SHEAR FAILURE MECHANISM OF RC WALL-TYPE PIERS UNDER CYCLIC LOADS

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INTRODUCTION

The objective of this study is to investigate shear failure mechanism of RC wall-type piers under cyclic loads and also evaluate JRA (Japan Road Association) design code recommendations on design of such members particularly whether or not they can be classified in deep beams category. If they are in deep beam category, mechanism of failure results higher shear capacity than conventional form of shear failure with large shear span to depth ratio which is also basis of JRA design code. It this paper only experimental responses and analytical predictions are presented and discussed. The finite element method employed for this study is presented in some other publications where in reliability, robustness and objectivity of the method is already examined and evaluated (Salamy et al. 2005).

EXPERIMENTAL INVESTIGATION

Two RC walls have been tested in Public Works Research Institute during the year 2004 in order to investigate shear behavior of such members under cyclic load condition. Existence and development of diagonal cracks have been measured by two displacement transducers installed in locations where occurrence of the shear cracks has the highest possibilities. It is found that JRA design code does not take into account extra shear capacity of RC wall-type piers if shear span (here is wall height) to depth ratio of the wall falls in deep beam category and produce more shear capacity (Kobayashi et al. 2005). It is well explained by quite number of experimental investigations that for members with small shear span to depth ratio, conventional shear resistance mechanism yields very conservative prediction. Arch action which is formed in such members enhances shear capacity of the member significantly. Experiment results of this study also confirmed formation of different shear resistance mechanism similar to that observed in deep beams particularly.

Fig.1. Detail of specimens
Fig.2. Envelope of cyclic response of specimens
Test specimens comprise of two RC walls with shear span (height) to depth ratio of 1.5, in deep beam category, under one and two directional cyclic loads respectively. Since specimens are wall-type member, longitudinal and lateral reinforcements are smeared out all over the wall in order to produce a smooth distribution of stress over the member. Structural detail of specimens is shown in Fig.1 and Fig.2 illustrates envelope of cyclic responses of both specimens in positive direction. It is observed that in one-directional loading condition (No.1), bending cracks are developed in higher load than two-directional (No.2) load while shear cracks developed in almost same load level. This implies that shear crack might be independent to loading pattern while is dependent to level of the applied load. Overall load capacity is not affected by loading pattern where in both specimens almost identical load capacity is obtained.

**ANALYTICAL INVESTIGATION**

Analytical study by means of nonlinear finite element method is carried out subsequently. Finite element method applied for numerical modeling here is almost similar to the one used for RC deep beam behavior investigation in previous study which is reported elsewhere (Salamy et al. 2005). Since failure mode is dominated by shear, analytical responses show sensitivity to the employed crack model as well as solution scheme where in numerical difficulties have been encountered. In order to study sensitivity of prediction to crack model, both rotating and fixed crack models have been applied. Fixed crack model, however, has a range of shear retention factor which is left to the user choice; consequently, depend on the applied retention factor, results in a range of conservative, for smaller factor, and over estimated prediction for larger factor. On the other hand, rotating crack model results robust but conservative prediction in terms of load capacity of the member. Bond slide phenomenon is also taken into account for certain reinforcements. Other parameters have been considered in analyses are those of concrete confinement effect, concrete compressive strength reduction due to lateral cracks, steel hardening model, effect of foundation for full model simulation, interface elements between foundation and supporting pad as well as pre-stressing effect of anchoring bars which produce preliminary cracks before loading process. Concept of constant fracture energy of concrete is applied to the entire analysis of this study in order to eliminate mesh dependency in predicted response.

**Material Model for Concrete in Tension**

Concrete in tension before cracking is assumed to be linear elastic and after tensile strength is reached, it will follow an exponential softening path derived empirically by Hordijk (1991), shown in Fig.3, and determined by the following equation.

\[
\frac{\sigma}{f_t} = \left(1 + \left(\frac{c_1}{w_c} \right)^3 \right) \exp\left(-c_2 \frac{w}{w_c}\right) - \frac{w}{w_c} \left(1 + c_1\right) \exp(-c_2)
\]

(1)

where \( w \) is the crack opening; \( w_c \) is the crack opening at the complete release of stress which is a function of Mode I fracture energy \( G_f' \) (Eq.2); \( \sigma \) is the normal stress in crack and \( f_t \) is the tensile strength of concrete in one dimension system or effective tensile strength in two dimension system. Values of the constants are \( c_1 = 3 \) and \( c_2 = 6.93 \).

