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Behaviour of reinforced concrete walls subjected to alternating dynamic loads

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ABSTRACT : This paper compares the results of testing performed to determine the behaviour of reinforced concrete walls subjected to alternating dynamic loads with the results of design, regulatory verification and analytical calculations of the wall structures. It also summarizes the observations recorded during the testing and indicates directions for investigating the behaviour and safety offered by these structures in response to alternating dynamic forces such as those exerted by an earthquake. The walls tested were either solid or provided with a central or eccentric opening. The method employed was to: test scale model walls for strength, displacement, stress and stiffness, perform the design and verification calculations on regulatory and analytical bases, compare the results of these calculations with the results of tests conducted on scale models at the Centre Expérimental du Bâtiment et des Travaux Publics CEBTP in 1987 and 1988, and in the laboratories of the Commissariat à l'Energie Atomique (Mechanical Engineering and Technology Department) in 1988 and 1989. The test and calculation results are presented in table forms and on curves. They indicate specially the relationships of the forces, damping and stiffness to displacement and to the frequency of the alternating dynamic signals. Qualitative variables are also summarized, especially damage and cracking phenomena. The study conducted describes the design and verification methods normally used for reinforced concrete walls which form the main structures intended to protect building against dynamic phenomena such as earthquakes.

1 DESCRIPTION OF THE TESTS

The tests performed at the CEBTP in 1987 and 1988 were conducted on ten scale models the dimensions of which are: width 1.50 m, height 0.75 m, thickness 0.10 m. The models are made of reinforced concrete with a rod mat diameter of 6 mm, spacing 100 x 100 mm within the medium plane of the walls, and two embedded columns with four 12 mm diameter bars enclosed by lateral ties of diameter 3 mm every 100 mm. These ten scale models are composed of: 3 solid shear walls named PH1, PH2, PH3; 4 shear walls provided with a central opening (width 0.50 m, height 0.25 m) named PH4, PH5, PH6, PH7; and 3 shear walls with an eccentric opening (width 0.50 m, height 0.25 m) named PH8, PH9, PH10.

The purpose of the tests at CEBTP is to study the behaviour of squat shear walls (height to width ratio = 0.5) with low reinforcement ratio (0.283 %) that can be found in buildings on nuclear sites subjected to alternating shear as occurring during an earthquake.

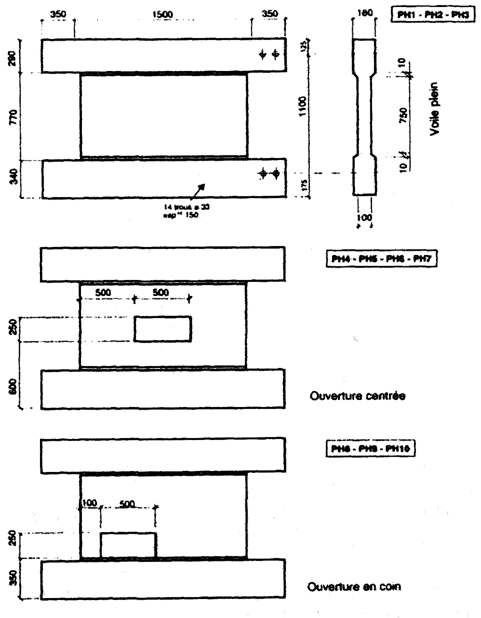

Figure 1. Scale models at CEBTP

Table 1. Ultimate strength from tests/ultimate strength from experimental formula - Unit 10^4 N

ITEM CEBTP	M	B et A	P	K	F	H	Vu+	Vu-
PH1	61.9	81.5	58.9	60.6	55.8	63.3	57.61	-
PH2	58.4	76.8	57.1	58.7	53.9	60.0	57.55	-
PH3	60.9	80.3	56.2	57.8	53.1	52.6	55.39	55.39
PH4	37.5	35.1	37.1	38.2	35.3	38.4	31.25	-
PH5	37.3	34.9	36.5	37.6	34.7	32.3	31.57	30.1
PH6	36.2	34.1	33.2	34.1	31.1	37.3	31.37	-
PH7	36.0	33.9	35.4	36.4	33.5	31.4	31.37	32.25
PH8	32.5	38.7	31.9	32.8	30.1	33.4	55.10	-
PH9	32.4	38.7	30.9	31.8	29.1	33.4	32.21	-
PH10	32.0	38.2	30.9	31.8	29.1	33.1	50.49	32.60
ITEM CEA	M	B et A	P	K	F	H	Vu filtered	
PJ1	18.1	22.2	18.8	17.0	15.6	15.3	12.5	
PJ2	18.1	22.2	19.1	17.6	16.2	15.3	16.8	
PJ4	18.5	22.7	19.0	17.4	16.0	15.5	15.2	
PJ11	19.0	23.4	20.1	18.6	17.2	15.9	17.0	
PJ5	11.6	9.87	12.3	10.7	9.83	7.66	10.3	
PJ6	11.9	10.1	12.8	11.3	10.4	7.80	9.8	
PJ8	10.6	11.4	10.9	9.49	8.69	8.38	8.8	
PJ9	11.1	12.0	12.1	10.7	9.91	8.68	8.5	

