Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.IV)

6-6-16

INELASTIC BEHAVIOR OF REINFORCED CONCRETE DUCTILE FRAME UNDER CYCLIC LOADING

HSU Yunfei[1] HU Qingchang[1] YU Hong[1]

[1]Beijing Institute of Architectural Design, Beijing, PRC

SUMMARY

Based on a series of reinforced concrete beam-column joint tests, earthquake resistant design method of frame joints including shear strength computation of joint core had been established[1]. In order to verify the applicability of the suggested method to multistoried frame structure and investigate the effect of joint details on the seismic behavior of frame, cyclic loading test of one half scale two-bay three-storey reinforced concrete frame has been carried out. The investigation and analysis of the failure mechanism, strength, ductility and beam bar slip effect of the frame with strong columns and weak beams have been conducted and discussed.

INTRODUCTION

The testing model of the frame was designed according to current code of seismic design[2] and handbook for the design of earthquake resistant buildings[3]. It was aimed to simulate the first to third stories of two-bay seven-story building in the region of seismic intensity 8. Figure 1 shows the dimensions and reinforcements of the testing model.

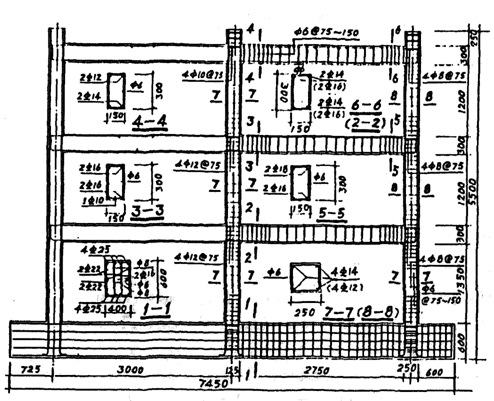


Fig. 1 The Test Specimen

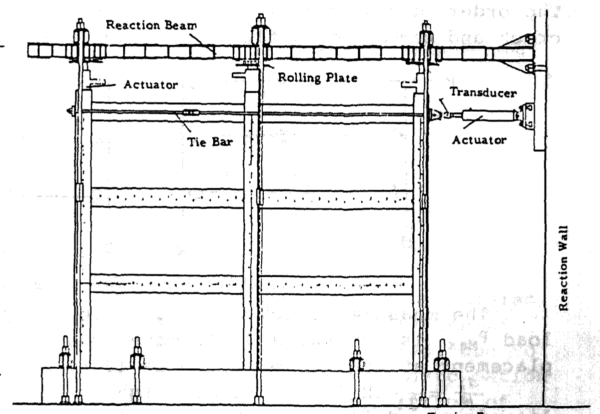


Fig. 2 The Test Setup

The model was installed on a quasi-static testing foundation. The horizontal load was applied through a hydraulic actuator fixed on the reaction wall. The constant vertical loads applied at the top of columns were 300 KN for exterior columns and 500 KN for interior column. No vertical loads were applied on beams in order to avoid the complication due to stress redistribution. The test setup is shown in Figure 2.

The cyclic loading procedure is shown in Figure 3.

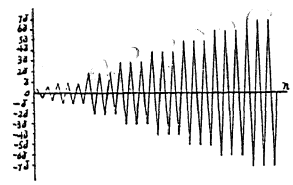


Fig. 3 Loading Cycles

ANALYSIS OF EXPERIMENTAL RESULTS

1. Failure Mechanism and Ductility

The envelope of hysteretic loops of testing horizontal load P and top displacement defines the P- Δ skeleton curve. It is shown in Figure 4.

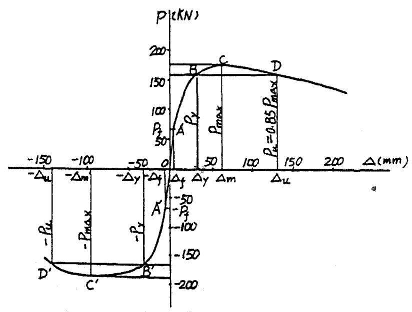


Fig. 4 P- Δ Skeleton Curve

The failure point is defined as the point in the load displacement curve recorded that its load level is equal to 85% of the maximum load and not less than the yield load. The frame failed with the beam plastic hinge mechanism. The order of the occurrence of the plastic hinges is shown in Figure 5. The crack and damage situation of the frame model is indicated in Figure 6.

