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ASEISMIC CAPACITY OF BONDED AND UNBONDED PRESTRESSED CONCRETE FRAMES

ZHU Bolong[1] SU Xiaozu[2]

[1]Research Institute of Engineering Structure, Tongji University, Shanghai, China

[2]Department of Engineering Structure, Tongji University, Shanghai, China

SUMMARY

Single span-single story bonded and unbonded prestressed concrete frames were experimented, three of which were tested under static cyclic loading, another three were tested on shaking table simulating earthquake conditions. A computer program for the calculation of hysteresis loops far into descending part of PC frames was developed. Based on the static test, a restoring force model was put forward which was then testified by the system identification method put forward in this study.

INTRODUCTION

During the 1964 Alaskan earthquake, an unbonded prestressed concrete(UBPC) slab-column structure named "Four Seasons Apartment Building" collapsed (Ref.1), which thereafter caused suspicion, anxiety and controversy about the aseismic behavior of UBPC and bonded prestressed concrete(BPC). Many scholars have since contributed to the solution of the problem, and these contributions were reflected by the FIP's changing attitude towards the use of PC structure in seismic zones. However, up to our knowledge, we have not found any study of PC frame far into descending part, and method of hysteretic analysis of PC frame far into descending part does not exist. Meanwhile, we have not found any earthquake simulation shaking table study of PC frame. Moreover, the above mentioned controversy still exists, which is inconsistent with engineering practice. Therefore, the purpose of this paper is to study the aseismic behavior of PC frames.

STATIC STUDY

Cyclic Loading Test

The specimen is shown in Fig. 1. These specimens were made: B-1 was grouted; UB-1 had ducts but was left unbonded; and for UB-2, the unbonded tendons were first greased and wrapped up in plastic sheet and then put in place before the concrete was poured (cast-in type). The material properties of specimens are listed in Table 1 and 2. The proof stresses of the tendons on jacking were all taken as 490.5 N/mm^2. During test the value of prestress loss was less than 49.5 N/mm^2. Four vertical forces were applied on the beam and remained unchanged, and then cyclic force was applied.

The hysteresis curves of horizontal force P vs horizontal displacement D of the specimens are shown in Fig. 2 and 3.

It is seen from the test results that the specimens can develop plastic hinges. After the test, the prestress loss of unbonded frames is negligible, whereas the prestress loss in plastic hinge zones of the bonded frame can be as great as 70% of original prestress.

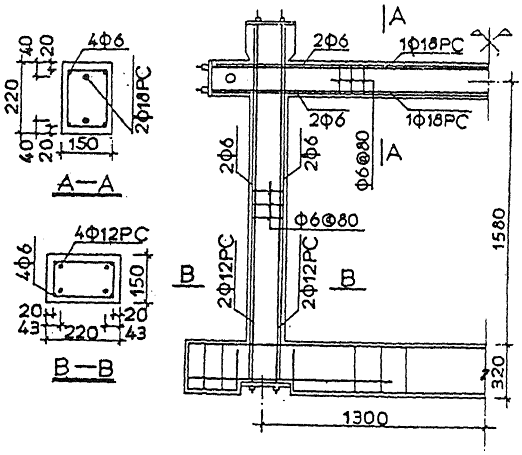


Fig. 1 Specimen

Table 1 Properties of Tendon and Reinforcement

Type	Area cm^2	Yield Strength N/mm^2	Limit Strength N/mm^2
ϕ 6.5	0.32	245	363
ϕ18PC	2.49	736	922
ϕ12PC	1.10	883	1079

Table 2 Properties of Concrete and Grout

Type	Specimen	Age days	Cubic Strength N/mm^2
Concrete	UB-1	167	61.7
	UB-2	77	45.9
	B-1	159	43.3
Grout	B-1	46	29.5

