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EXPERIMENTS OF MINIATURE SPHERICAL TANK SUBSTRUCTURES AND ELASTIC-PLASTIC ANALYSIS

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SUMMARY

Structural characteristics of spherical tanks results in two important problems. One is the interaction between inner fluid and spherical shell, the other is substructures supporting the sphere. The authors carried out the experimental studies on the performance of substructures systematically. At the end, it is shown that elastic-plastic analysis method proposed by the authors can simulate the experimental results fairly well.

INTRODUCTION

The past studies on spherical tanks are summarized as follows : (Ref.1).

(1) Vibrational tests using a miniature tank containing fluid to investigate the free mass ratio by H. Shibata and K. Sogabe
(2) Loading tests on the connection of supporting column to spherical shell to study stress state by S. Yamamoto and E. Kawada
(3) Dynamic tests of a spherical tank to pursue the yield process due to buckling of bracing members by H. Akiyama

However, systematic studies on the basic performance of substructures have not been carried out. The authors made miniature tank substructures with moment resistant frames and braced frames. The substructures were tested under cyclic loading conditions, then restoring force-displacement relations were obtained. On the other hand, the elastic-plastic analysis method proposed by the authors can simulate fairy well experimental results on (Ref.2).

(1) a connection of supporting column to spherical shell, and
(2) a beam-column and bracing system structure.

EXPERIMENTAL METHOD AND RESTORING FORCE CHARACTERISTICS

Aspect of Model Substructures The complementary half of a whole spherical shell was formed by plastic spinning process from SPC steel plate. Flange plate was welded at the equator plane and fastened with bolts to circular thin plate so that the horizontal force may be distributed evenly over the columns.
The material of supporing columns, pipe section, was STK41. Top of the columns was welded to spherical shell, and bottom was pin jointed to the base for braced frames and clamped for moment resistant frames. The abbreviated designation of the models is as follows, where n is the total number of columns.

Braced frame : BT-T -n : tension bracing (slenderness ratio : large)
BT-C -n : compression bracing (slenderness ratio : small)
BT-CS-n : compression bracing (slenderness ratio : medium)
Moment resistant frame : RT-C-n : column collapsing frame

RT-B-n : beam collapsing frame

The dimensions of the models are shown in Fig.1, and mechanical properties of members in Table 1. Loading tests was held by the use of dymanic actuator system of Inst. of Indust. Sci., Univ. of Tokyo. Loading scheme is shown in Fig.2, where P is the loading force.

Restoring Force-Displacement Relations Obtained from Experiment The models were tested under cyclic loading conditions controlled by being constant displacements which were increased every few cycles. Experimental results are shown in Fig.3 on P-δ and Fig.4 on P-θ, where the dotted line shows that damage such as cracks occurred in substructure. Numerals in parentheses are the serial number of loading cycles. Characteristics is summarized as follows for n = 6.

(1) BT-T-6 Bracing member is the same shape as tension test specimen and fastened to gusset at both ends so that buckling occurs out of structural plane. Buckling mode is shown in Fig.5, where effective slenderness ratio λ_e = 128. P-δ relation is reversed S shape and converges in a few cycles. Crack occurred at welded part in the 4th displacement step. P-θ relation fluctuates considerably.

(2) BT-C-6 Bracing member is X shape and fastened at both ends. Bracing members buckled from the root of gusset in the 2nd displacement step as shown in Fig.5, where λ_e = 56. P-δ relation is spindle shape and converges in a few cycles. Crack occurred at welded part in the 4th displacement step. P-θ relation is stable till the crack occurs.

(3) BT-CS-6 Bracing member is X shape and fastened at both ends. Bracing members buckled out of the structural plane as shown in Fig.5, where λ_e = 56. P-δ relation is spindle shape with reversed S and converges in a few cycles. Fasteners slipped in the 4th displacement step. P-θ relation is stable till fasteners slip.

(4) RT-C-6 P-δ relation is spindle shape and stable. Crack occurred at welded part in the 2nd displacement step. P-θ relation is stable.

(5) RT-B-6 P-δ and P-θ relations are the same as RT-C-6. Crack occurred at welded part in the 4th displacement step.

