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SOME COLLAPSE TESTS FOR THE LARGE SCALE MODELS OF THE NUCLEAR REACTOR FACILITIES BY SHAKING TABLE

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ABSTRACT: After the 1995 Hyougoken-Nanbu earthquake, the models of concrete containment vessels and large scale piping systems were shaken by Tadotsu shaking table up to failure of the specimens. The failure modes of the specimens were clarified. The ultimate strength and seismic margin of specimens were estimated. After these tests, some seismic capacity tests of active components are being conducted.

Key Words: PCCV, RCCV, large scale piping, collapse, fatigue, margin

INTRODUCTION

After the 1995 Hyogoken-Nanbu earthquake, some collapse tests were conducted by NUPEC under the sponsorship of the Ministry of Economy, Trade and Industry (METI). After these tests, some seismic capacity tests are being conducted by Japan Nuclear Energy Safety Organization (JNES) taking over the projects from NUPEC.

The models of concrete containment vessels and the large scale piping systems were shaken by Tadotsu large high performance shaking table up to failure of the specimen.

PCCV TEST

The objectives of the test were not only to prove the structural integrity and the functional soundness of the PCCV but to grasp the seismic margin of the PCCV (Sasaki 1998, Sasaki 1999a).

The test model was consisted cylindrical wall with tendon, upper slab, base slab and liner plate as shown in Fig.1.

The top dome was excluded because the PCCV would collapse through shear cracks in cylindrical wall and the dome wouldn't affect to the failure of the wall. The scale of 1/10 for overall configuration, 1/8 for cylindrical wall thickness, 1/4 for liner plate thickness were selected. Additional weight of 434 tons was installed at upper slab.

A design seismic motion for an actual PCCV was applied to the vibration tests with some modification on acceleration and frequency contents corresponding to the scale of specimen. The maximum acceleration amplitude of the input seismic motion for each of tests was increased step wise up to the capacity of the shaking table.

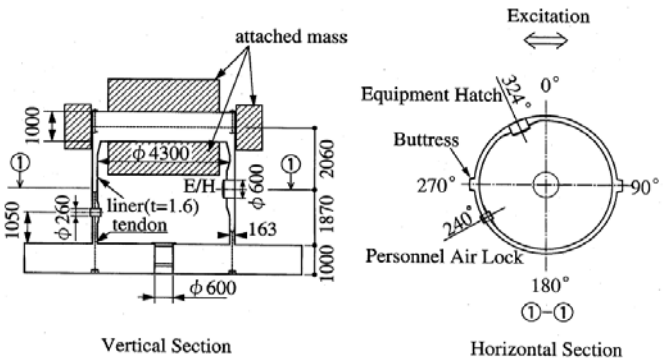


Fig.1 Configuration of the PCCV model

Bending cracks occurred at bottom of the cylindrical wall in the test of S1 input. Shear cracks occurred at lower part of the cylindrical wall in the test of S2 input. Shear cracks were spread to the entire cylindrical wall in the test of two times of S2. Shear slipping failure occurred in the wall nearby the equipment hatch and led to total collapse of specimen in the test of five times of S2 input. The crack distribution on the surface of the PCCV model after the collapse is shown in Fig.2. The air-tightness of the liner plate was maintained until the concrete wall failed.