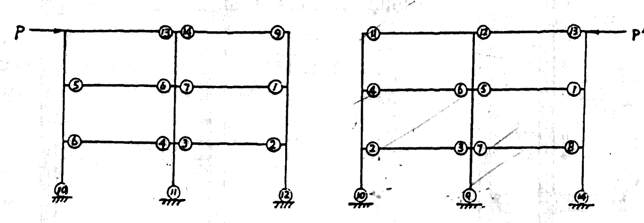


Fig. 5 Plastic Hinge Occurrence Order

The measured crack load P_f is 70 KN, yield load P_y is 163 KN, maximum load P_{Max} is 188 KN, and ultimate load P_u is 164 KN. The maximum lateral displacement at the top of frame is 13.66cm. The displacement-height ratio $\frac{\Delta_u}{H}=\frac{1}{34}$ (H is the total height of frame). The effective displacement ductility factor defined by the ductility at the point of ultimate load is $\mu_{\Delta *}$ =4.37 (forward loading direction) to 4.61 (backward loading direction). The maximum drift occurred at the second story, and its value δ_{u2} =5.27cm. The drift-story

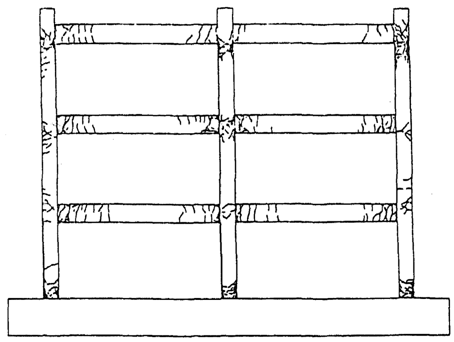


Fig. 6 The Crack and Damage of the Frame

height ratio $\delta_{u2}/h_2=1/28$ (h_2 is the story height of second story). The result shows that this model frame possesses enough deformability and ductility.

The hysteretic loops of load-displacement relationship recorded in the test show that the frame has adequate energy dissipation behavior, since there is no obvious pinching effect (Figure 7-Figure 10).

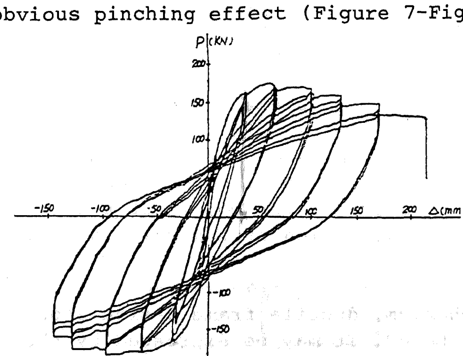


Fig. 7 P-Δ Hysteretic Loop

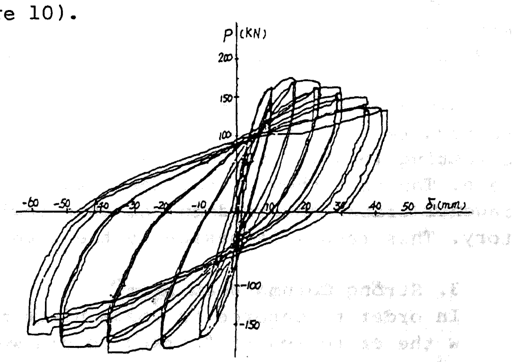


Fig. 8 P-δ_1 Hysteretic Loop

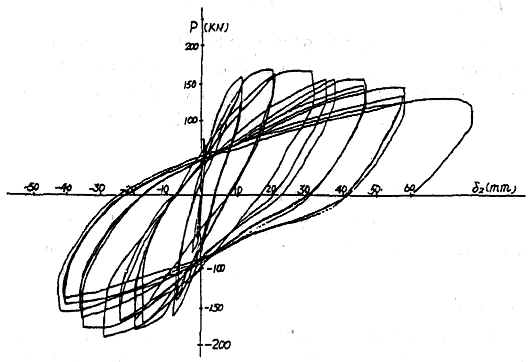


Fig.9 P-δ_2 Hysteretic Loop

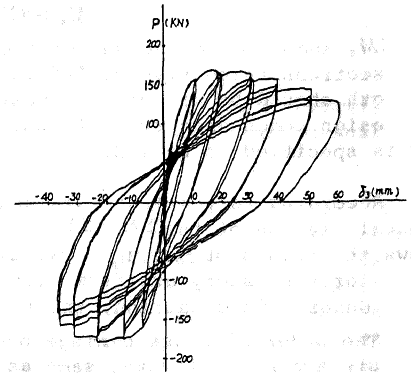


Fig.10 P-δ_3 Hysteretic Loop

Because the failure mechanism of the frame is beam plastic hinge mechanism, the overall deformation of the frame is mainly due to the plastic rotation of the beam hinges, but once the plastic hinge at the column base occurred, due to the effect of the axial compressive force in the column, its plastic deformation developed faster than that of the beam hinge. Test showed the contribution of shear deformation of joint core to the plastic rotation of beam was only 1%, hence it is negligible in the deformation of total frame.

