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

9-1-8

BEHAVIOR AND MODELLING OF REINFORCED CONCRETE STRUCTURAL WALL ELEMENTS

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SUMMARY

In this report the behavior and modelling of 11 tested structural walls with a height/length ratio of 1.5 is described. Five of the walls were tested on an earthquake simulator whereas the other six walls were tested under cyclic static conditions.

EXPERIMENTAL PROGRAM

Test Setup for Dynamic Tests:

Figure 1 shows the earthquake simulator. The test setup represents a single degree of freedom system with a mass of 7.2 tons which is supported by four hinged columns. These columns allow the movement of the mass in the direction of movement of the simulator, but transverse movements are not possible. The specimens were bolted to the shaking table. The mass is connected to the specimen by use of a fork hinged at both ends which transmits the inertial force of the mass to the specimen. The fork consists of two arms that introduce the horizontal load equally to both sides of the specimen. No vertical force was transmitted from the mass to the specimen.

A system with a rigid connection between the wall and the mass would have in the initial uncracked stage a fundamental frequency of approximately 20Hz. Therefore, a spring was introduced between the wall and the mass. By this mean, the frequency was reduced to approximately 4Hz, which is closer to typical frequencies of real structures. The spring can be interpreted as representing the upper stories of a building.

Test Setup for Cyclic-Static Tests:

In Figure 2 the cyclic-static setup is shown. The application of the horizontal force is not developed by a mass, but by a hydraulic jack. The hydraulic jack is mounted on a steel frame. The specimens are mounted and prestressed to the base of the steel frame. The hydraulic jack was displacement controlled through a computer.

Test Setup for Introduction of Axial Load:

Three specimens were tested with axial load. The axial load was obtained by using 8 prestressed external bars which were mounted on both sides of the specimen. Because of the

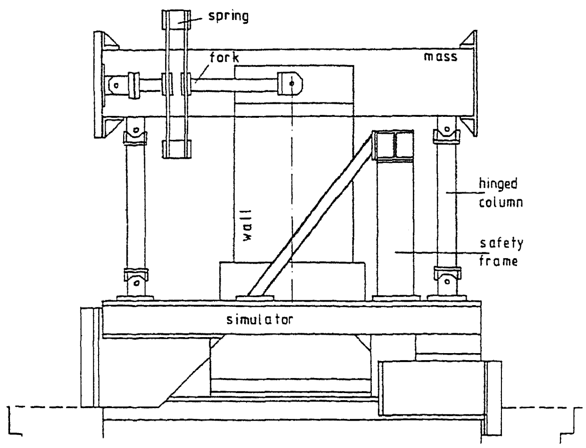

Figure 1: Test Setup for Dynamic Tests

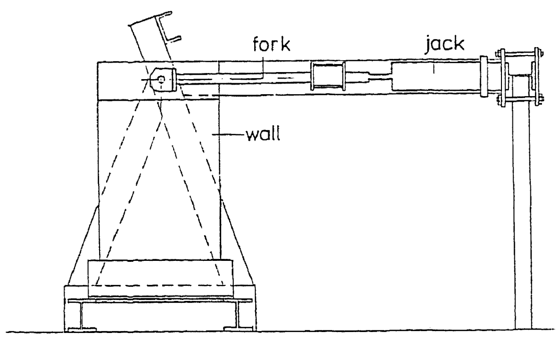

Figure 2: Test Setup for Cyclic-Static Tests

vertical displacement changes of the specimen during the tests, small displacement changes could have caused big changes in the axial load. To prevent this effect, springs were placed between the specimen and the prestressing bars.

Loading History on the Shaking Table:

The hydraulic system of the shaking table was controlled by a computer system which allows simulation of measured earthquake motions. Each test, dynamic as well as cyclic-static, consisted of 3 runs. In the first run, the tensile strength of the specimen was reached, but the steel stresses were linear. The second run was so designed that the yield strength of the reinforcement was to be reached. In the third run the wall was loaded to maximum capacity. The first and second runs were loaded with the "El Centro 1940" loading history. In the last run a harmonic sinusoidal waveform was used.

Loading History for Cyclic-Static Tests:

In order to be able to compare the dynamic and static tests, the measured top displacements of the dynamicly tested specimens were used as input for the hydraulic jack, but 100-times slower. The original part of the response in the dynamic tests of 6 seconds was increased to 600 seconds in the cyclic-static test.

Instrumentation:

In all tests the forces in the fork were measured by two load cells. The axial forces in each bar were measured with load cells. At the top of the wall, the horizontal and vertical displacements were measured. The displacements and crack widths in several points of the specimens were also measured.

Test Program:

Eleven structural walls have been tested. In order to be able to investigate the influence of the vertical and horizontal reinforcement, the cross-section and the axial force on the cyclic behavior at all stages of damage, the test program shown in Table 1 was chosen. 5 of the walls were tested on the earthquake simulator, whereas the other 6 walls were tested under cyclic static conditions. In both cases the external force was applied in the same manner. The dimensions of the structural walls and the typical arrangements of the reinforcement are shown in Figure 3.

