The Performance Evaluation
of RC Wall Building

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1. Introduction

It is considered that the seismic performance of RC wall building is based on high strength, high rigidity, and coupling effect of the ground-superstructure with them. How much of the high strength and high rigidity can the specification of wall length ratio prescribed in the AIJ design standards for Box-type reinforced concrete building ensure? Then, whether it can explain that RC wall building was almost non-damage by damage earthquake with that high strength and high rigidity until now. The evaluation of seismic performance is tried by the new verification method (limit strength calculation) of the revision Building Standard Law enforced in June, 2000, and by AIJ design standard for Box-type reinforced concrete building.

2. The relationship between strength and wall length ratio

Table 1 summarized the test result of the full scale Box-type reinforced concrete building specimen. About average shear stress of 2.1N/mm^2 has been obtained at maximum strength of the test specimen. Test specimen figure and results are also shown in figure 1. And, the first shear first crack is observed at average shear stress of 1.1～1.3N/mm^2. Figure 2 is a relationship between shear stress and drift angle obtained by the experiment of the structural wall. From this figure, shear crack is observed at the average shear stress of 1.5～2.5N/mm^2 and the average shear stress in maximum strength is over 2.3N/mm^2.

In the case that the average shear stress at the maximum strength is assumed as 2.3N/mm^2, and elastic response shear force coefficient at the first story of RC wall building for earthquake motion which will possibly occurred is assumed to be 1G, the required cross sectional area of structural wall per unit floor area are listed in Table 2 according to the building weight per unit floor area. The building standard law has prescribed elastic response shear force coefficient of 1G in the short period region. From the test result of structural wall members, necessary wall area ratio is 24000～28000mm^2/m^2, in the case the weight of the RC wall building was 12～14kN/m^2, and each structural wall can maintain the maximum strength. As standard wall length ratio at first floor of RC wall buildings of 5-floor, Box-type reinforced concrete building design standard has prescribed 150mm/m^2, and 180mm standard wall-thickness. Wall area ratio by this specification becomes 27000mm^2/m^2. From the result of the full-scale experiment, however, average shear stress of the structural wall at the

AIJ design standard for Box-type reinforced concrete building
Please refer to the URL below
http://www.aij.or.jp/jpn/databox/2004/040414-2.pdf

maximum strength of a building is 2.0N/mm^2, and it is necessary to also give the RC wall building any ductility.

3. The relationship between rigidity and wall length ratio

Drift angle (R) of the structural wall is evaluated as sum of shear component (Rs) and bending component (Rb), and it is possible that it is shown according to the following equilibrium.

$$R = Rs + Rb = \frac{2 \cdot Q}{Aw \cdot E}\left\{\kappa(1+\nu) + (3y-1)\cdot(\frac{h}{l})^2\right\} \qquad \text{(Eq. 1)}$$

here, Aw: Wall area (mm^2), E: concrete Young modulus(21kN/mm^2), κ : Shape factor on the shearing rigidity(1.2), Poisson ratio of the concrete(1/6) h: wall height(mm), l: wall length, y: deflection height ratio.

Deflection point height ratio y in the Box-type reinforced concrete building generally becomes unity in the case which wall length l is lengthened, but it assumes 0.4～0.6 from design examples, etc., 0.5 here aversely. Though the whole bend deformation can not disregard the deformation in the transverse direction, it can be disregarded in the longitudinal direction in which seismic problem is considered. And, the ratio of bending deformation to shearing deformation of the wall is expressed by equibrium 2, because there is the specification that the value of (h/l) is under (10/3) in design standard for Box-type reinforced concrete building.

$$Rb/Rs = \frac{(3y-1)}{1.4}\cdot(\frac{h}{l})^2 \qquad \text{(Eq. 2)}$$

However, the ratio of bend deformation and shearing deformation is maximum in h/l=10/3, and it becomes 1:4. The shearing deformation angle is calculated from the following equation with 1/16260, when the weight per unit area of the RC wall building was made to be 12kN/m^2, and whole drift angle which also considered the bend deformation becomes 1/3200.