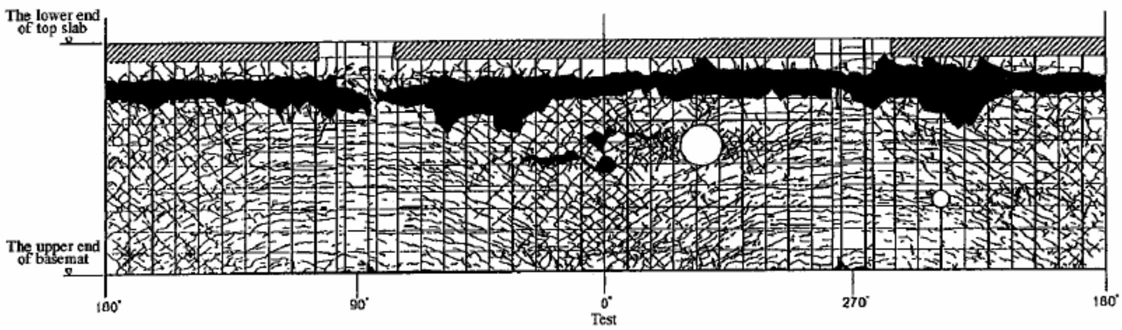


Fig.2 Crack distribution on the surface of the PCCV model after the collapse

The relationship between shearing force and horizontal displacement through the numerical simulations was compared with one through the tests as shown in Fig.3. Although the simulations were slightly larger than the test results, the both were almost identical. The seismic margin of specimen was evaluated through equivalent energy velocity method. The seismic margin of the specimen was considered to be about six times S2.

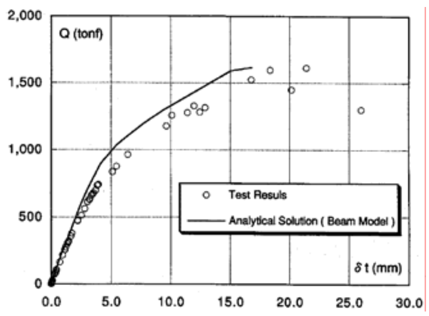


Fig.3 Relationship between shearing force and deformation of PCCV

RCCV TEST

The objectives of the test were, as same as the tests for the PCCV, to prove structural integrity and functional soundness of the RCCV, and to grasp the margin of the RCCV (Hattori 1999, Sasaki 1999b).

The test model of RCCV was consisted cylindrical wall, upper slab, base slab, ring plates fixed on the cylindrical wall and liner plate as shown in Fig.4. The ring plates were introduced to take the restraining effect of surrounding floor slab into account. The scale of 1/8 for overall configuration, 1/10 for wall thickness and 1/4 for liner plate thickness were selected. Additional weights were installed on the upper slab.

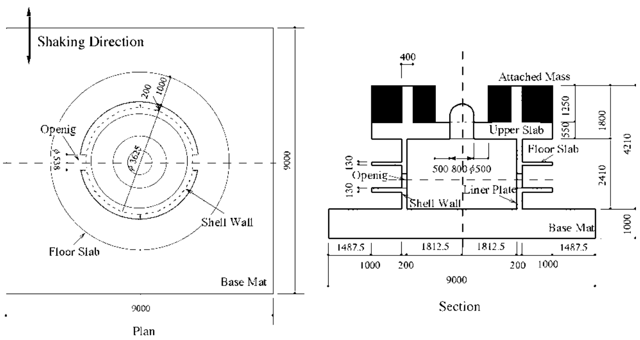


Fig.4 Configuration of the RCCV model

The standard seismic motion for seismic design study was applied to the tests. The maximum acceleration amplitude of input motion for each of tests was increased step wise up to the capacity of the shaking table.

Bending cracks occurred at the flange portion on base of the shell wall, and shear cracks were also observed at the web portion in the 1.3S2 input excitation. In the 9S2 input excitation, the shear force reached the maximum value at the horizontal deformation angle of about 10×10^{-3} and the specimen fractured at about 18×10^{-3}. The concrete shell wall broke away and the reinforcing bars were exposed after the 9S2 excitation. The shear buckling also occurred in the liner plate nearby the access tunnel opening and the liner plate reached to the breaks in the 9S2 excitation. Fig.5 shows the crack distribution on the surface of the RCCV model after the collapse.

Seismic margins of the specimen were evaluated by the equivalent energy velocity and by the simulated strain. The seismic margin of the specimen was considered to be 7.4 and 7.7 respectively.