No.	*Code*	*Type*	*Reinforcement*		*Axial*	*Static*
			veritical	*horizontal*	*force*	*Dynamic*
1	T01	R	6ø6 mm	2ø6 mm,e=15	no	dyn
2	T02	T	6ø6 mm	1ø6 mm,e=15	no	dyn
3	T03	T	6ø8 mm	1ø6 mm,e=15	no	dyn
4	T04	R	6ø6 mm	-	no	dyn
5	T05	R	6ø8 mm	2ø6 mm,e=15	no	dyn
6	T06	T	6ø8 mm	1ø6 mm,e=15	no	sta
7	T07	T	6ø6 mm	1ø6 mm,e=15	yes	sta
8	T08	T	6ø8 mm	1ø6 mm,e=15	yes	sta
9	T09	T	6ø6 mm	1ø6 mm,e=15	no	sta
10	T10	R	6ø6 mm	2ø6 mm,e=15	no	sta
11	T11	R	6ø6 mm	2ø6 mm,e=15	yes	sta

R = rectangle, T = barbell shape

Table 1: Test Program of Structural Walls

RESULTS OF THE EXPERIMENTAL TESTS

Final crack patterns of walls 2 to 10 are shown in Figure 4. All walls developed diagonal cracks at low load levels. In general, specimens with rectangle cross-section exhibited more bending type behavior, whereas walls with barbells had visible cracks before bending cracks occured in the barbells.

Figure 5 shows the shear force - top deflection curve for wall 10 in the first run. The tensile strength of the concrete is reached at about 35 KN, recognizable by the bend in the hysteresis envelope. By comparing the area of the hysteresis loops, it is seen that primary cycles have higher energy dissipation than secondary cycles. Since steel stresses are far below yielding, the energy is primarily dissipated by bond slip and slip along cracks. A calculation

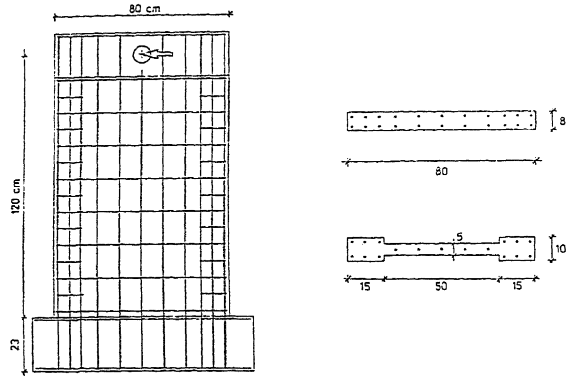

Figure 3: Arrangement of Reinforcement and Cross Sections

of the equivalent damping showed up to 5% in the primary cycles and around 2 - 3% in the secondary cycles. The hysteretic curves of specimens 6 and 7 are shown in Figure 6. Both walls have the same cross-section. Wall 7, however, was loaded by an axial force of approximately 140 KN. It is seen that the hysteretic loops of both walls are different at same load and deflection stages. The axially loaded wall shows hardly any pinching. This can be attributed to the axial force which forces the cracks to close completely in compression so that no slip along cracks is possible. Depending on cross section, axial force and reinforcement ratio, different failure modes can occur. Bar fracture has been observed for walls with low vertical reinforcement ratios. The capacity of the specimen is limited by the tensile strength of the vertical reinforcement. The maximum shear capacity agrees well with the calculation for an underreinforced beam.

Web crushing has been observed for walls with barbells and axial force or with barbells that have had higher reinforcement ratios. Due to the thin web, principle compressive stresses are higher than in walls with rectangular cross section. An axial force increases the principle compressive stresses and can therefore reduce the load bearing capacity. This failure mode occurs rather suddenly. The shear capacity is less than the bending capacity.

ANALYTICAL MODELLING

Although the failure of the structural walls with rectangular cross-sections was similar to typical bending type behavior, the formation of distributed cracks can not be simulated with beam elements with inelastic hysteretic springs at the ends, which was tried in a first step. It was found that the behavior was far too stiff, even with a fiber model. Evaluation of the test results indicated that the measured top displacement is developed by the entire cracked wall region and not only by the major crack at the base.

A detailed analysis to investigate the measured and observed behavior was started by using the FEM-method. The wall was modelled by 8 or 12 noded isoparametric membrane elements. A cyclic orthotropic model which includes tension stiffening was used to simulate concrete behavior, Figure 7. The smeared crack approach was assumed to be adequate and the direction of the cracks was assumed to be orthogonal to the current principle strain direction in tension. It was found that the cyclic behavior prior to steel yielding must be modelled by a tension stiffening model which includes the influence of bond between steel and concrete.