ELASTIC-PLASTIC ANALYSIS METHOD

Stress Analysis of Spherical Shell-Connected Member Joint A numerical method for spherical shell subjected to thrust load or bending moment through connected member is developed by the author, applying the theory on "Symmetrical Bending of Shallow Spherical Shells" presented by TIMOSHENKO. (Ref.3).

When an earthquake happens, spherical shell is subjected to external forces N (equivalent stiffness K_{PX}), moment M (K_M) and M_{TR} (K_{TR}) through columns. Equivalent stiffness is decided by tank diameter D, shell thickness t and column diameter d shown in Fig.6. In case of D = 100, t = 0.2 and d = 6 cm, it is obtained that K_{PX} = 38.8ton/cm, K_M = 1710 ton·cm/rad, K_{TR} = 294 ton·cm/rad.

Elastic-Plastic Frame Analysis Method

(1) Beam-Column Element Plastic stress and strain increments are derived mathematically from the plastic potential flow theory, assuming that relation between generalized stress and strain is perfectly plastic, and yield function expressed by generalized stress also represents the plastic potential. If the process of loading is continued after the yield point has reached, a material work-hardens and the initial yield surface will change its form depending on the increasing plastic deformation. In order to describe work-hardening mathematically, two theoretical hypotheses are presented. One is isotropic work-hardening which presents the situation when the yield surface expands uniformly and retains its initial shape. The other is kinematic work-hardening which assumes that the yield surface undergoes a translation, like a rigid body without changing its initial form. (Ref. 4).

Y. Ueda applied the plastic flow rule to the plastic hinge method and derived the elastic-plastic stiffness matrix of beam-column element. (Ref.5).

M. Hanai applied a kinematic work-hardening rule (Ref.6), then the authors added both isotropic and kinematic work-hardening rules to the stiffness matrix presented by Y. Ueda. (Ref.2,8).

(2) Bracing System The authors presented the numerical analysis methods of bracing systems subjected to repeated thrust load by applying the open form stiffness to the plastic hinge method. In this analytical model, the brace is assumed to remain linear, whenever loaded in thrust, except for a central plastic hinge location. Kinematic hardening and isotropic hardening rules are applied to the plastic hinge, and the plastic deformation is decided by the plastic potential theory. (Ref.7,8).

RESTORING FORCE-DISPLACEMENT RELATIONS OBTAINED FROM ANALYSIS

The P-δ relations are shown in Fig.7 for BT-T-6 and RT-B-6. These analytical results coincide with experimental ones shown in Fig.3 fairly well. Fig.8 shows the axial force-bending moment hysteresis at the plastic hinge and axial force-ductility ratio hysteresis of bracing member of BT-T-6. From these hysteresis, it is shown that the analytical results were computed on the hypotheses correctly.

CONCLUSION

The authors carried out the experimental studies on the performance of spherical tank substructures and investigated the restoring force characteristics. On the other hand, the analytical results computed with the method proposed by the authors coincide with experimental ones fairly well. Therefore analysis method proposed by the authors is available for the seismic design of spherical tank substructures.

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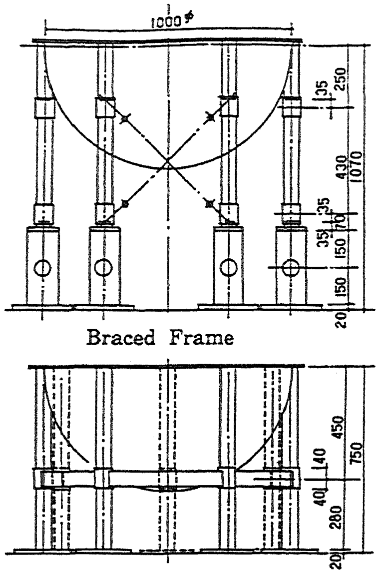