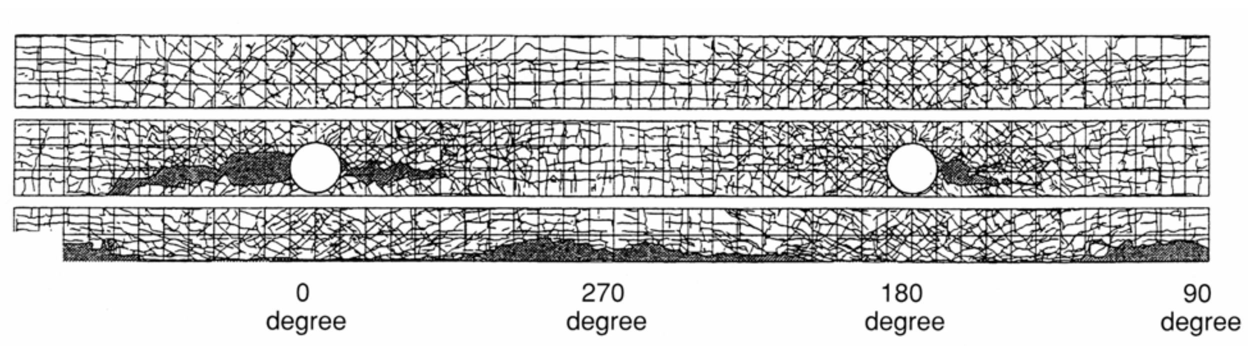
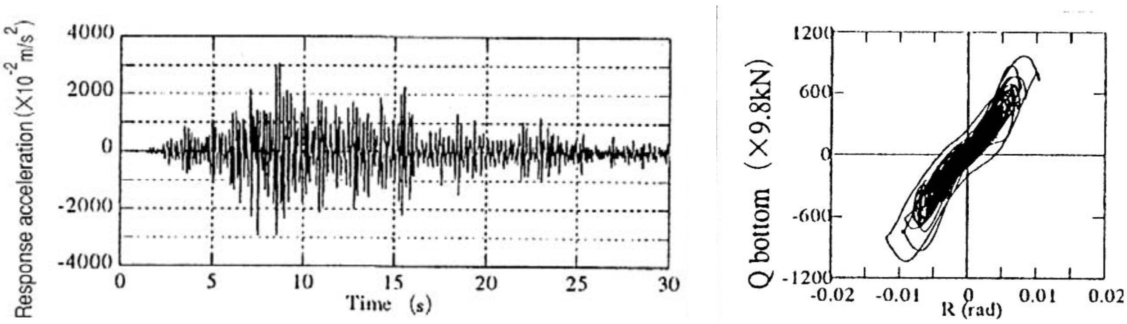
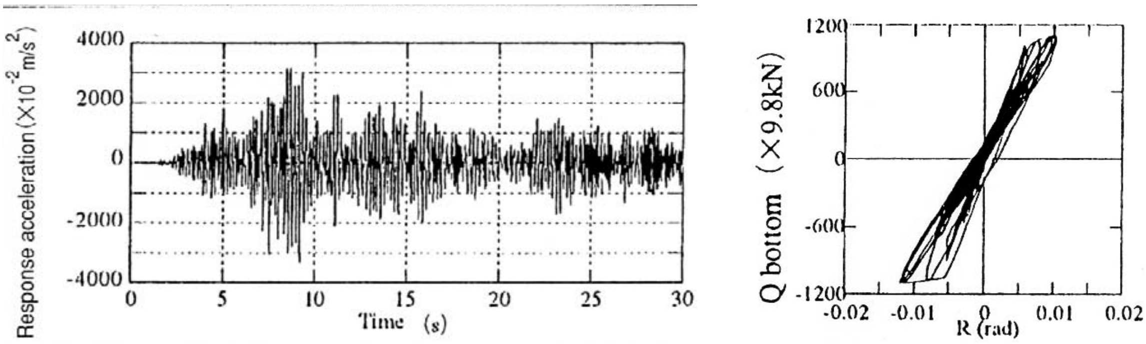


Fig.5 Crack distribution on the surface of the RCCV model after the collapse

The numerical simulations of the tests were done using some restoring force characteristics including current design method. Fig.6 shows the response acceleration on the upper slab and the shear force-deformation angle relation in the 5S2 input test. It was confirmed that the simulations were almost coincident with test results.