$$\begin{aligned} &Rs = 1.2Q/(AwG), \\ &Aw = Lw \cdot t \cdot Lx \cdot Ly \qquad \text{(Eq. 3)} \\ &Q = 12 \cdot Lx \cdot Ly \cdot N \cdot 0.2 \end{aligned}$$

Here, Q: shear force in the first story at C0=0.2, Lw: wall length ratio at the first story (150mm/m2), t: wall thickness (180mm), Lx: building length in longitudinal direction (m), Ly: building width in transverse direction (m), N: number of story (5).

Though the above is the case in which deflection point height ratio was fixed in 0.5, it assumes 1.5(l/h) as the result which deflection point height ratio is proportional to the wall length at present. As the result, bending to shearing deformation ratio Rb/Rs becomes 3.62 as the maximum values at h/l of 2.25, as it is shown in figure 3, and whole deformation becomes 1/3500. From the examination of the elementary elasticity rigidity, it will be able to ensure almost 1/3000 rigidity in the first design, if regulation for standard wall length ratio and wall-thickness of specification is satisfied. In the meantime, the research result by the analysis, which evaluated structural wall in structure plane in the equal span frame, is shown in tables of 3. Largest inter-story drift in this model becomes about 1/2200.

4. The relationship between high rigidness, high intensity and seismic performance

The examination is carried out by the factors used in the design example of design standard for RC wall buildings. The following are caused by notification of ministry of construction related to the limit strength calculation: Calculation in the period and calculation of damping. The design example is 5-story building. The parameter was made to be inter-story drift angle in the first design phase and ground period, sway spring constant. The first design is the design which made shear force coefficient of first story to be 0.2. Periods of the superstructure on fix base condition are the 0.2 seconds from 0.57 seconds. Inter-story drift angle in the first design of each story is 1/4000 from 1/500. The rigidity of sway spring of the ground for the large earthquake assumed 6.22E05(kN/m) in the 1 kind ground and 2.26E06(kN/m) and 2 kind ground. Sway period (Tsw) in this case becomes 0.21 seconds and 0.4 seconds, respectively. The ground period was made to be 0.2 seconds in the 1 kind ground the, and 0.4,0.6,0.8 second in 2 kind ground. Under the above condition, limit strength calculation has been done as the superstructure remains in elastic. It is possible to show the relationship between Tg/Tr and damping reduction in equation 4. Damping coefficient of sway spring was chosen with 15% in the case that Tg/Tr was under 1.0, and 30% in case over 2.0, and it was obtained by the linear interpolation in the interval.

$$
\begin{aligned}
&Fh = 15/(1+10h)\\
&h = \left\{(Tsw/Tr)^2 \cdot (Tg/Tr) \cdot 0.15 + (T0/Tr)^2 \cdot 0.05\right\} \qquad \text{(Eq. 4)}\\
&0.15 < (Tg/Tr) \cdot 0.15 < 0.3
\end{aligned}
$$