\[
w_c = 5.14 \frac{G_f'}{f_t}
\]

(2)

![Fig.3. Tensile fracture model for concrete](image1)

![Fig.4. Compression fracture model for concrete](image2)
Material Model for Concrete in Compression

Concrete in compression is modeled by a modified parabolic relationship between stress and strain to take into account fracture energy of concrete in compression (Feenstra, 1993). Concrete is assumed to be elastic up to \( \frac{1}{3} f'_c \), which deformation can be totally exhausted after unloading. Permanent deformation will be formed after this point and ultimate strain as a function of fracture energy and corresponding to the characteristic length parameter can be calculated. Figure 4 along with the following equations are representing this model, which in equivalent stress is determined in terms of equivalent strain.

\[
\bar{\sigma} = \begin{cases} 
\frac{f'_c}{3} \left( 1 + \frac{4}{e'_c} - \frac{2}{e'_c^2} \right) & \text{if } \bar{\varepsilon} < e'_c \\
\frac{f'_c}{3} \left( 1 - \left( \frac{\bar{\varepsilon}}{e'_c} - 1 \right)^3 \right) & \text{if } e'_c < \bar{\varepsilon} < e_u 
\end{cases}
\]

(3)

\[
e_u = \frac{4}{3} \frac{f'_c}{E_c}
\]

(4)

Consequent to the length parameter association, ultimate strain will be a function of compressive fracture energy, length parameter \( h \), \( f'_c \) and also \( e_u \) as below.

\[
e_u = 1.5 \frac{G_c}{h f'_c} - \frac{11}{48} e_u
\]

(5)

Since in this model concrete is assumed to be linear elastic up to \( \frac{1}{3} f'_c \), therefore pre-peak energy will be taken into account by a correction factor \( \frac{11}{48} e_u \) in Eq.5. Constant value for \( G_c = 50 N/mm \) is adopted in analyses throughout.

Results in this paper belong to only wall model (Fig.5, right) with rotating crack assumption and confinement effect. Shear strain produced during load cycles versus shear crack pattern of experiment are shown in this figure. The results, however, show very good correlation between test and prediction in terms of location, direction and crack characteristic. Figure 6, on the other hand, depicts the results of the wall under monotonic and cyclic load. As can be seen, load capacity is deteriorated significantly in terms of peak load and post peak response. Envelope of cyclic load is compared with monotonic load response and test results. In this figure, monotonic response has better agreement with experiment, though still under-estimated, but pre-peak and post-peak are in similar trend as experiment. In contrary, cyclic response shows not only smaller peak load but also a sudden decrease of load capacity just a few cycles after the peak. Fixed crack model is also examined and the results showed an increase in peak load and after the peak, load capacity was sustained to up to a certain deflection. It is found that, although rotating crack

Fig.5. Test ultimate crack pattern (left) and shear strain predicted (middle) and finite element mesh (right).
model can predict cyclic behavior of the member to some extent, but a mixed model with very low shear resistance in crack surface might improve the results. To this end the results can be used for further investigation of RC wall-type piers since the results are consistence, and also ensure a safety margin for structures with shear failure possibility. The prediction, though conservative, but can be used for practical purposes as well as parametric study on wall-type piers behaviors. One reason for this conclusion is in many analytical simulations, predicted load capacity goes beyond actual load capacity of the member. This is very dangerous situation if the engineers rely on such result for design since shear failure usually takes place in very brittle manner with no load reservation after the peak load. This method however gives a safety margin with acceptable overall load-displacement behavior. The results of this study is extended to evaluate damage level of some similar structures during 2004 Chuetsu-Niigata earthquake.

CONCLUSIONS

Experimental and analytical studies on RC Wall-type piers have been carried out in Earthquake Engineering Research Team of Public Works Research Institutes during year of 2004 and 2005. Experimental results are already discussed elsewhere more in detail. In order to establish a platform for further investigation with less dependency on test results, a numerical simulation with finite element method is proposed for analytical investigation. The method was examined in previous study on RC deep beam behavior and reported in some publications. The results of those studies are utilized here to predict behavior of wall-type members. Although analytical results have been conservative in terms of maximum load capacity, but overall behavior and mode of failure could be adequately captured by analysis. The results can be used for either design of RC walls and also further study on RC wall-type piers such as parametric or sensitivity analysis.

REFERENCES


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