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

Masaya HIROSAYA¹, Yasuhiro MATUZAKI², and Eiji MAKITANI³,

¹Building Research Institute, Ministry of Construction, Tsukuba, Ibaraki, Japan
²Department of Architecture, Science University of Tokyo, Japan
³Department of Architecture, Kanto Gakuin University, Japan

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, authors introduced here a standardized method to estimate seismic capacity of this kind of structures in simplified and rational way.

INTRODUCTION

Recently 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 special structural 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 INDUSTRIALIZED R/C CONSTRUCTION AND THE PRINCIPAL ASEISMATIC ELEMENTS

In Japan where severe earthquakes occur so often, many medium-rise apartments 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
openings are used to be irregularly 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 structural 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 specimen and reaches to occupy around 30% total capacity in maximum.
d. When horizontal load is statically applied to a plane or solid specimen concentrically in compressive way, compressive forces act in beams and the bearing capacity of the specimen increases fairly due to the increased capacities 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 deterioration 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 0.1F_c (F_c: 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 considerably 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 desired 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 each other by the floor panel and where vertical ribs of the adjacent wall panels are connected with each 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 extent and strength of floor panels. So, it was designed 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 extent becomes important and it was designed to account two bolts at each 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 quantitatively basing on these assumptions 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_{wi}, of this kind of building with a certain arrangement of wall panels can be expressed in the following equation.

\[ M_{wi} = n_{wi} \cdot M_{woi} + \sum_{i=1}^{m} (n_{Ni} \cdot M_{Ni} + n_{ci} \cdot M_{ci}) \]  \hspace{1cm} (1)

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

\[ M_{bvi} = Z \cdot D_{s} \cdot C_{o} \cdot \sum_{i=1}^{m} (A_{i} \cdot A_{fi} \cdot W_{i} \cdot h_{i}) \] \hspace{1cm} (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 "continuous 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 structure and 0.55 in this case)
\[ C_{o} \]: standard shear coefficient to severe earthquake (1.0)
\[ A_{i}, A_{fi}, W_{i} \]: total floor area and average unit total weight at i-th floor
\[ h_1 \]: height where horizontal force act measured from the ground floor level

On the other hand, the coefficient \( F_{esi} \) 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 discussed by the following equation.

\[ M_{li} \geq M_{rci} = F_{esi} \cdot M_{ovi} \]  

(3)

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

\[ M_{li} \geq n_{wi} \cdot M_{woi} \cdot \phi_{Nci} \]  

(4)

\[ \phi_{Nci} = \min [1 + \frac{n_{wi}}{n_{wi}} (\bar{N}_{i} \cdot M_{Ni} + \bar{n}_{ci} \cdot M_{ci})] \]  

(5)

\[ \bar{N}_{i} = N_{Ni}/n_{wi}, \quad \bar{n}_{ci} = N_{ci}/n_{wi} \]  

(6)

\[ M_{woi} \leq 0.55 W_{O} \cdot \sum A_{fi} \cdot h_{ei} \]  

(7)

\[ W_{O} = \frac{W_{1} + W_{2}}{2} \]  

(8)

\[ h_{ei} = \max \left( \frac{A_{i} \cdot A_{fi} \cdot W_{i} \cdot h_{i}}{W_{O} \cdot \sum A_{fi}} \right) \]  

(9)

\[ \phi_{Nci} \cdot N_{woi} = \frac{M_{ovi}}{M_{woi} \cdot \sum A_{fi}} \leq \frac{0.55 W_{O} \cdot h_{ei}}{M_{woi}} \]  

(10)

\[ M_{rci} = F_{esi} \cdot N_{woi} \cdot M_{woi} \cdot \phi_{Nci} \cdot \sum A_{fi} \]  

(11)

Here, the value of \( \phi_{Nci} \) shown by Eq. (5) can be put in to a constant 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 \( h_{ei} \) 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 necessary for unit floor area, can be put into a constant using these constants, \( \phi_{Nci} \) and \( h_{ei} \) as shown in Eq.(10). Resultantly, Eq.(12) can be derived from Eqs.(1), (4) and (11).

\[ n_{wi} + \frac{m}{i=1} (n_{Ni} \cdot \bar{N}_{Ni} + n_{ci} \cdot \bar{n}_{ci} \cdot M_{ci}) \geq F_{esi} \cdot N_{woi} \cdot \phi_{Nci} \cdot \sum A_{fi} \]  

(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 plankings with customers.
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. Resultantly, authors showed that it is possible to examine seismic performance required to each case of design by counting the number of existing bearing wall panels and the boundary effects due to their arrangement.

REFERENCES


![Typical Structural Planes of Full-Scale Wall-Typed Specimens](image1)

![Average Unit Shear Stress (\(\overline{\tau}\))-Deflection Angle at the Top the Specimen "SF"](image2)

![Average Unit Shear Stress at the Maximum Strength of Full-Scale Wall-Typed Specimens](image3)
Fig. 4 Perspective View of Effect due to Normal Wall and Continuous Wall Panels

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

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