Building period on fix base condition, coupled period considering sway, sway spring constant in proportion to the ground period, damping coefficient of the coupled system, and the required base shear coefficient are shown in table 4 in every inter-story drift angle in the first design. In this time, it is assumed that the ground period becomes 1.7 times as its initial period for the examination in the safety limit. The relationship between the ratio of coupled period with building and ground to the period in the ground, Tg/Tr, and damping coefficient, required strength is shown in figure 4. Damping of sway spring is very effective, when Tg/Tr is over 1.5, and response shear force coefficient becomes 0.4～0.45 approximately. However, response shear force coefficient exceeds 0.5, when the rigidity is low on fix base condition, that is to say, inter-story drift angle in the first design is under 1/1000. Response shear force coefficients of 0.45 introduces the shear stress of the structural wall of 1.0N/mm2. This intensity of stress is under the shear crack strength of structural wall. Response shear force coeffient in the large earthquake becomes 0.45, if Tr/Tg is greater than 1.5, that is to say, inter-story drift angle of RC wall building on usual 2 kind ground in the first design is under 1/1500. In the meantime, in the region of Tg/Tr under 1.5, required shear force coefficient increase. Required shear force coefficient become 1.0 in fix base condition. Box-type reinforced concrete building, which is built on the rock, is correspondent to the above situation. It seems to have to consider sliding between superstructure and rock to some extent for the shear force. By the high rigidity with which high strength accompanies, Box-type reinforced concrete building seem to be the structure which are almost behave in the elastic condition against the large earthquake which very rarely occurred. In the meantime, the period is extended, when Box-type reinforced concrete building reached its strength, and even if it is on the 2 kind ground, damping by sway spring can not be expected. Required shear force coefficient becomes 0.56, when the drift angle at maximum strength of 1/200 and shear force coefficient at maximum strength of 0.8, and damping of whole building of 10% is assumed. In this case, the period on fix base condition is 0.9 seconds, and that is about 1.1 seconds on coupled system. Damping of the superstructure becomes dominant while damping of sway spring does not affect the damping of the coupled system almost. Even in this case, it can be estimated that the response of Box-type reinforced concrete building surpasses the crack strength a little.

5. Conclusion

The background of excellent seismic performance of this structure by AIJ design standards for Box-type reinforced concrete building was proven by the calculation. The main numerical reasons are as follows. (1) Building behaves approximately in elastic response of 1G, if it is based on regulation for wall length ratio. However, some extent ductility is required with the result of the full-scale experiment of Box-type reinforced concrete building. It seems to cover ductility by structure specification of AIJ, etc. (2) Observing regulation for standard wall length ratio and wall-thickness, as rigidity in the first design can ensure inter-story drift angles of 1/2000. (3) In large earthquake, Box-type reinforced concrete building built on the 2 kind ground positions under the response that estimates the generation of the shear crack by the coupling effect with the ground by ensuring the rigidity. For the same structure, on 1 kind ground, let's must consider the sliding between base and rock. (4) Response shear force coeffient is estimated considerably small about 0.56, even if ultimate limit of this structure is assumed from the full-scale experiment with maximum strength and that deformation, damping coefficient. And it estimates also large damage with that it is avoided. It is considered to show numerically that this structure is the structure, which can stand the large earthquake with large capacity margin. The safety of individual building can be rationally evaluated, if limit strength calculation in this time is done. The key in limit strength calculation is rigidity and strength. On the rigidity, though there will be a complicated technique, however, the development of the technique conveniently required is desired. And, the specified estimation method is desired on limit strength, and limit deformation. In addition, elucidation of the Response State of this structure, which is built on the solid soil, will be also necessary.

Table 1 Test results of large-scale Box-type RC buildings

	t (cm)	lw (cm/m^2)	Aw (cm^2/m^2)	σ_B ⁽³⁾ (kg/cm^2)	Pw (%)	shear crack τ_{cr}(kg/cm^2)	max. strength τ_u(kg/cm^2)	τ_{max}/σ_B	drift angle of 1st story at max. strength
5FWRC(1)	18	15	270	230	0.28	13.0	21.6	0.094	7.3/1000
5FWRC(2)	15	12	180	230	0.25	11.0	21.0	0.091	7.1/1000

（1） Shinagawa, Endoh: Experimental test results of WRC with setback vertically and horizontally, BRI annual report 1970.

