (2015). However, when the orthogonal wall is attached, the reinforcement is 1-D13 added to. The slab reinforcement is D13 @ 200mm.

2.2 Test Specimen

The above five-story building is reduced to 1 / 2-scale five-story building, in which the lower two stories (from the first-floor wall to the third-floor beam) are reduced as it is, and the upper three stories are modeled for loading. The cross-section of the 4th floor beam is determined so that the horizontal strength of the half scale 5-story building and the test specimen are almost equal. Figure 1 shows a plan view and axis diagram of the specimen. Each member section is listed in Tables 1 and 2. When calculating the base shear coefficient, the weight of the specimen is assumed to be when the average shear stress of 0.45 N / mm^2 occurs in the 1st-story bearing wall in the loading direction when the story shear force coefficient of Co = 0.2, and the total weight ΣW is 0.45 A1 / 0.2 = 1881 kN (A1: Total cross-sectional area of the first floor bearing wall in the direction of force [mm^2]). The actual weight of the specimen is 1100 kN at 1 FL and above and 1006 kN at 2 FL and above. For reference, the horizontal force distribution for the 1/2 scale five-story building and the specimen is shown in Fig. 2. Using these lateral force distributions, 1344 kN (CB = 0.72) for 1/2 scale 5-story building and 1394 kN (CB = 0.74) for the test specimen are calculated (the concrete strength is Fc = 21 N / mm^2, and the yield strength of the reinforcing bars is 1.1times of the nominal yield strength).

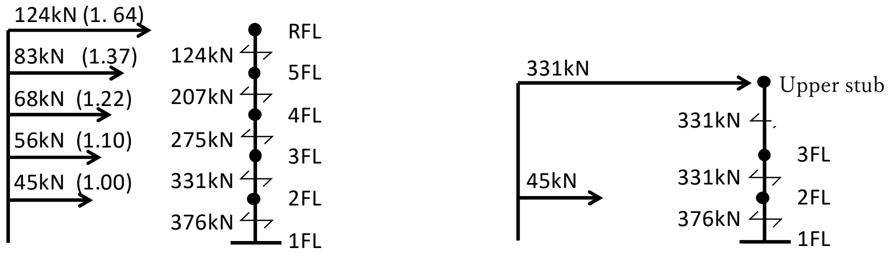


* Thickness of slab is 100 mm.

Figure 1. A plan view and axis diagram of the specimen

2.3 Loading Method

The lateral forces are applied at the top stub and at the 2nd floor in the positive and negative direction. The lateral force distribution is determined so that the shear forces and the overturning moments in the 1st and 2nd story are approximately equal to the 1/2 scale 5-story building (lateral force distribution is shown in Fig. 2 (a)). The ratio of the horizontal force is 1: 7.358 for the test specimen. In loading schedule, the first two cycles are controlled based on shear force coefficient, $C_B = \pm 0.1, \pm 0.2$, and then the loading is controlled by the deformation angle of the lower two stories, $Rc = \pm 1/2000, \pm 1/1000, \pm 1/400$ (2), $\pm 1/200$ (2), $\pm 1/133$ (2), $\pm 1/100$ (2), $+ 1/80$ (number of cycle in parentheses) .



a) 1/2 scale 5-story building

b) Specimen

Figure 2. Latral force distribution when Base shear coefficient Co=0.2

Table 1. list the bar arrangement of beams

Symbol	Main upper rebar	Main bottom rebar	Shear rebar
2G1,3G1	2-D13	2-D13	1-D6@75
2G2,3G2	1-D16, 1-D13	2-D16, 1-D13	1-D6@50
4G1, 4G2	4-D16	4-D16	2-D10@100

Table 2. list the bar arrangement of walls

Symbol	Vertical rebar	Horizontal rebar	Rebar at wall edge
1st and 2nd layer			
W1	1-D6@125	1-D6@125	1-D16 + 1-D13 (external edge), 1-D16 (inner edge)
W2	1-D6@125	1-D10@125	1-D16
W3	1-D6@125	1-D6@125	1-D16 + 1-D13 (outer edge), 1-D16 (inner edge)
W4	1-D6@125	1-D10@100	1-D16
W5	1-D6@125	1-D6@125	1-D16 + 1-D13
3rd and 4th layer			
W1～W4	2-D13@200	2-D10@100	4-D19
W5	1-D6@125	1-D6@125	D13 + D13

2.4 Material Properties

Tables 3 and table 4 list the material properties of the reinforcing bars and concrete used in the experiment. High-strength concrete is used above 4 FL.