At the ultimate load stage, the recorded ductility factors of the beam hinges were from 4.5 to 10.7, and the concrete in those regions had not crushed yet, but the rotation ductility factor of the plastic hinge region of the interior column had reached the number around 12, and the concrete of all of the plastic hinges of the three columns at the base crushed severely. The final collapse of the frame was caused by the failure of the column portion. The rotation ductility of the column hinge affects the ductility of the total frame significantly.

2. Strength and Rigidity

The situation of strength with respect to corresponding deformation defines the rigidity of structure. Slow and uniform degradation of rigidity represents adequate earthquake resistant behavior.

Although significant amount of residual deformation can be observed after the yielding of frame, but the slow rate of degradation of strength (9.4-15.3%) and rigidity (5.1-17.2%) after three loading cycles designates the adequate behavior of ductile frame.

Before and after testing, the dynamic behavior of model frame had been measured by pulsative movement. The fundamental period T_1 before testing is 0.091 S. After testing T_1=0.167 S. the period of vibration is about 90% longer.

Since only the hoops in joint core of interior column at second story level are required in shear strength calculation, i.e. the shear in joint core due to testing load is greater than shear resisting capacity of the joint core concrete. The test showed that there was no damage in the joint core except fine diagonal cracks occurred in the core region of the interior column at the second story. This result is basically the same as the situation of the calculation.

3. Strong Column Weak Beam

In order to enforce the beam hinge mechanism, ductile frame design should follow the criterion of "strong column weak beam". It may be expressed by the following expression for each beam-column joint.

$$\Sigma M_c \geqslant B \Sigma M_b, \quad B > 1$$

ΣM_c and ΣM_b are the sum of the ultimate flexural strength of column and beam sections respectively. "B" is a strengthening factor. Column flexural strength should be calculated under the combining action of axial force. Different design codes specify different values of "B". In reference (3) the value of "B" is specified to be 1.25.

According to the test data and the material properties of the model frame, the calculation of the $\Sigma M_c/\Sigma M_b$ values of all joint were carried out. Figure 11 shows the values of $\Sigma M_c/\Sigma M_b$ calculated for each joint are from 1.42 to 2.86, and those for each story are from 1.55 to 2.09. All those values are greater than 1.25. Under this condition, the frame behaved as a beam plastic hinge mechanism.

The order of plastic hinge occurrence and other results of elasto-plastic analysis are basically the same as the test results. That means the analysis procedure adopted can be used to estimate the other situation of this frame.

Another design of the same frame model with reinforcing details corresponding to the condition of B=1.25 and B=1.0 were carried out for comparison with the testing one. The same elasto-plastic analysis procedure was adopted to calculate the plastic hinge occurrence and process. When B=1.0 the result is that the plastic hinge occurs at column base first. This situation is worse than that of the testing frame. However with B=1.25, a mixed mechanism of beam hinge and column hinge can be obtained, the occurrence of plastic hinges of all columns in one story can be avoided.

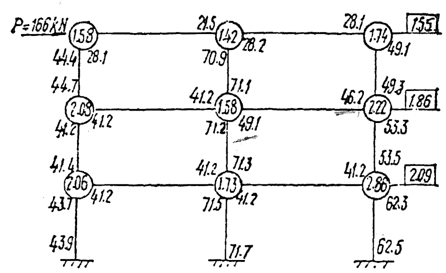
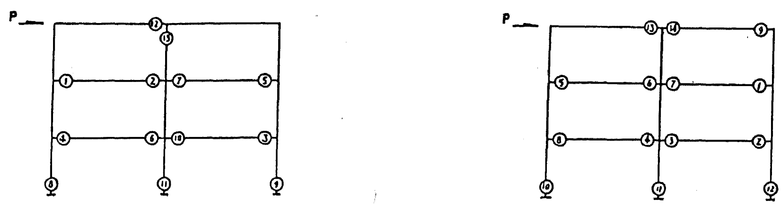
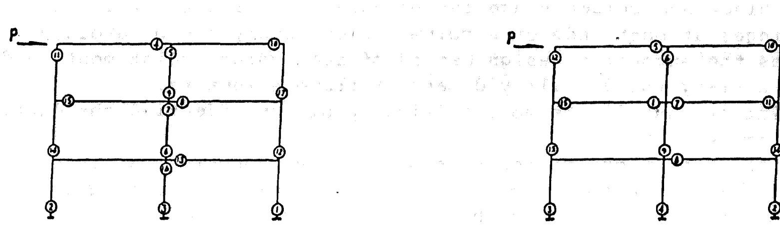