The tests performed at the CEA/DEMT in 1988 and 1989 were conducted on 13 scale models the dimensions of which are: width 0.75 m, height 0.375 m, thickness 0.05 m.

These 13 scale models are composed of: 7 solid shear walls named PJ1, PJ2, PJ3, PJ4, PJ11, PJ12, PJ13; 3 shear walls provided with a central opening (width 0.25 m, height 0.125 m) named PJ5, PJ6, PJ7 and 3 shear walls with an eccentric opening (width 0.25 m, height 0.125 m) named PJ8, PJ9, PJ10.
They complete the CEBTP tests introducing the input frequency of the exciting signal. The values and test curves are issued from the report Ref. 1 (CEBTP) and Ref. 2 (CEA/DEMT).

2 COMPARISON BETWEEN THE SHEAR STRENGTH MEASURED FROM THE TESTS AND THE SHEAR STRENGTH CALCULATED FROM EMPIRICAL FORMULA

The ultimate shear strengths are calculated with experimental formula from Ref. (3).
The measured ultimate shear strength is taken equal to the maximum lateral load applied by the jack in CEBTP tests at low frequency and equal to the internal load FV = F JACK - M. γ in CEA/DEMT tests where M is the dead load at top of the wall (1.5 t) and γ the acceleration. Table 1 compares the measured ultimate shear strength with the results from empirical formula. In this table the capitals are those of the authors and Vu test is the measured value of the shear strength. The sign + or - indicates whether the effort is measured when the jack goes out or when it comes in. Table 1 shows a relationship between the test results and the empirical formula results. This relationship is pertinent for CEBTP tests at low frequency (except for PH8 which has a non-symmetrical behaviour). The relationship is more spread out for the CEA/DEMT tests.

3 COMPARISON BETWEEN THE SHEAR STRENGTH FROM THE TESTS AND FROM CALCULATIONS WITH CODES BAEL 83, ACI 318-83 and 349-85, CEB-FIP, ATC 3.06.

The ultimate shear forces are computed with the formulas from various codes such as BAEL 83,

Table 2. Shear strength Vs + Vc BAEL, ACI, ATC, CEB-FIP ; Unit : 10^4 N

	BAEL 83			ACI		ATC		CEB-FIP	
PH	Vn	Vs	Vs*	Vn	Vs	Vn	Vs	Vn	Vs
1	35.8	21.1	30.7	38.8	19.6	37.2	23.1	31.8	20.7
2	34.1	21.1	30.7	37.2	19.6	36.1	23.1	30.5	20.7
3	35.4	21.1	30.7	38.4	19.6	37.0	23.1	31.7	20.7
4	21.8	13.1	9.57	18.5	12.1	22.8	14.3	17.9	12.9
5	21.7	13.1	9.57	18.5	12.1	22.7	14.3	18.0	12.9
6	21.2	13.1	9.57	18.2	12.1	22.4	14.3	17.4	12.9
7	21.1	13.1	9.57	18.2	12.1	22.3	14.3	17.2	12.9
8	19.0	11.8	18.0	20.7	10.9	20.1	12.9	15.3	11.6
9	19.0	11.8	18.0	20.7	10.9	20.1	12.9	16.7	11.6
10	18.8	11.8	18.0	20.6	10.9	20.1	12.9	16.6	11.6
PJ									
1	10.3	6.19	8.09	11.0	5.72	10.4	6.74	9.0	6.06
2	10.3	6.19	8.09	11.1	5.72	10.4	6.74	9.16	6.06
3	10.2	6.19	8.09	11.0	5.72	10.4	6.74	9.06	6.06
4	10.5	6.19	8.09	11.2	5.72	10.6	6.74	9.24	6.06
11	10.8	6.19	8.09	11.4	5.72	10.7	6.74	9.28	6.06
12	11.1	6.19	8.09	11.7	5.72	10.9	6.74	9.58	6.06
13	10.9	6.19	8.09	11.5	5.72	10.8	6.74	9.78	6.06
5	6.41	3.84	2.52	5.45	3.55	6.51	4.18	5.11	3.76
6	6.60	3.84	2.52	5.53	3.55	6.62	4.18	5.22	3.76
7	6.56	3.84	2.52	5.52	3.55	6.60	4.18	6.07	3.76
8	5.84	3.46	5.00	6.26	3.20	5.92	3.77	4.91	3.38
9	6.13	3.46	5.00	6.48	3.20	6.08	3.77	5.14	3.38
10	6.03	3.46	5.00	6.41	3.20	6.02	3.77	4.87	3.38

ACI 318-83, ACI 349-85, CEB-FIP, ATC 3.06.