（2） Matsushima: Experimental study on full-scale 5-story WRC building, BRI annual report 1968

（3） Compressive strength of concrete

Table 2 Required Wall are ratio(Aw) for 5-story WRCbuilding

Building weight per unit floor area w (kN/m^2)	Required wall area ratio Aw (mm^2/m^2)
10	21700
12	26100
14	30400

The relational expression of wall area ratio (Aw) and shear stress (τ_u), building weights per unit floor area (w) is $\tau_u \cdot Aw = w \cdot 5$

Table 3 Inter-story drift angle at the allowable stress design stag for standard base shear coefficient of C0=0.2 of WRC building model

story	1	2	3	4	5
Inter−story drift angle	1 /2797	1/2130	1/2399	1/3076	1/4636

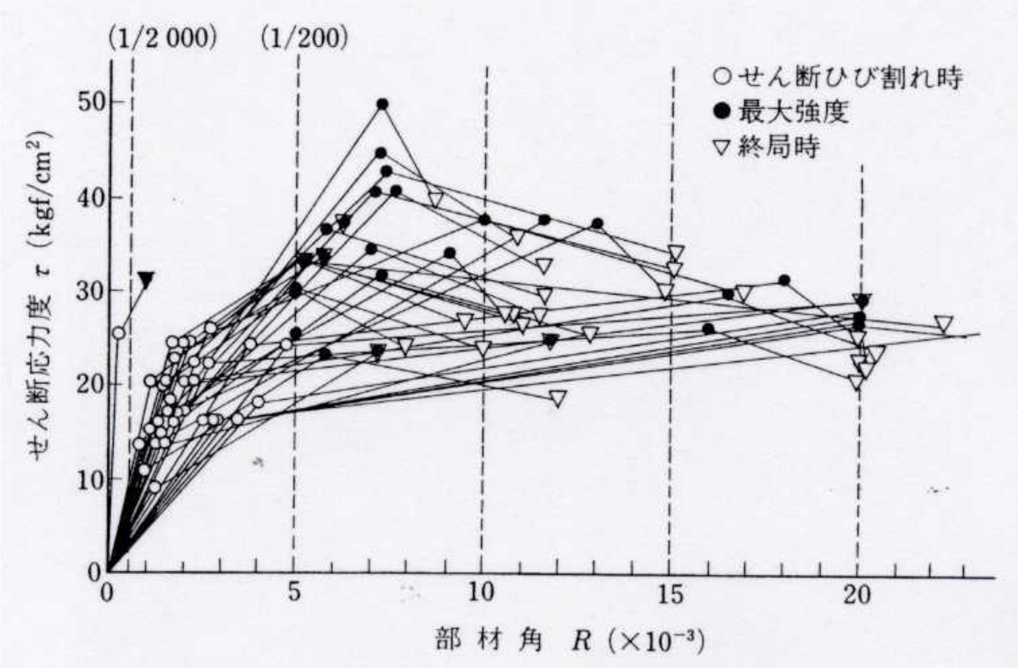
Model and analytical condition :
Story height : 2.85m Number of story : 5
Span : 2.7m x 5
Girder : 0.2x0.6m Wall : 0.2x0.675m
Rigid zone : Wall-girder connection