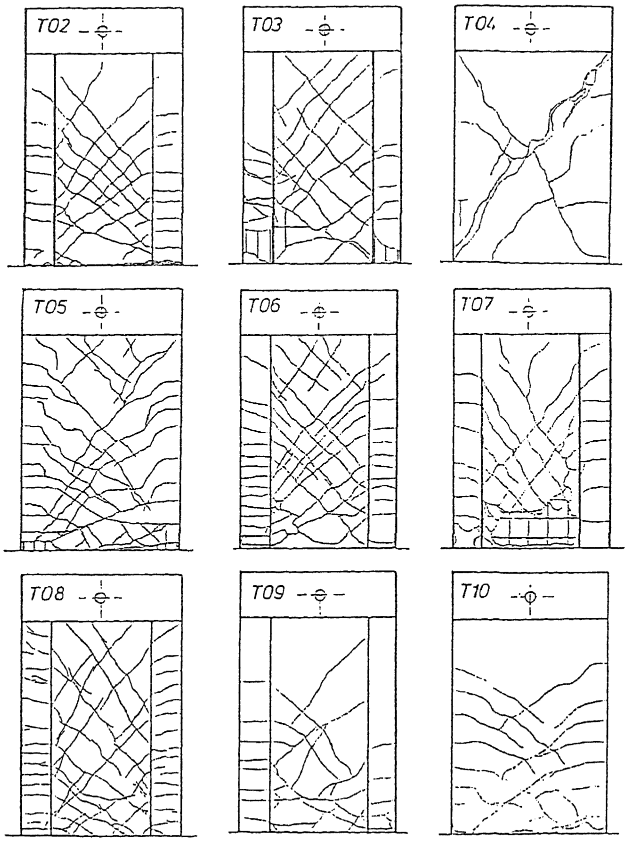

Figure 4: Crack Pattern of R/C Structural Walls

Therefore, the concrete model in Figure 7 was extended by hysteretic rules to simulate the observed behavior on a smeared basis.

Conclusion

For a realistic modelling of the nonlinear cyclic behavior of reinforced concrete walls it has to be considered that the shape of the hysteretic loops is not constant. It has been observed that the shape depends on the axial force, cross section and reinforcement ratio. It was observed that energy dissipation was higher in primary cycles than in secondary cycles. Calculation of the equivalent damping showed that walls have small damping values as long as steel reinforcement is not yielding. This has to be considered if a wall is designed to stay below yielding. It was further observed that well designed walls had stable hysteretic loops up to a stiffness degradation of 10.

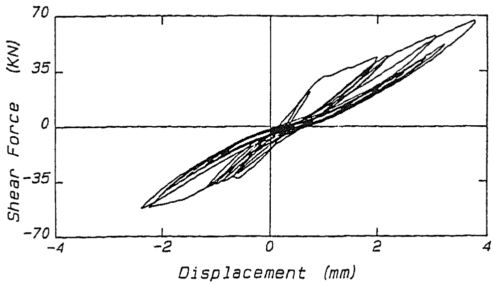

Figure 5: Hysteresis T10-Run1

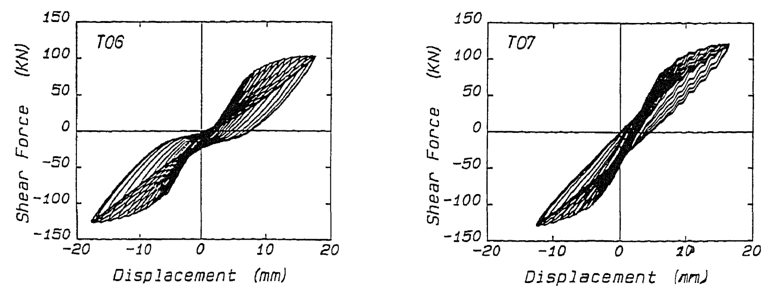

Figure 6: Hysteresis T06-Run3 and T07-Run3

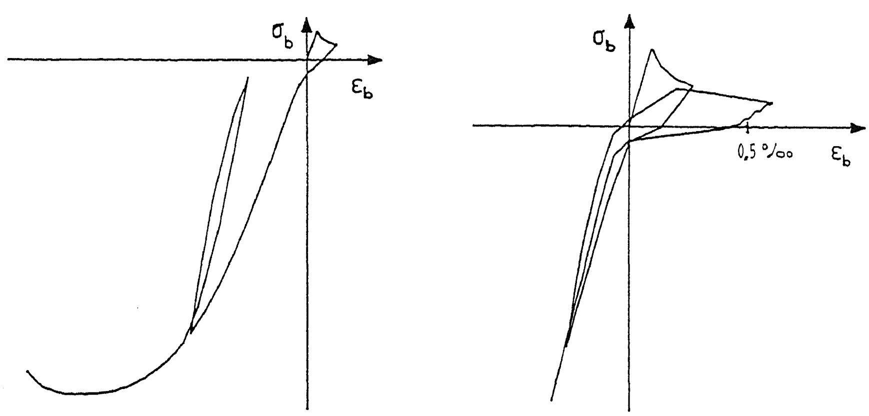

Figure 7: Concrete Model