Table 3. Material property of reinforcing bars

Size	material	σ_y[N/mm^2]	ε_y [μ]	E_s [kN/mm^2]
D6	SD295A	343	1871	183
D10	SD295A	351	1935	182
D13	SD295A	360	1908	189
D16	SD295A	355	1959	181

3. TEST RESULTS

3.1 Load v.s. Deformation

Figure 3 to Figure 6 show the base shear force v.s. the deformation angle of *Rc* (control deformation angle), the yield of reinforcing bars in the lower 2 stories (no yield of reinforcing bars has been confirmed in 3 stories), the deformation mode and final fracture condition of the specimen (after *Rc* = +1/80 cycle). The calculated horizontal force is plotted in Fig. 3 with a chain line, and Figure. 4 shows the loading cycle by which the reinforcing bar has yielded (that is, the yield strain in Table 3). Figure. 4 shows Y2-Y3 and Figure. 6 shows Y1-Y2, so both results do not correspond to. Please note that the crack pattern in Fig. 6 are sketched from inside. As shown in Fig.3 and Fig.4, this specimen has bending yield at foot of the W4 at *Rc* = 1/2000 cycle, and at the W2 foot and W5 (orthogonal wall) foot at *Rc* = 1/1000 cycle. Bending yield and tensile yielding occur at the *Rc* = 1/400 cycle, bending yield at the W1 and W3 foots, and shear yielding at the inner wall at the *Rc* = 1/200 cycle. Maximum strength is 1580 kN. This value is 13% higher than the calculated value of 1394 kN. Increasing the lateral force, the concentration of deformation occurs into the 1st story (Fig. 5), so the deformation angle of the 1st story at the maximum strength (*Rc* = + 1/200) is +1/168, and the deformation angle at the 2nd story is larger than +1/245.

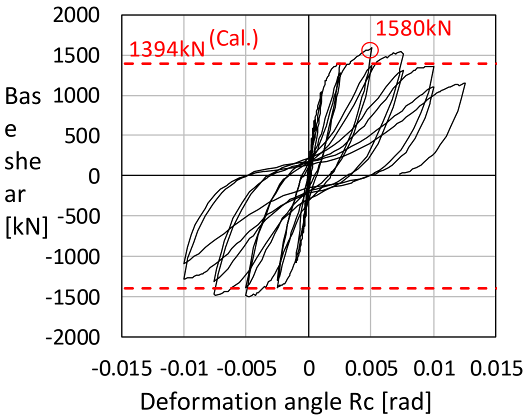
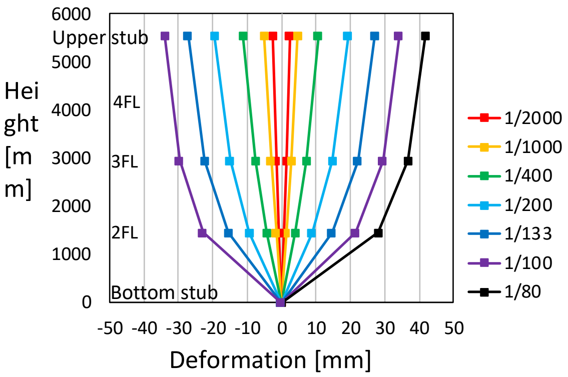


Figure 3. Base shear v.s. drift at lower 2-story Rc



* Results of 2nd cycle are shown after Rc = 1/400

Figure 5. Deformation mode at each peak

Figure 6 shows the cracks that occur in each member of the specimen. In this figure, 1W2N, 1W4, and 2W4 have less shear damage comparing to other members (1W4 and 2W4 have no shear yield (Fig. 4)). This is thought to be due to the fact that the slip failure of both walls preceds the shear failure because the slip of the wall foot is observed during the experiment. In addition, although less than half of the beam main bars are observed to yield, because the bending cracks that occur at the end of the beam propagate toward into the joint with the wall. Yield may occurs inside the joint, not at the beam end where a strain gauges are affixed.