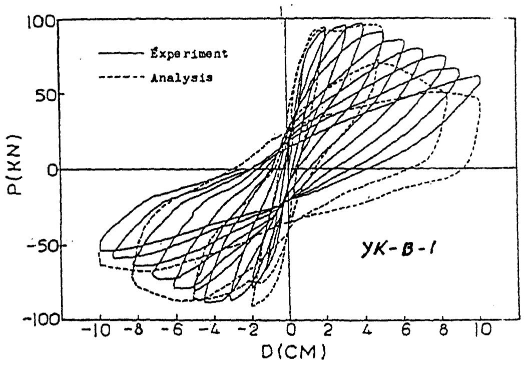


Fig. 2

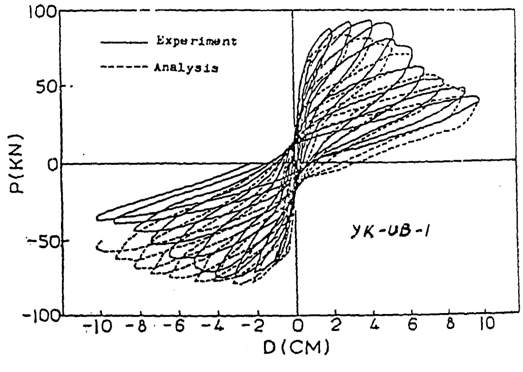
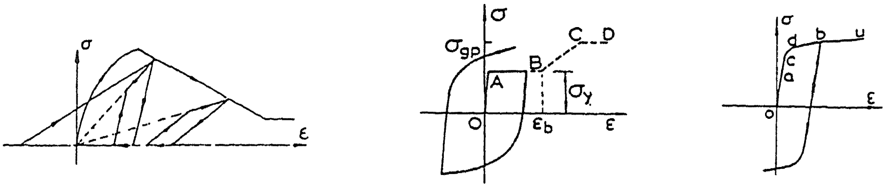


Fig. 3

Finite Element Simulation

A new FEM algorithm for nonlinear hysteresis analysis of PC frame far into descending part is put forward, in which the updated Lagrangian approach is adopted. All geometric parameters are varied with the variation of current displacements. Every member of the frame is divided into segments along its length, each segment being an element. Both material and geometric nonlinearities are considered. The stress-strain relations of concrete and steel are shown in Fig.4.



(a) concrete (b) non-prestressed reinforcement (c) tendon

Fig. 4 Stress - Strain relations

The bond-slip relation between tendon and grout is taken as

$$s = 0.05543\tau/R_r$$

where s is slip (in cm), τ and R_r are the bond stress and nominal strength of grout (in N/mm^2), respectively. Bond failure occurs if $\tau > 0.116R_r$ and thereafter the slip is free.

The self-correcting incremental method is adopted in global computations. Automatic shift between increment force and increment displacement is controlled by the local slope of the load-displacement hysteresis curve. A FORTRAN program was developed based on the algorithm. The program can simulate the whole process of the specimen, including prestressing, working load and cyclic load application. Computed results of specimens are shown by dashed lines in Fig. 2 and 3.

DYNAMIC STUDY

Shaking Table Test

Fig. 5 shows the dynamic specimens, in which UB-D1 is of cast-in type.

