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SEISMIC PERFORMANCE OF LOW-RISE PRECAST REINFORCED CONCRETE STRUCTURE —STANDARDIZATION OF METHOD TO ESTIMATE SEISMIC CAPACITY—

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SUMMARY

This paper presents a brief description on standardization of method to estimate seismic capacity of industrialized low-rise housing structures of precast reinforced concrete construction. As one of the industrialized housing structure in Japan, there is a precast wall panel structural system which is composed of mainly medium-size wall panels and floor panels. By seismic collapse test on a full-scale solid specimen by this system, it was made clear that several kinds of components besides structural members in plane enlarge fairly the horizontal bearing capacity of the structure. Basing on the analytical and experimental results such as the above, authers introduced here a standardized method to estimate seismic capacity of this kind of structures in simplified and rational way.

INTRODUCTION

Recntly in Japan, industrialized housing systems are progressing year by year. The medium-size reinforced concrete precast panel structure being reported here was developed as one of the systems for low-rise housings about 25 years ago and houses more than 150,000 dwelling units had been already constructed by this system. These industrialized houses are regarded as buildings of sepcial strucutral system and they must be approved by the minister of construction. For getting the approval and reducing the time to get it, it is necessary to compile a method to estimate their seismic performance and also to simplify it.

Further in order to ensure the adequate seismic safety to the regulated severe earthquake design load, it is also important to standardize the rational seismic estimation method by adequately counting principal seismic resistant elements. Under the above-mentioned backgrounds, authors tried to standardize a simplified and rational estimation method for the seismic performance of this kind of structure basing on the test results on structural elements and the solid specimen and the analytical ones.

HOUSING STRUCTURES BY INDUSTRIARIZED R/C CONSTRUCTION AND THE RPINCIPAL ASEISMATIC ELEMENTS

In Japan where severe earthquakes occur so often, many medium-rise appartments are of cast-in place or precast R/C wall construction and private houses of R/C are also mainly wall typed ones. As not a few large or small opennings are used to be irregulally designed in wall planes, seismic performance of walled-type buildings have been mainly discussed experimentally due to difficulty of theoretical solution(Refs. 1, 2, 3).

Typical data of seismic experiment on large-scale solid specimens are shown in Figs 1 and 2. Fig.3 shows the experimental and calculated average unit shear stresses at the maximum horizontal bearing capacity on the typical solid specimens. From these figures and so on, the followings are pointed out.

a. Horizontal bearing capacities of solid specimens of R/C wall construction being similar to the actual buildings are highly influenced not only by strength of structural members in plane but also by the elements normal to the direction of earthquake action.

b. Component of bearing capacity being carried by the strucatural members in plane are only from 30% to 60% total capacity.

c. Out of the other effective elements, the most typical ones are the effect to bending capacity of beams by reinforcements in floor slabs and the effect to shear capacity of beams by concrete of the slabs. Especially, the effect to bending capacity of beams increases as increase of horizontal deflection of the sepecimen and reaches to occupy around 30% total capacity in maximum.

d. When horizontal load is statically applied to a plane or solid specimen concentratively in compressive way, compressive forces act in beams and the bearing capacity of the specimen increases fairly due to the increased capacityes of the beams. This effect would be neglected in actual structures.

e. In case of the medium-size panel structures, bearing capacity of a solid specimen is influenced by several elements such as effect by walls normal to bearing walls, effect by continuous arrangement of bearing walls, effect by sagging panels and so on. Resultantly the bearing capacity of the solid specimen reaches to around three times the capacity being estimated only by independent bearing wall panels.

f. On the other hand, plastic deformation ability of each specimen was generally excellent and any distinguished deteriolation of bearing capacity was not observed at around 1/100 of deflection angle. In order to get excellent deformability, it is important to keep the average shear unit stress at the maximum capacity less than around 0.1Fc (Fc : concrete strength) and to make the calculated shear capacity larger than the capacity at the flexure mechanism.

QUANTITATIVE ESTIMATION OF ASEISMATIC EFFECTS

As mentioned above, seismic bearing capacity of solid specimen being similar to actual structures was made clear to be considerablely enlarged by the other factors than the structural members in plane. Therefore, it is necessary to estimate quantitatively the effects.

As reported in the previous report(Ref.4), in case of the medium-size panel structure, the following four factors beside the bearing wall panels were mainly recognized to be effective to increase the bearing capacity of the whole structure.

a. Bending capacity of bearing wall panels
b. Effect due to wall panels normal to bearing walls ("Normal effect")
c. Effect due to continuous arrangement of bearing walls("Continuous effect")
d. Effect due to bending capacity of sagging(horizontal) wall panels
e. Effect due to compression force acting in sagging walls being induced by horizontal loading

Out of these effects, the effect (e) can not be expected in actual buildings under earthquake. On the other hand, the effect (d) tends not only to increase the capacity but also to make deformability of the wall panel to which it connect deteriorate. Therefore, it is usual to make it invalid by putting adequate slit between the sagging wall panel and the bearing wall panel.