(Test result)



(Analysis result)

Fig.6 Response acceleration on the upper slab and Q-R relation of the RCCV in the 5S2 input test

PIPING TEST

The objectives of the tests were followings (Suzuki 2002, Suzuki 2003, Suzuki 2004).

1) to clarify the elasto-plastic response and ultimate strength of nuclear piping.
2) to ascertain the seismic safety margin of the current seismic design code for piping.
3) to prepare new analytical tools for elasto-plastic response analysis and evaluation of fatigue damage accumulation.

The piping component tests, simplified piping system tests, and large-scale piping tests were conducted. Various piping components, such as elbow, tee, reducer etc., and two models of simplified piping systems with 2D run and 3D run were tested. Two models of large scale (200A) piping system were provided for the tests. The models of large scale piping were arranged 3 dimensionally and were composed of elbow, tee and nozzle so the models represented actual nuclear piping. One had the piping supports as same as actual piping. Another had different supports from the former in order to increase response of the piping. The elbow model for dynamic loading tests and the large scale piping model are shown in Fig.7 and Fig.8 respectively.

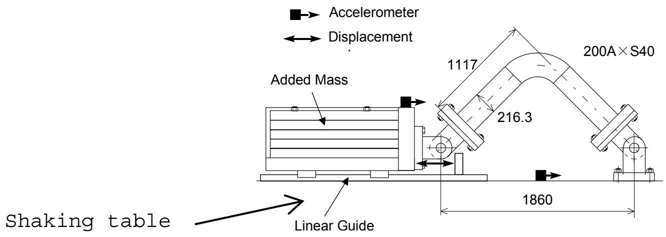


Fig.7 Elbow specimen for dynamic tests

The following loading tests were done for the piping components. the quasi-static cyclic loading under sinusoidal deflection control and the dynamic cyclic loading under inertial force due to seismic excitation and sinusoidal excitation. For the simplified piping systems and the large scale piping systems, seismic excitation tests were done using shaking table.

The postulated seismic motion on the floor of a reactor building excited S2 ground motion were applied for the seismic shaking tests.

Fig.8 Large scale piping system model for ultimate strength tests

All specimens of the piping component tests, simplified piping system tests and large scale piping system tests failed through low cycle fatigue with ratcheting.

It was clarified that the fatigue lives of the piping components at given strain range were about 1/5 of the fatigue lives of the parent materials for carbon steel and about 1/2 of those for stainless steel. It was considered that the fatigue life of the piping components was reduced not only by ratcheting strains but also by size effect, complex stress state and surface roughness, etc.. Fig.9 shows the fatigue lives of piping components.

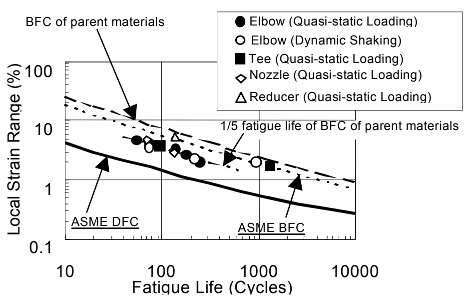


Fig.9 Fatigue lives through the piping component tests

In the shaking tests of piping systems, the resonant frequency was decreased and damping ratio was increased when excitation level was increased. The ratio of dissipated energy in each elbow or nozzle to the whole hardly changed during the excitation.

On the fifth run in the series of the ultimate strength test shaken resonant seismic input motion, the large scale piping system failed with low cycle fatigue manner at the elbow where the largest strain was forecasted. The fatigue damage accumulation (usage factor, UF) until a crack penetrated through the wall in the ultimate strength tests was estimated to be more than 1.82 by the measured strain range.