Table 4 Building stiffness, Soil period, Damping, and Rerquired Strength

	Period of SSI system (Tb)	Soil period (Tg)		1.7 * Tg/Tb	Damping of sway efffect	Damping of building	Damping of SSI system	Required Strength Coefficient
R=4000	0.45	2nd Kind	0.80	3.02	0.30	0.05	0.25	0.42
	0.45	2nd Kind	0.60	2.27	0.30	0.05	0.25	0.42
	0.45	2nd Kind	0.40	1.51	0.23	0.05	0.19	0.50
	0.29	1st Kind	0.20	1.17	0.17	0.05	0.12	0.68
Fix end	0.20			0.00	0.00	0.05	0.05	0.98
R=3000	0.46	2nd Kind	0.80	2.96	0.30	0.05	0.24	0.44
	0.46	2nd Kind	0.60	2.22	0.30	0.05	0.24	0.44
	0.46	2nd Kind	0.40	1.48	0.22	0.05	0.18	0.53
	0.31	1st Kind	0.20	1.10	0.16	0.05	0.10	0.73
Fix end	0.23			0.00	0.00	0.05	0.05	0.98
R=2000	0.49	2nd Kind	0.80	2.78	0.30	0.05	0.22	0.46
	0.49	2nd Kind	0.60	2.08	0.30	0.05	0.22	0.46
	0.49	2nd Kind	0.40	1.39	0.21	0.05	0.16	0.58
	0.35	1st Kind	0.20	0.97	0.15	0.05	0.09	0.79
Fix end	0.28			0.00	0.00	0.05	0.05	0.98
R=1500	0.52	2nd Kind	0.80	2.62	0.30	0.05	0.20	0.49
	0.52	2nd Kind	0.60	1.96	0.30	0.05	0.20	0.49
	0.52	2nd Kind	0.40	1.31	0.20	0.05	0.14	0.62
	0.39	1st Kind	0.20	0.87	0.15	0.05	0.08	0.82
	0.33			0.00	0.00	0.05	0.05	0.98
R=1000	0.57	2nd Kind	0.80	2.39	0.30	0.05	0.17	0.53
	0.57	2nd Kind	0.60	1.79	0.27	0.05	0.16	0.56
	0.57	2nd Kind	0.40	1.19	0.18	0.05	0.11	0.68
	0.45	1st Kind	0.20	0.76	0.15	0.05	0.07	0.86
Fix end	0.40			0.00	0.00	0.05	0.05	0.98
R=500	0.69	2nd Kind	0.80	1.97	0.29	0.05	0.13	0.64
	0.69	2nd Kind	0.60	1.48	0.22	0.05	0.11	0.71
	0.69	2nd Kind	0.40	0.99	0.15	0.05	0.08	0.80
	0.60	1st Kind	0.20	0.57	0.15	0.05	0.06	0.91
Fix end	0.57			0.00	0.00	0.05	0.05	0.98

*R: Inter-story drift angle at the allowable stress design stag for standard base shear coefficient of C0=0.2

*2nd Kind: Medium Soil, 1st Kind: hard soil



○ Shear Crack、● Max. Strength、▽ Ultimate Stage

Fig. 2 Shear stress vs. Drift angle of wall members (test results)