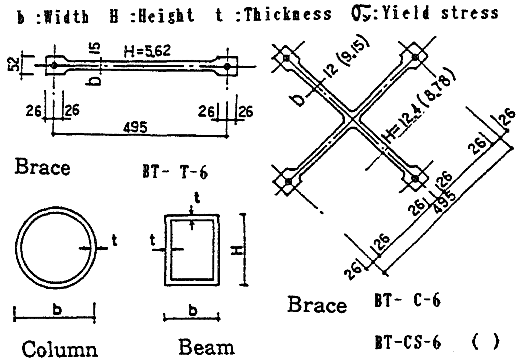
Moment Resistant Frame

Fig. 1 Dimensions of the Model

Table 1. Mechanical Properties of Members

Specimen	Members	b(mm)	H(mm)	t(mm)	σ_y (t/cm^2)
BT-T-6	Column Brace	60.7 15.0	----- 5.62	3.0 ---	3.955 3.44
BT-C-6	Column Brace	60.7 12.02	----- 12.41	3.0 ---	4.139 2.76
BT-CS-6	Column Brace	60.7 9.15	----- 8.78	3.0 ---	3.87 4.103
RT-C-6	Column Beam	60.7 60.56	----- 60.14	3.0 3.06	3.87 3.38
RT-B-6	Column Beam	60.7 30.13	----- 61.03	3.0 2.2	3.87 3.24
RT-C-12	Column Beam	60.7 60.1	----- 60.4	3.0 3.12	3.679 3.159
RT-B-12	Column Beam	60.7 30.25	----- 60.98	3.0 2.25	4.139 3.159
All Specimen	Shell	3.13	25.0	---	2.48