Accordingly, it was desided here to account only the effect (b) and (c). Fig. 4 shows a perspective view of the portion where the effects (b) and (c) are expected and Fig.5 shows their quantitative estimation. As shown in these figures, both effects are caused by the condition where top portions of the adjacent wall panels are connected with earch other by the floor panel and where vertical ribs of the adjacent wall panels are connected with earch other by steel bolts. Accordingly it becomes important to estimate their effective cross sectional areas and the shear strength. Out of these unknown factors, there are only few back data on effective extence and strength of floor panels. So, it was desided here to estimate them conservatively as shown in Fig. 5.

On the other hand, the effect due to normal wall panels is clearly influenced not only by the above-mentioned factors but by the anchor bolts at the base of the normal wall panels. Also concerning the effect by the bolts, the effective extense becomes important and it was desided to account two bolts at earch one side effective basing on the measured values of strain of the anchor bolts.

Values of the resisting moment due to each factor are estimated guantitatively basing on these asumptions and shown in Fig.5. Both values are, as understood from the figure, bigger than the capacity of one bearing wall panels. Using this result, the two bearing wall panels shown in Fig.4, have capacity corresponding to that of (2+1.04+1.18=4.22) panels in total.

However, it is very important for us to be careful so that the increased capacity in this way might not injure the plastic deformation ability of the whole structure. Explaining on the case of Fig.4, each bearing wall panel should not collapse in brittle way not under the shear force corresponding to flexure capacity of each panel but under the shear more than 4.22/2 times the flexure capacity.

TO STANDARDIZE ESTIMATION METHOD OF BEARING CAPACITY

Basing on the above-mentioned items, sum of resisting moments M_{Ii}, of this kind of building with a certain arrangement of wall panels can be expressed in the following equation.

$$M_{Ii} = n_{wi} \cdot M_{woi} + \sum_{i=1}^{m} (n_{Ni} \cdot M_{Ni} + n_{ci} \cdot M_{ci}) \quad (1)$$

On the other hand, total overturning moment M_{ovi}, at the base level of (i.th) floor due to design earthquake load can be expressed by Eq.(2).

$$M_{ovi} = Z \cdot D_s \cdot C_o \cdot \sum_{i=1}^{m} (A_i \cdot A_{fi} \cdot W_i \cdot h_i) \quad (2)$$

Here,

n_{wi} : number of the bearing wall panels at the i-th floor, in case when there are several kinds of walls with different wall length, n_{wi} shall be sum of coefficients due to effective ratio of their bending capacity.

M_{woi}: calculated moment capacity of the standard bearing wall panel at i-th floor.

n_{Ni}, n_{ci} : number of locations where "normal effect" or "continous effect" can be expected at i-th floor, respectively

M_{Ni}, M_{ci} : value of the equivalent resisting moment due to "normal effect" or "continuous effect", respectively

Z : zone factor (0.7-1.0)

D_s : structural coefficient due to ductility of each structure (0.30-0.55 in case of R/C strucure and 0.55 in this case)

C_o : standard base shear coefficient to severe earthquake (1.0)

A_i : coefficient showing distribution of horizontal forces

A_{fi}, W_i : total floor area and average unit total weight at i-th floor

h_i : height where horizontal force act measured from the ground floor level

On the other hand, the coefficient F_{es} is regulated to be considered in the actual seismic design basing on the eccentric distribution of horizontal rigidity of wall panels in each floor and on their relative difference between each story.

Accordingly, seismic performance of each building is fundamentally disussed by the following equation.

$$M_{Ii} \geqq M_{rci} = F_{esi} \cdot M_{ovi} \tag{3}$$

On the other hand, equations (1), (2) and (3) can be converted in the following simplified forms, respectively.

$$M_{Ii} \geqq n_{wi} \cdot M_{woi} \cdot \phi_{Nci} \tag{4}$$

$$\phi_{Nci} = \mathrm{Min}[1 + \sum_{i=1}^{m} (\bar{n}_{Ni} \cdot \bar{M}_{Ni} + \bar{n}_{ci} \cdot \bar{M}_{ci})] \tag{5}$$