Fig. 11 Values of $\Sigma M_c/\Sigma M_b$ of Different Stories and Yielding Moment Values (KN.m) of Beams and Columns at Each Joint
Values in "○" represents values of $\Sigma M_c/\Sigma M_b$ calculated for each joint
Values in "□" represents values of $\Sigma M_c/\Sigma M_b$ calculated for each story



a) Test Results (P_y =163KN, Δ_y =2.89cm) b) Analysis Results (P_y=151KN, Δ_y=2.64cm)
Fig. 12 Comparison of Tested and Analyzed Occurrence of Plastic Hinges



a) B=1 (P_{max} =220KN, Δ_{max}=3.88cm) b) B=1.25(P_{max} =201KN, Δ_{max} =3.64cm)
Fig.13 Occurrence of Plastic Hinges Obtained by Elasto-Plastic Analysis

4. Slip of Bar Anchorage

The anchorage portion of the longitudinal bars of the beams slided in the core region of the joint during the test. According to the slip values recorded at the joints of the second story, especially the comparison of the values of the interior and exterior column, one can see that the anchorage situation at the exterior column joint is much better than that of interior column. For example the diameters of beam reinforcements at interior and exterior joint of second story are 1/16 and 1/14 of the depth of column section respectively. At the ultimate stage, the total slip of the upper and lower bars in the beam at interior joint was 5.17mm and that of exterior joint was only 0.75mm.

Measurement of the strain of beam bars anchored in the joint core showed the penetration of yield into the column.

The rotation due to the bar slip at the interior joint is about 35% of the total rotation of the plastic hinge region at the beam end. The hysteretic loop of the load-slip relationship shown in Figure 14 indicates that the slip

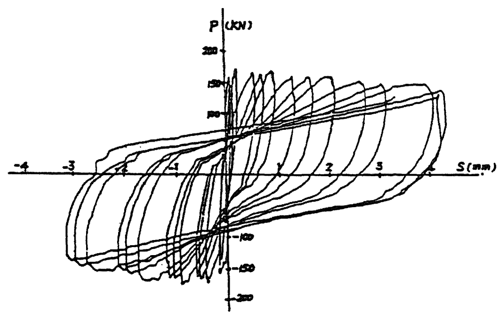


Fig.14 P-S (Load-Slip) Relationship of Upper Bar of Beam Reinforcement Anchored in Joint Core of Interior Column at Second Story

occurred after the yield of the beam bars and increased rapidly with the loading cycles. The flattening of the hysteretic loops designates the decrease of energy dissipation capability. Slip of bar anchorage also affects the shear transmission mechanism of joint core and weakens the shear resisting capability of joint core.

CONCLUSION

1. Experiment shows, beam hinge mechanism can be obtained, if the reinforced concrete frame is designed according to the seismic design code and satisfies the requirement of "strong column weak beam" with story factor B=1.55--2.09, the greater value is adopted for columns of lower story.
2. Elasto-plastic analysis designates, when story factor B=1--1.25 a mixed mechanism of beam hinge and column hinge can be obtained. With B=1.25, the occurrence of plastic hinges at both ends of a column in one story can be avoided.
3. Test proves the suggested design method of beam-column joint mentioned in Ref. (1) can satisfy the ductility demand of frame structure.
4. Column joint at base is the most critical position affecting the ductility of the total frame.
5. The rotation of beam due to the slip of beam bar anchorage at interior joint core is about 35% of the total rotation angle of beam plastic hinge. The slip in exterior joint is less serious than that of interior joint.

The authors are specially indebted to Mr. Chen Yufeng, Mr. Shi Chang, Mr. Hong Bainian and Mr. Lin Shaojun for their excellent collaboration in completion of the experiment and analysis.

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