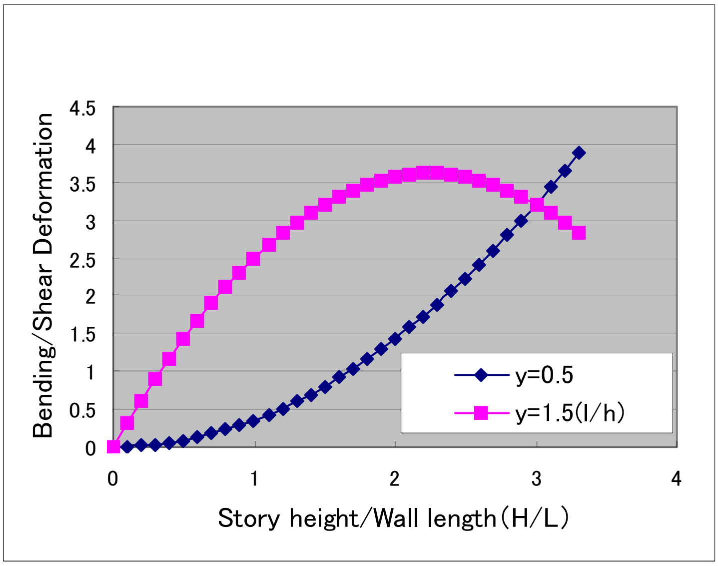


Fig. 3 Bending/Shear deformation vs. wall length/story height

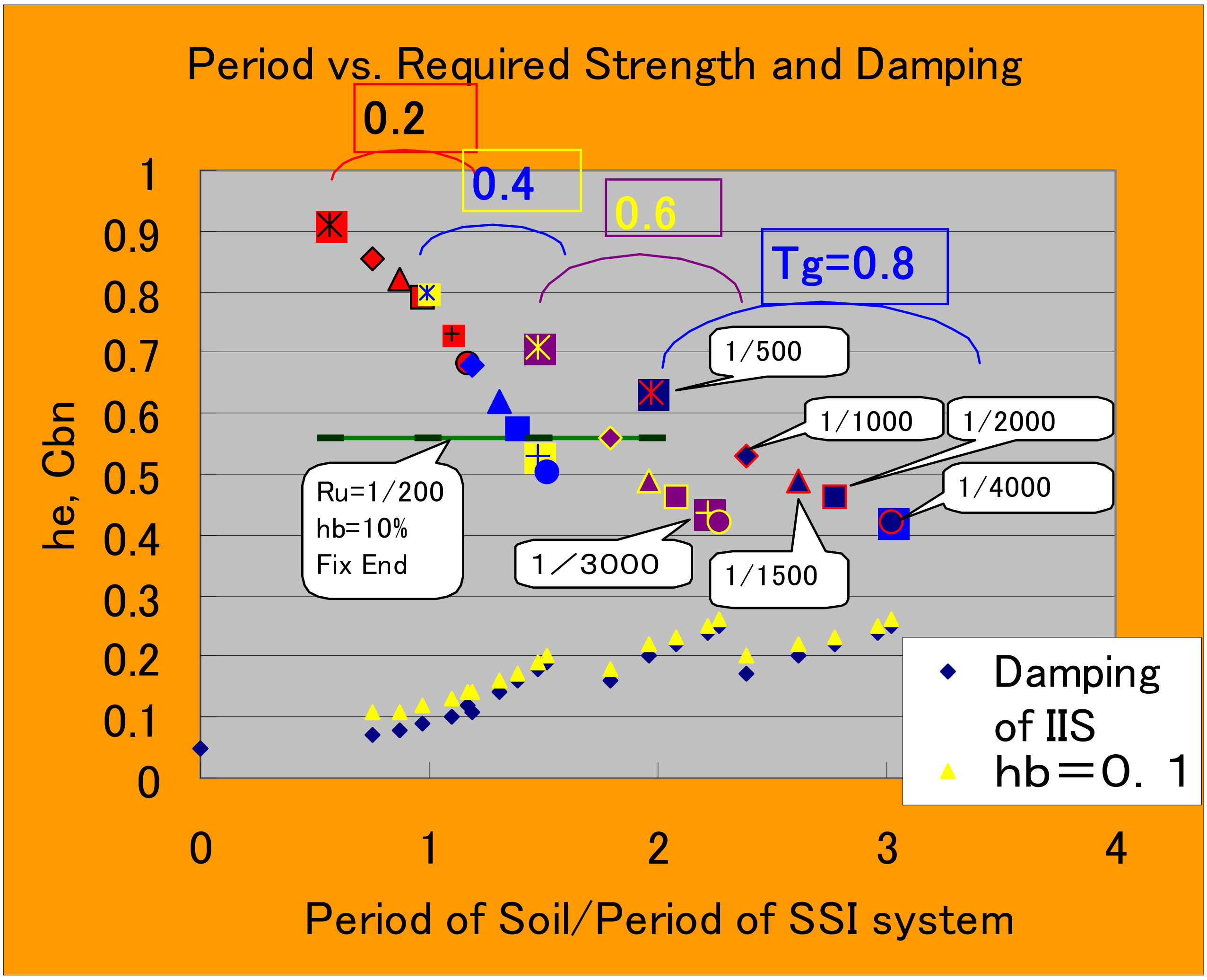


Fig. 4　Period vs. Required Strength and Damping