$$\bar{n}_{Ni} = N_{ni}/n_{wi}, \quad \bar{n}_{ci} = N_{ci}/n_{wi} \tag{6}$$

$$\bar{M}_{Ni} = M_{Ni}/M_{woi}, \quad \bar{M}_{ci} = M_{ci}/M_{woi}$$

$$M_{ovi} \leqq 0.55\ W_o \cdot \Sigma A_{fi} \cdot h_{ei} \tag{7}$$

$$W_o \fallingdotseq W_1 \fallingdotseq W_2 \tag{8}$$

$$h_{ei} = \mathrm{Max}\left[\frac{A_i \cdot A_{fi} \cdot W_i \cdot h_i}{W_o \cdot \Sigma A_{fi}}\right] \tag{9}$$

$$\phi_{Nci} \cdot N_{woi} = \frac{M_{ovi}}{M_{woi} \cdot \Sigma A_{fi}} \leqq \frac{0.55 W_o \cdot h_{ei}}{M_{woi}} \tag{10}$$

$$M_{Rci} = F_{esi} \cdot N_{woi} \cdot M_{woi} \cdot \phi_{Nci} \cdot \Sigma A_{fi} \tag{11}$$

Here, the value of ϕ_{Nci} shown by Eq. (5) can be put in to a coustant as a lower limit of the values being obtained on many actual buildings which were designed following the structural regulations on the principle for wall panel arrangement. The value of hei shown by Eq.(9) can be also put into a constant for each story, because difference among the values on many actual cases, which become different according to magnitude of snow load and ratio of weights of the first and second floor, is not so large. Furthermore, N_{woi}, which means the number of bearing wall panels neccessary for unit floor area, can be put into a constant using these constants, ϕ_{Nci} and h_{ei} as shown in Eq.(10). Resultantly, Eq.(12) can be derived from Eqs.(1), (4) and (11).

$$n_{wi} + \sum_{i=1}^{m} (n_{Ni} \cdot \bar{M}_{Ni} + n_{ci} \cdot \bar{M}_{ci}) \geqq F_{esi} \cdot N_{woi}\ \phi_{Nci} \cdot \Sigma A_{fi} \tag{12}$$

Taking a building with the simple plans and elevations as shown in Figs.5 and 6 as an example, actual method to count the unknown values in the left side of Eq.(12) is listed in Fig.5. Moreover, the unknown value, F_{esi}, in the right side of Eq.(12) can be calculated by a pocket computer with small capacity using computer program to calculate it fundamentally basing on the horizontal rigidity of wall panels and their arrangement.

Thus, examination on safety to severe earthquake can be easily carried out for each design example even by designers and even under discussion about plannings with custmers.

CONCLUSION

Authors proposed a simplified method to estimate seismic performance of low-rise precast R/C housing structures without floor tie beams, considering that their seismic property is influenced by various kinds of boundary effects. Resultanty, authers showed that it is possible to examine seismic performance required to each case of design by countering the number of existing bearing wall panels and the boundary effects due to their arrangement.

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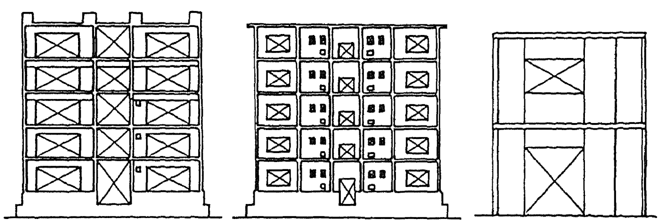


a) 8-Story, Cast-in-Place b) 5-Story, Large-Size-Panel c) 2-Story, Medium-Size Panel

Fig.1 Typical Structural Planes of Full-Scale Wall-Typed Specimens

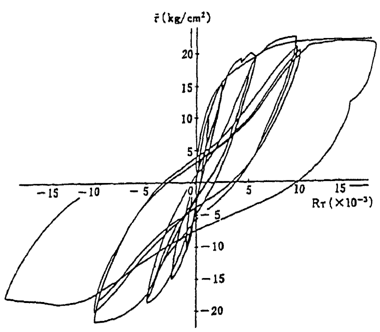


Fig.2 Average Unit Shear Stress (τ̄)-Deflection Angle at the Top the Specimen "8F"

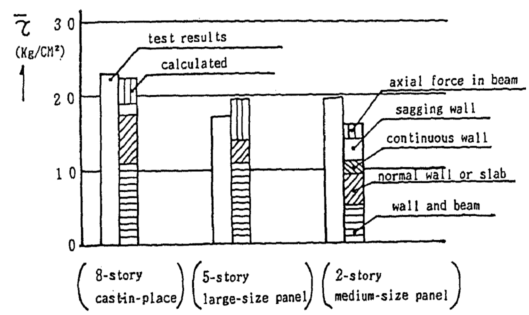


Fig.3 Average Unit Shear Stress at the Maximum Strength of Full-Scale Wall-Typed Specimens