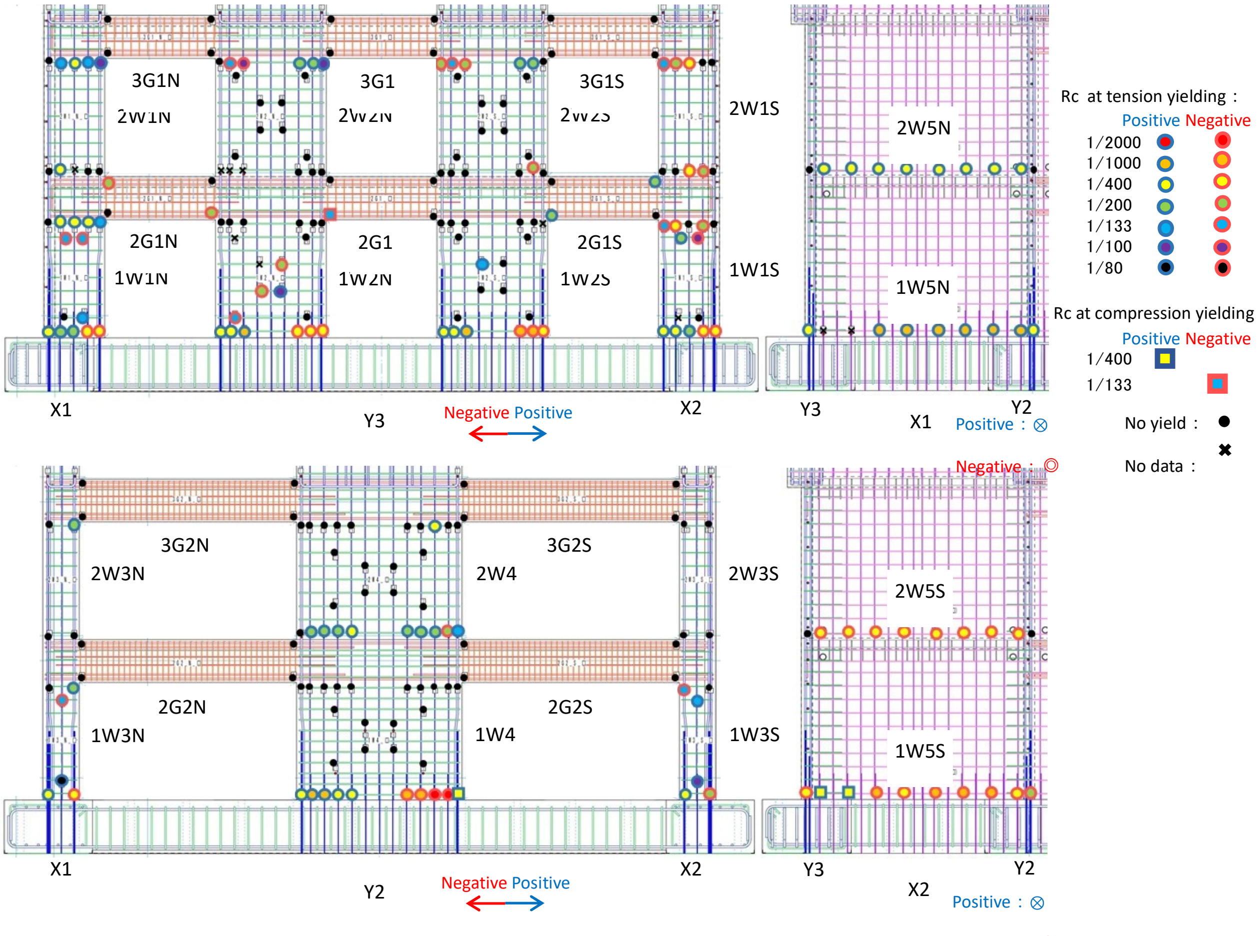


Figure 4. the yield of reinforcing bars in the lower 2 layers

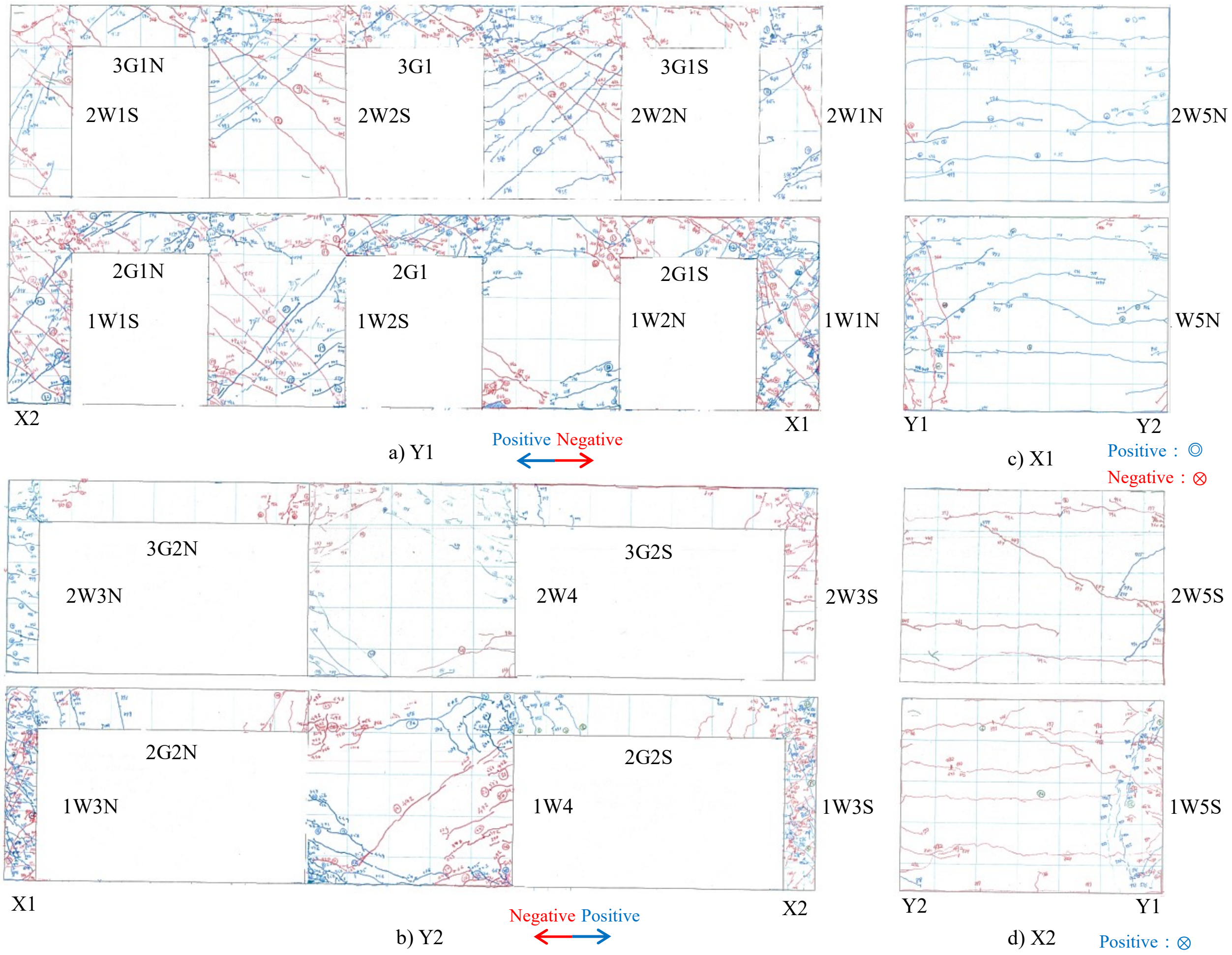


Figure 6. Final fracture condition

3.2 Hysteresis Damping

Using the load deformation relationship obtained in this experiment, the hysteresis damping constant h_{eq} of each loading cycle is obtained by the following procedure. a) First, the hysteresis energy consumption ΔW [kNm] in one cycle is obtained as the area surrounded by the hysteresis curve. b) Next, the potential energy W [kNm] of the equivalent elastic system is obtained by equation (1). In this formula, the average values of the potential energies (W_{+p} [kNm] and W_{-p} [kNm]) for positive and negative loadings are used. In addition, the maximum deformation value (δ_{+p} [m] and δ_{-p} [m]) and the maximum load value (Q_{+p} [kN] and Q_p [kN]) in the loading cycle do not always occur at the same time. The h_{eq} is determined using both maximum values (h_{eq} is evaluated (smaller) on the safe side).

$$W = (W_{+p} + W_{-p})/2 = \left(\frac{1}{2}Q_{+p}\delta_{+p} + \frac{1}{2}Q_{-p}\delta_{-p}\right)\Big/2 \quad (1)$$

c) Using the values obtained from a) and b), calculate the hysteresis decay constant *heq*.

$$h_{eq} = \frac{1}{4\pi}\frac{\Delta W}{W} \qquad (2)$$

Figure 7 shows the hysteresis damping constant, h_{eq}, calculated by the above procedure using the load deformation relationship of the total building. The h_{eq} is about 8% to 14% in the first loading cycle, and about 7% to 12% in the second loading cycle (Rc = 1/400 cycles and after).