The strains at the surface of the elbow and nozzle, etc. were simulated using the ABAQUS shell element and two types of hardening rule, the linear kinematic hardening rule (LKH) and the non-linear kinematic hardening rule (AF-OW). The strain range on the elbow in the quasi-static loading test by the LKH rule was well predictable the test result. Furthermore, the simulation by the AF-OW rule could predict accumulation of the hoop strain as shown in Fig.10.

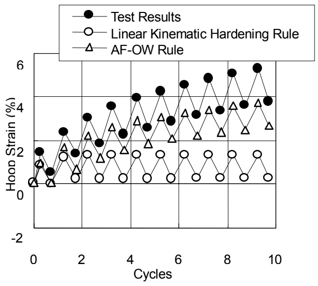


Fig.10 Hoop strain time history on the elbow's outer surface

The hoop strain on the outer surface of the elbow in the 2D simplified piping system shaken seismic motion is shown with the numerical simulation by AF-OW hardening rule in Fig.11.

The UF in the ultimate strength tests of the large scale piping model was estimated by numerically simulated strain range, the Linear Minor Rule and the fatigue life curve determined from the component test results. The estimated UF were 1.8.

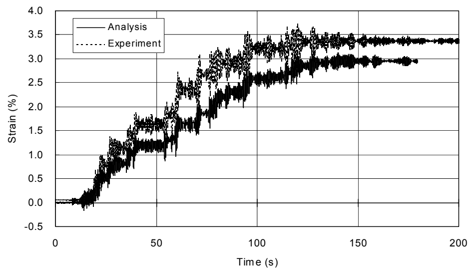


Fig.11 Strain time history at flank on the elbow's outer surface

The intensity of the input seismic motion applied to the ultimate strength tests was what the calculated seismic stress by design rule, pseudo-elastic stress, was about 9 times the current allowable limit (3Sm). The safety margin included in the current design rule, such as allowable limits and design response analysis methods, will be discussed later.

ELECTRIC CABINETS TEST AND HORIZONTAL PUMP TEST

Seismic capacity tests for some active components are being conducted by Japan Nuclear Energy Safety Organization (JNES) under the sponsorship of METI after the piping test above (Iijima 2004).

The objectives of these tests are to clarify the seismic capacity, the maximum ability maintaining its safety function against seismic disturbance, and to clarify the critical failure mode under the seismic load. These tests are also intended to provide the test data to evaluation of the fragility, failure probability, for Seismic probabilistic Safety Assessment (SPSA).

In these tests, electric cabinets, horizontal pump, control rod drive and vertical pump are being tested until end of 2005FY.

The above components were selected from among the active components which were important to safety taking Fussel-Vesely index by the preliminary study of PSA into account.

The Reactor Building Closed Cooling Water (RCW) pump which has flow rate of 1250m^3/h and 8 types of electric cabinets, such as relay cabinet and motor control center, were shaken with seismic motion up to max. acceleration of 6G by Tadotsu large high performance shaking table with the active vibration amplifier.

CONCLUDING REMARKS

After the 1995 Hyogoken-Nanbu earthquake, some collapse tests were conducted. Through these tests, the failure modes and ultimate strength of the concrete containment vessels, PCCV and RCCV, excited by seismic load were clarified. The response of the specimens by the numerical simulations were compared with the test results. The margins of the specimens were estimated.

The failure mode of the nuclear piping excited by seismic load was also clarified to be low cycle fatigue. The fatigue lives of the piping components and the piping systems were clarified by the tests and the fatigue lives of those by the numerical simulations were compared with the test results. The margin of the specimens and actual piping were estimated.

After these tests, some seismic capacity tests of the active components excited by seismic load are being conducted.

These tests were conducted under the technical advises of the executive committee. Author would like to express my sincere thanks to Professor Heki Shibata, the chairman of the committee, for his significant help, and to express my deepest gratitude to all committee members concerned.

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