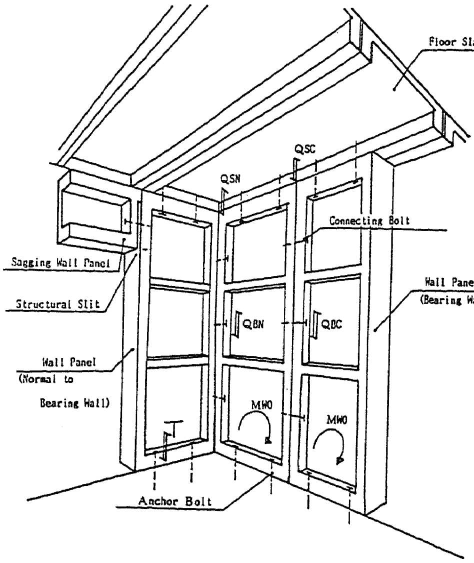
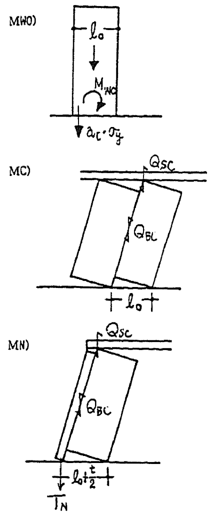


Fig.4 Perspective View of Effect due to Normal Wall and Continuous Wall Panels



$$M_{wo} \fallingdotseq 0.8a_t \cdot \sigma_y \cdot \ell_o + 0.45N\ell_o$$
$$= 0.8\times2.87\times3.5\times\ell_o + 0.45\times4.5\times\ell_o$$
$$= 10.06\ \ell_o\ (t\cdot m)$$

$$Q_{SC} = Q_{SN} = A_c \cdot {}_cf_s = 15\times12\times20\times10^{-3} = 3.6t$$
$$Q_{BC} = Q_{BN} = a_s \cdot {}_sf_s = 3\times1.33\times\frac{3000}{\sqrt{3}}\times10^{-3} = 6.9t$$
$$M_C \fallingdotseq (Q_{BC}+Q_{SC})\times\ell_o$$
$$= 10.5\ \ell_o = 1.04\ M_{wo}\ \text{(Per one story)}$$

$$T_N = 2(4)\times2.87\times3.5 = 20.1\ (40.2)\quad (t)$$
$$M_N \fallingdotseq \text{Min}\ [(Q_{BC}+Q_{SC}),\ T_N]\times(\ell_o + t/2)$$
$$= 11.9\ \ell_o = 1.18\ M_{wo}\ \text{(Per on story)}$$

Fig.5 Quantitative Comparison of Wall Capacity (Mwo) with Effect of Continuous Wall Panel (Mc) and Normal Wall Panel (MN)

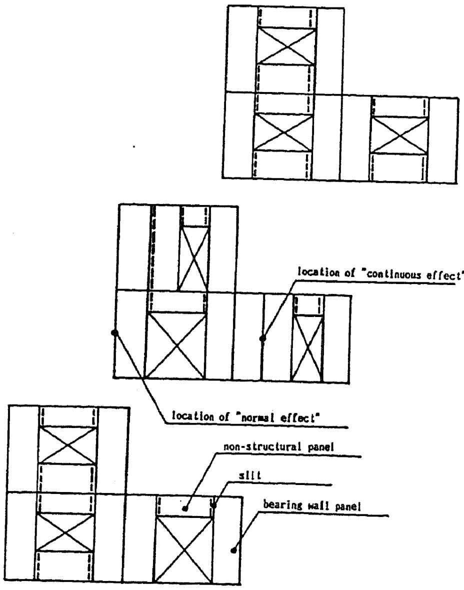
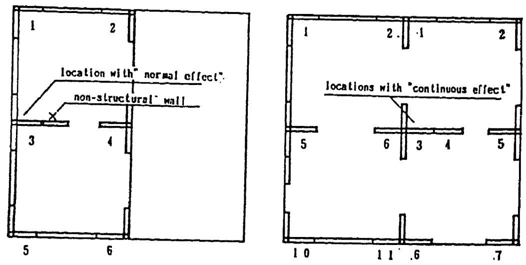


Fig.6 An Example on Arrangement of Bearing Wall Panels in Structural Planes and Locations where "Normal Effect" or "Continuous Effect" Could be Expected



Story	number of bearing wall panels		number of locations with "normal effect"		number of locations with "continuous effect"		equivalent number of bearing wall panels
	n_{w2}	n_{w1}	n_{N2}	n_{N1}	n_{c2}	n_{c1}	
2nd	—	6	—	2(L) 1(T)	—	—	$9.52n_{W1}$
1st	6	7	2(L) 1(T)	—	—	4	$22.48n_{W2}$

Fig.7 Example to Calculate Seismic Capacity by Counting Numbers of Panels and Other "Effect"