3.3 Residual Seismic Capacity

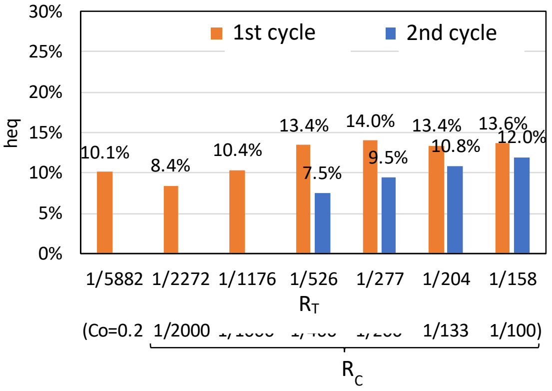


Figure 7. Hysteresis damping constant

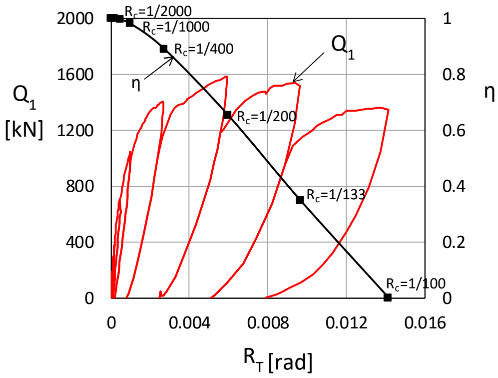


Figure 8. Q_1 vs R_T and η vs R_T

Figure 8 shows the relationship between the Q_1 v.s. R_T envelope and η v.s. R_T on the positive loading side. In order to evaluate the relationship between the deformation of the building and the residual energy absorption capacity (η), the seismic performance reduction factor η defined in reference, JBDPA (2015), is referred to. In the load deformation relationship during positive loading obtained by experiment, the total energy that can be absorbed by the building up to Rc = 1/100 cycles (total area surrounded by red line in Fig. 8) then, from its value, the value excluding the energy consumed by each deformation angle is defined as the residual absorbable energy, and the seismic performance reduction factor η is calculated by taking the ratio of the latter to the former. This building has a residual absorbable energy of about 83% at a deformation angle Rc = 1/400 and about 55% at 1/200.

4. RESPONSE AND DAMAGE EVALUATION

Based on the above experimental results, the response of the WRC building used in this experiment against an extremely rare earthquake is predicted, and the damage situation at that time is examined.

4.1 Response evaluation method

The response is obtained by the response and limit strength calculation method, NILIM (2015), using the load deformation relationship and the hysteresis damping constant, *heq*, obtained in the previous chapter. The total weight of the WRC building is 1881 kN as described in Section 2.2, and the mass distribution is assumed that the mass of one story, *m*, is in each of the 1st story and the 2nd story, and the mass of upper three stories is concentrated at the top stub center position level (a height of 5.54 m from 1 FL) as shown in Fig.9.

a) First, the effective mass m_e [t], representative displacement x_e [m], representative height He [m] and equivalent acceleration S_a [m / s2] is obtained by equations (3) to (6).

$$m_e = \left(\sum_{i=1}^{n} m_i x_i\right)^2 \Big/ \sum_{i=1}^{n} m_i x_i^2 \qquad (3)$$

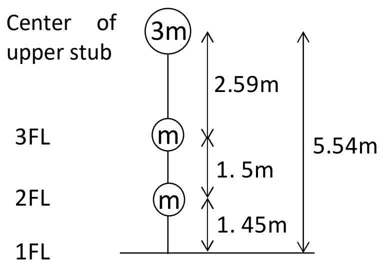


Figure 9. Assumption of mass distribution

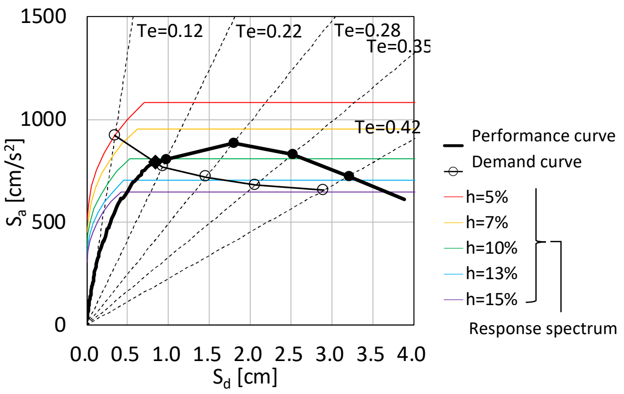


Figure 10. Estimation of earthquake response (calculation)