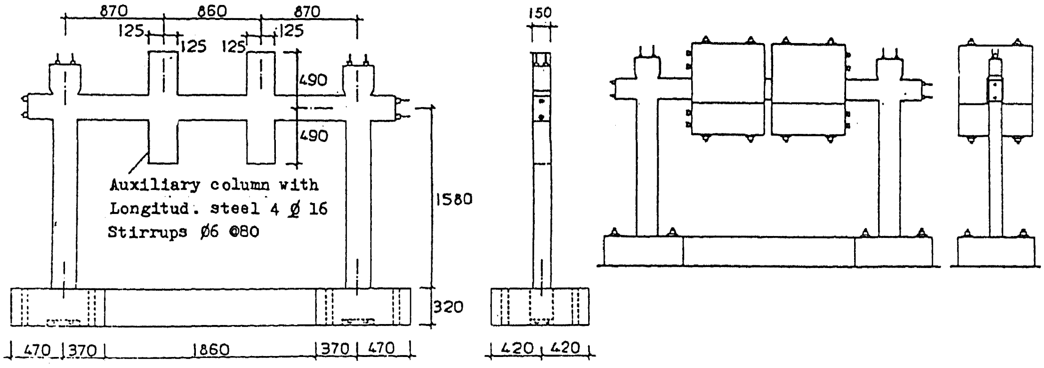


Fig. 5 Specimen and mass block

The tendon and reinforcement of dynamic specimens are the same as static specimen . Other properties of dynamic specimens are listed in Table 3 and 4. A 1300 kg RC mass block was installed at each auxiliary column(Fig.5). The mass blocks, whose weight acted at the third points of the beam, did not constrain the deformation of the beam.

The inputs used include : 1) codified artificial earthquake vibration for type III soil (G3 vibration)(Ref.3); 2) sinosoidal vibration (sin vibration), whose frequencies are taken as the current resonance frequency of the specimen; 3) artificial earthquake acceleration shown in Fig.6 (W vibration).

Table 3 Properties of Concrete and Grout

Type	Specimen	Age days	Strength N/mm^2
concrete	UB-D1 (UBPC)	119	40.7
	B-D1 (BPC)	146	48.0
	K-D1 (RC)	100	37.1
Grout	B-D1 (BPC)	68	37.4

Table 4 Tendon Stress before Test (N/mm^2)

Specimen	Tendon Locations					
	Beam		Left Column		Right Column	
	Upper	Lower	Outer	Inner	Outer	Inner
UB-D1	429	410	438	426	425	420
B-D1	423	423	432	437	430	417

The test was performed on the 4X4 m shaking table in Tongji University. All the specimens were excited with the same program: firstly G3 vibrations of increasing amplitudes were used, then sin vibrations were used, finally W vibrations of increasing amplitudes were used until the specimens were seriously damaged.

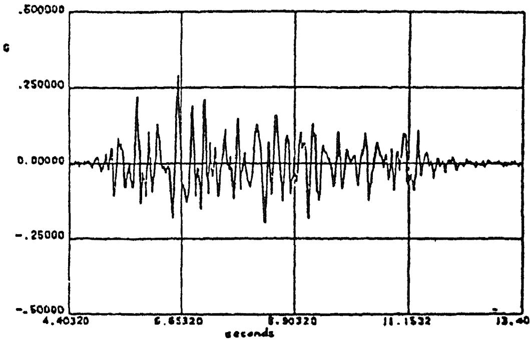


Fig. 6 W vibration (accelerogram)

After sin vibrations had been performed, specimen K-D1 was seriously damaged, UB-D1 was less damaged, while B-D1 almost showed no concrete spalling. All the specimens did not collapse after the test.

It is found from the test results that 1) unbonded tendons were always in tension state, while bonded tendons may be loaded into compression state; 2) bonded tendons may yield, while unbonded tendons were always within elastic range.

Compared with the RC specimen, prestressed specimens exhibited higher natural frequency f (Fig. 7), lower damping, and smaller displacement response (Fig. 8). By comparision of absolute acceleration responses(seismic action), it is found that B-D1 had the highest strength, UB-D1 the intermediate, and K-D1 the lowest (Fig. 9). Correspondingly, K-D1 entered descending part the earlist, UB-D1 the intermediate, and B-D1 the latest.

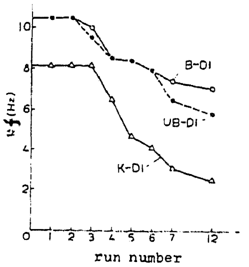


Fig. 7 Frequencies of specimens

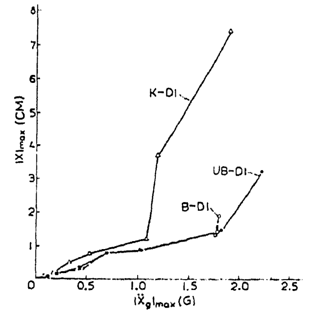


Fig. 8 Peak-value of displacement response vs peak-value of input accel. (G3 runs)