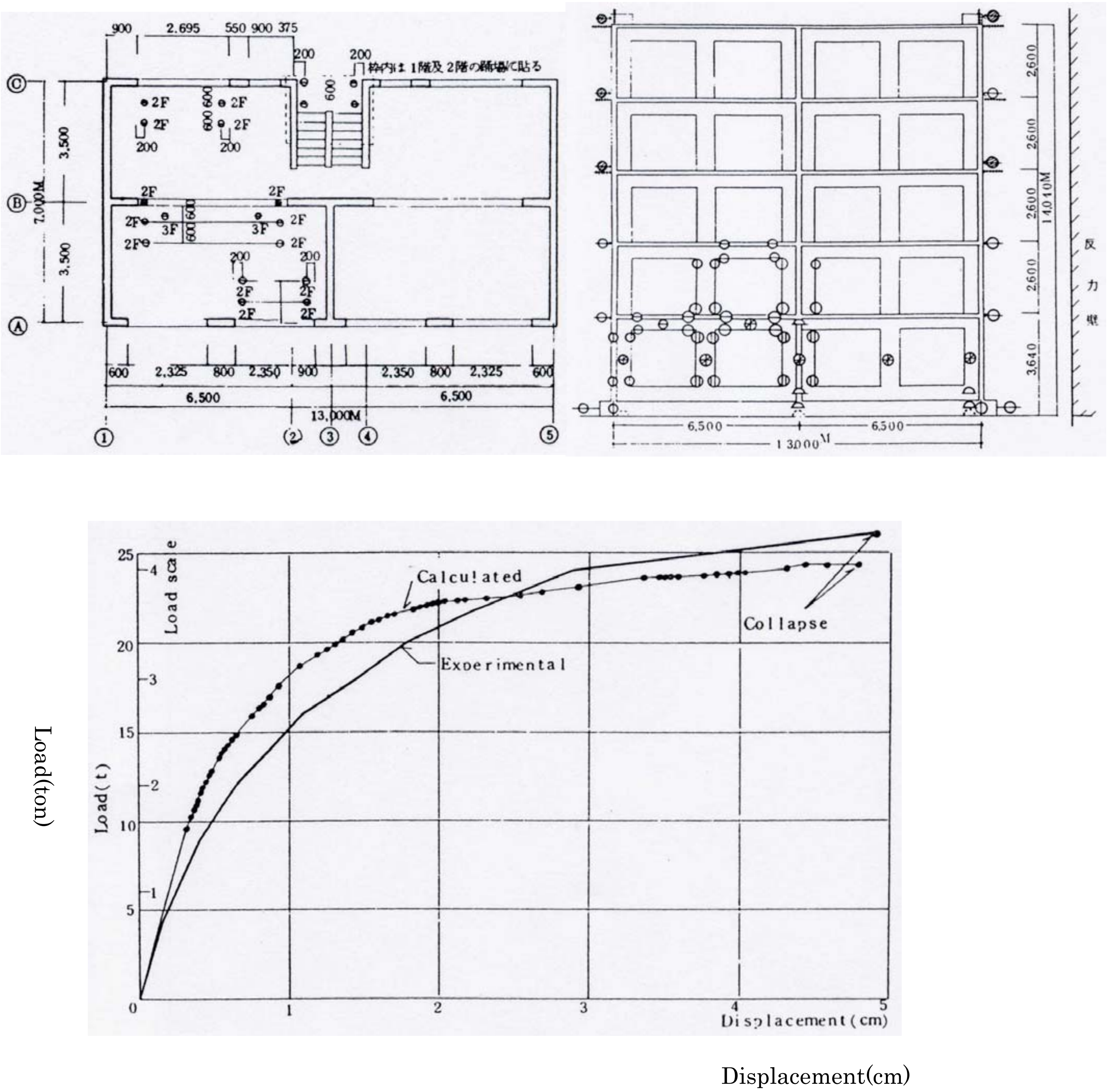


Fig. 1　5-story WRC full-scale test
(Matsushima: Experimental study on full-scale 5-story WRC building, BRI annual report 1968)