$$x_e = \sum_{i=1}^{n} m_i x_i^2 \Big/ \sum_{i=1}^{n} m_i x_i \tag{4}$$

$$H_e = \sum_{i=1}^{n} m_i x_i H_i \Big/ \sum_{i=1}^{n} m_i x_i \tag{5}$$

$$S_a = Q_1 / m_e \tag{6}$$

Here, n is the number of mass points ($n = 3$ in this study), and m_i [t], x_i [m], and H_i [m] are the mass, displacement, and height of the mass point i (i = 1, 2, 3), respectively.

b) Obtain the response spectrum S_a, S_d for extremely rare earthquakes based on the NILIM (2015). The ground type is assumed to be the second type ground, the seismic activity coefficient $Z = 1.0$, and the hysteresis damping constant is assumed to be 5%, 7%, 10%, 13%, and 15%.

c) Equivalent damping constant h_{eq} is obtained by adding viscos damping of 5% to 0.8 times the hysteresis damping constant calculated in the previous chapter (using the result of the second cycle) (Table-5). The performance curve of the equivalent single degree of freedom system is obtained, and the intersection of the curve and the required curve is obtained as a response deformation as shown by symbol ▲ in Fig. 10.

Table 5. h_e at each *Rc* (*Rc*: Drift angle of lower 2-story)

R_c	− (Elastic)	1/400	1/200	1/133	1/100
x_e	−	0.97cm	1.79cm	2.52cm	3.20cm
h_e	5%	11.0%	12.6%	13.6%	14.6%

4.2 Response evaluation result

Figure 10 shows the result of the calculation of the limit strength by the procedure in the previous section. In this figure, the performance curve of the reduced system is represented by a thick black solid line, the response spectrum is represented by a solid line of each color corresponding to the equivalent damping constant *h*, and the required curve is represented by a black thin solid line. From the figure, the maximum response deformation of the reduced system for extremely rare earthquakes is calculated to be 0.84 cm. At this time, the deformation angle *Rc* of the lower two stories was *Rc* = 1/480 (1 story: 1/457, 2 stories: 1/504), which is less than 1/400.

4.3 Damage of WRC building against large earthquake

Examining the damage situation of the WRC building at the response deformation angle to the extremely rare earthquake, the specimen does not reach the maximum strength (*Rc* = 1/200) (Fig. 3).), Bending yielding of wall members occur, but no shear yielding occur (Fig. 4), and the seismic performance reduction factor η is about 0.8 (Fig. 8). Considering the above results, it is considered that the WRC building used in this paper has sufficient damage prevention performance against a large earthquake.

5. CONCLUSIONS

The damage prevention ability of a WRC building in the event of a large earthquake is evaluated based on a static loading test of a specimen focusing on the lower two stories of a 1/2 scale 5-story typical prototype WRC building. The findings obtained are summarized below.

(1) In this specimen, the bending yield of the wall starts from the deformation angle 1/2000 cycle, the tensile yield of the orthogonal wall starts from 1/1000 cycle, and the shear yield starts from 1/200 cycle and the maximum strength is obtained.

(2) The seismic performance reduction factor calculated with the ultimate deformation as the deformation angle of 1/100 is about 0.85 at the deformation angle of 1/400 and about 0.6 at 1/200.

(3) Based on the load-deformation relationship and the hysteresis damping constant obtained by the experiment, the response of the WRC building during a large earthquake is estimated by the “Response and the ultimate strength method”, and the drift angle of the lower 2-story is 1/480.

(4) At the same drift angle, the building does not reach its maximum strength, bending yielding occurs, no shear failure occurs, and the seismic performance reduction factor is about 0.8.

The WRC building is considered to have high damage prevention performance against large earthquakes. It is necessary to ensure high damage prevention ability against large earthquakes, some structural requirements might be added for example to apply strength to wall beams.

In the future, we plan to conduct further detailed analysis of the results of this experiment, including slip failure at the wall foots,

6. Acknowledgments

A part of this research is carried out as a project to promote building standards development in the Ministry of Land, Infrastructure, Transport and Tourism in FY2017. The experiment is carried out at the Earthquake Engineering Research Laboratory of Yahagi Construction Industry, and many students of Yamaguchi University, the University of Tokyo, and Nagoya University help this test. I would like to express our sincere appreciation to all those involved.

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