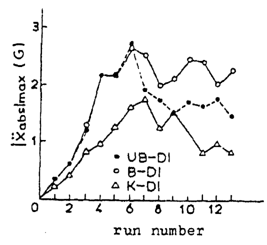


Fig. 9 Peak-value of absolute accel. response (G3-sin runs)

System Identification

In a shaking table test with many test runs of consecutively increasing amplitudes, the specimen experiences every stage of a whole nonlinear process. Obviously the information of the structural model is contained in the recorded time series if these tests run. For such materials as prestressed concrete, whose behavior depends on its deformation history, the method of system identification should take into account the continuity of deformation history at the conjunctions of test runs. What we put forward is just such a method.

Suppose n test runs are conducted in the experiment. Let Ti represents the recorded time series corresponding to i-th test run. Generally the parameter identification can be conducted separetely on Ti (i=1,2,..., n). In order that such identification is meaningful, account must be taken of the motion history of the model, that is, the model in time series Ti+1 must be made to move on the basis of the model state at the end of Ti. The final model parameters are obtained from statistical treatment of the parameters identified from each Ti (i=1,2,..., n). If the standard deviation of each parameter is sufficiently small, the identified parameters are considered correct.

The mathematical model used is

$$M\ddot{X} + C\dot{X} + P(X) = -M\ddot{X}g$$

where M is the mass, C the damping coefficient, X the relative displacement response, $\ddot{X}g$ the input ground acceleration, P(X) is the restoring force model shown in Fig. 10, which is based on the result of static test.

Identification result shows that the above model is correct. The complete models of PC specimens are identified, which show that the strength of B-D1 is 30% higher than that of UB-D1. Part of the identified and recorded reletive acceleration reponses is shown in Fig. 11.

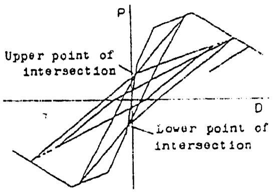
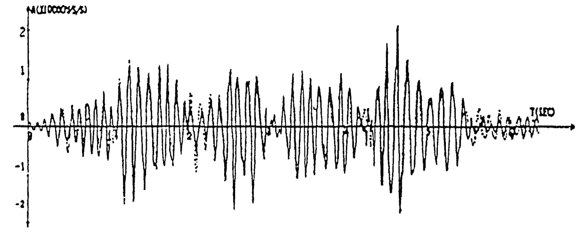
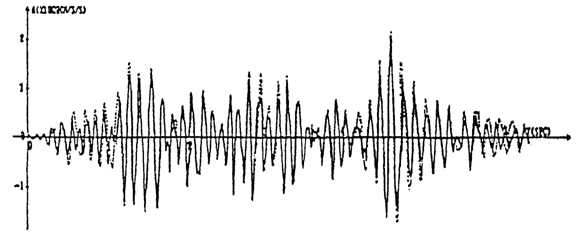


Fig. 10 Restoring force model



(a) UB-D1, 5 x G3 run



(b) B-D1, 6 x G3 run

——— Experimental ......Identified

Fig. 11 Comparison between identified and experimental acceleration responses

CONCLUSIONS

1) Under the conditions of the test, the aseismic behavior of PC is better than that of RC. It rationally designed, UBPC frame with reliable anchorages can be used as aseismic structures.

2) Cyclic loading test and shaking table test of PC frames are carried out, based on which a restoring force model is put forward, which, together with the whole mathematical model, is testified by the system identification method put forward herein.

3) After completion of the static test, the prestress loss of unbonded frame is negligible, whereas the prestress loss in plastic hinge zones of bonded frame can be as great as 70% of the original prestress.

4) An algorithm of finite element full range hysteresis analysis of PC frames is put forward. A corresponding general computer program is developed, which can compute the hysteresis curve of restoring force of PC frame with arbitrary loading path including descending part.

5) When the aseismic response of frame is less than the ultimate strength of bonded specimen but larger than that of unbonded, the latter may suffer damages.

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