b :Width H :Height t :Thickness σ_y:Yield stress



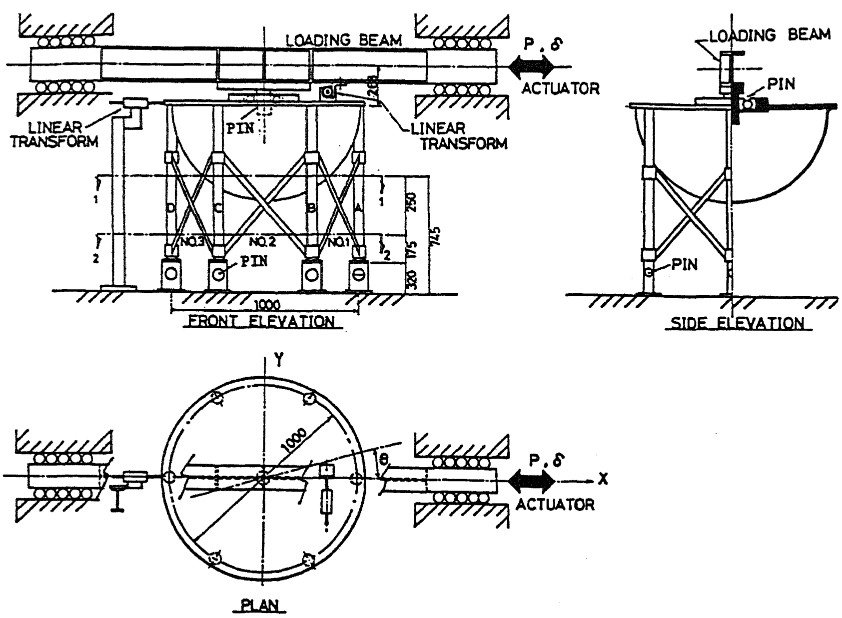


Fig. 2 Loading Scheme

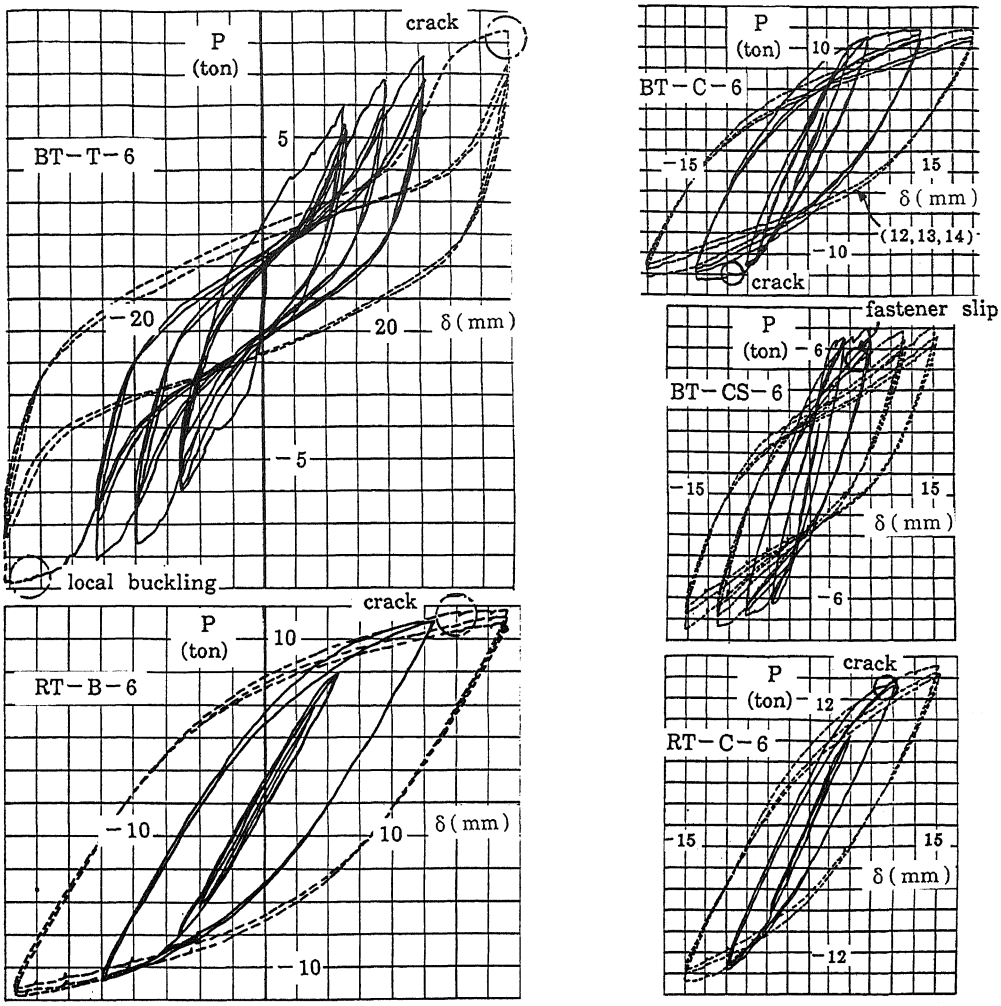


Fig. 3 Experimental Results on P−δ Relations

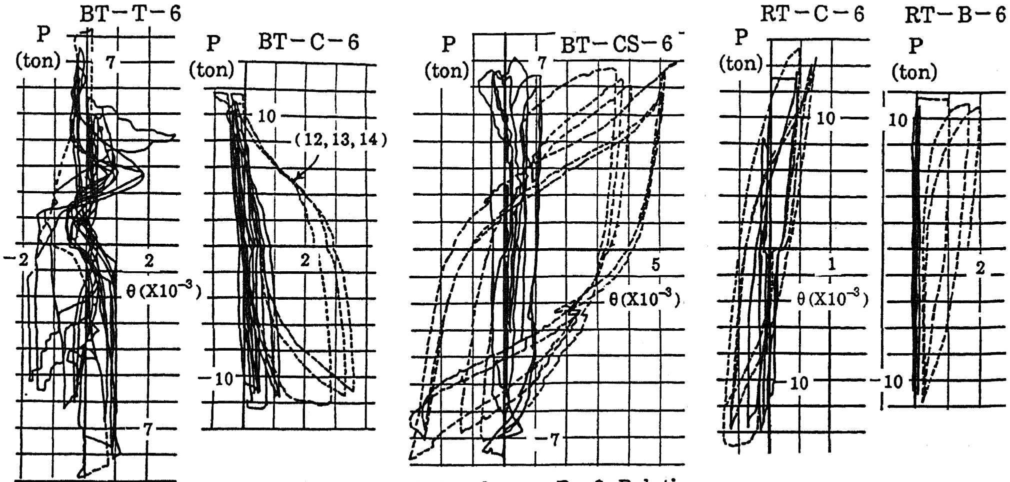


Fig. 4 Experimental Results on P−θ Relations

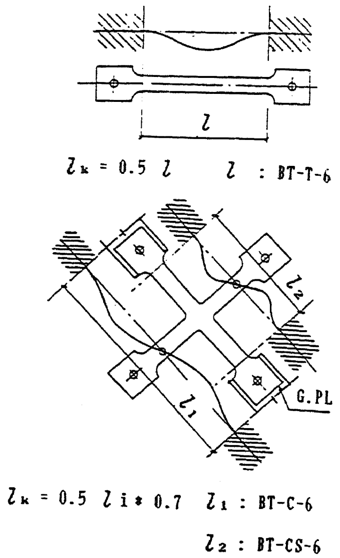


Fig. 5 Buckling Mode