The ultimate shear strength have been computed with the various codes taking into account the shear strength Vs provided by shear reinforcement and the shear strength Vc provided by concrete, and the sum Vn = Vs + Vc.

The comparison between the maximum shear forces during tests (see Table 1) and the maximum shear strength (see Table 2) shows no discrepancy and the test/BAEL code comparison enables us to approximate the ratio V test/Vn BAEL:
- in CEBTP tests: between 1.4 and 1.7;
- in CEA/DEMT tests: between 1.1 and 1.7.

This ratio is greater than 1.4 when calculating Vn with the BAEL bracket formula. The ratio V test/Vs is greater than 1.7.

4 QUALITATIVE OBSERVATIONS

The observations of the failure scheme of the scale models in CEBTP tests and CEA/DEMT tests show the main role of the compressive *struts of concrete (cracking along the diagonals* and crushing of concrete at both ends of the struts), and the main role of vertical tensile braces provided by the reinforcement bars on each side of the wall (see horizontal cracking on Fig. 2). The failure scheme appears to be the historical sum of the shear effect in one direction and in the opposite direction.

It is then possible to observe the vulnerability of the zones at the crossing of the struts inside which the concrete is subjected to alternate tension and compression stresses and is crushed out of the wall.

In the case of a wall with central opening the behaviour is symmetrical and the failure scheme

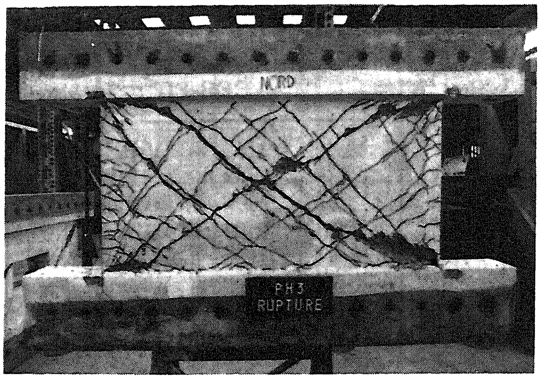

Figure 2. CEBTP test on PH3

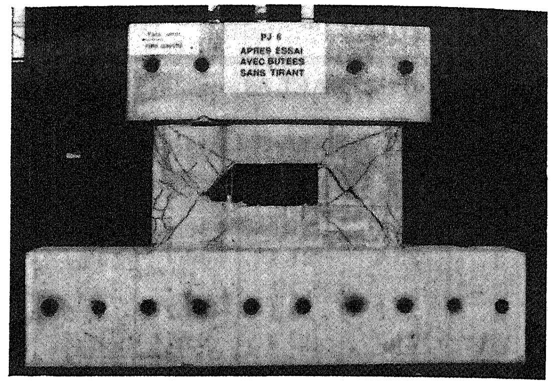

Figure 3. CEA/DEMT tests on PJ06

is very different from those with solid walls, but there are still two concrete struts on each side of the opening. In the case of eccentric opening the failure scheme also shows two concrete struts. In the latter case the brittleness is due to the single column, which is seriously damaged in most tests.

5 CONCLUSION

The tests demonstrate the effective behaviour of concrete through struts and lead the designer to place the reinforcing bars along frames which ensure the equilibrium of the concrete compression struts. They underline the brittleness due to a single column associated with solid walls.

A comparison between the measured and calculated shear strength shows that the empirical formulas are reliable enough and within the limits of the scale model test conditions; it indicates an allowance for unexpected extra shear loads of 10 % to 40 % beyond the maximum shear strength calculated from the codes.

These conclusions are of course bounded by the specific parameters of the test models, particularly scale range (1/4 to 1/8 of the actual walls) and reinforcement with a single rod mat.

The tests conducted at CEBTP and CEA/DEMT have been useful in gaining a better understanding of the shear wall structure behaviour under alternating shear loads such as those induced by an earthquake. It is hoped that this analysis will ease the designing of these structures.

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