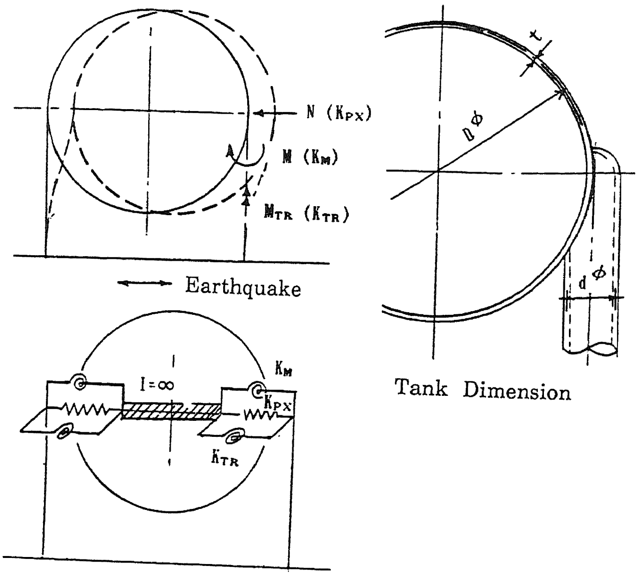


Fig. 6 Analytical Model of Spherical Tank

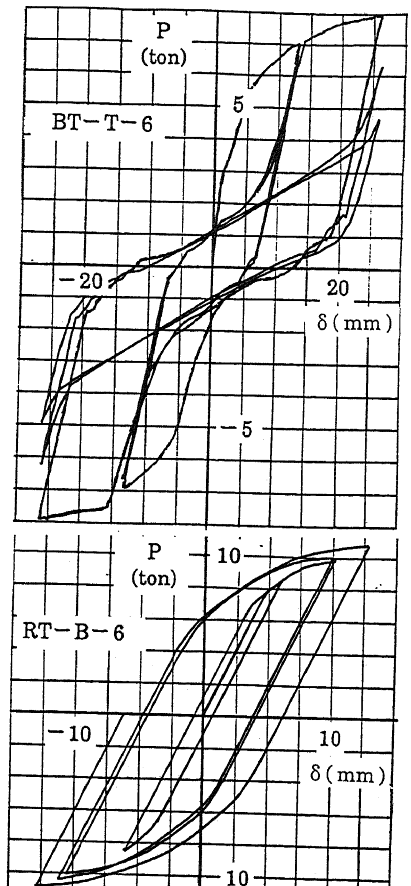
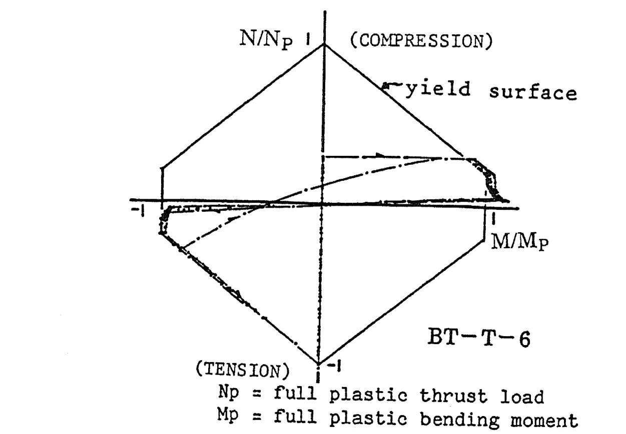
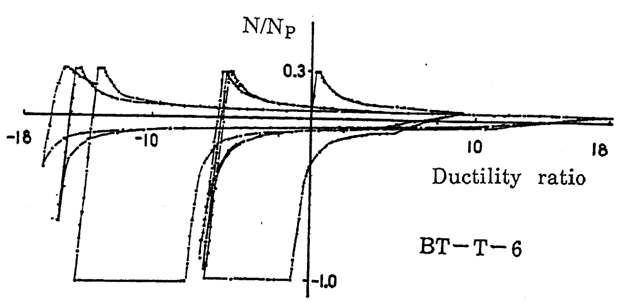


Fig. 7 Analytical Results on P−δ



Axial Force−Bending Moment Hysteresis at Plastic Hinge



Axial Force−Ductility Ratio Hysteresis

Fig. 8 Analytical Results of Bracing Member