SEISMIC PROVING TEST OF A PRESTRESSED CONCRETE CONTAINMENT VESSEL (PCCV)
--- Evaluation of restoring force characteristics and seismic margins ---

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ABSTRACT

The concrete containment vessels (CCVs) in nuclear power plants are the final barrier to prevent radioactive materials from spreading. The CCVs are required to maintain structural and functional Integrity even under severe earthquakes. Since 1980, a series of seismic proving tests of nuclear power facilities has been carried out by the Nuclear Power Engineering Corporation (NUPEC), using the large-scale and high-performance shaking table at the Tadotsu Engineering Laboratory. The tests are sponsored by the Ministry of Economy , Trade and Industry (METI) of Japan.

NUPEC completed seismic proving test for 1/10 scaled model of a prestressed concrete containment vessel (PCCV) with steel liner installed inside the cylinder wall. NUPEC has finished all project tasks and evaluations by the end of March 2000 through the past eight- year project . The objectives of the test are not only to prove structural and functional integrity of a PCCV but also to grasp the seismic margins of the test model and the actual PCCV.

In this paper, as a summary for the PCCV total activities, the following two major items are emphasized. First, a simple method for evaluating the restoring force characteristics of PCCV is newly proposed considering the effects of steel liner stiffness and prestressing by hoop tendons . The test results are compared with those obtained by the proposed method and good agreements are confirmed as to the relationship between shear force and shear deformation. Second , seismic margins are evaluated considering both the capacity of leak-tightness and ultimate strength of a PCCV cylinder wall. The concept of cumulative energy input(CEI) proposed by the last author is adopted for the evaluation.

In conclusion , both the test model and the actual PCCV have almost the same seismic margin of around 6 times of CEI compared with the design level of S2 ground motion(Extreme design earthquake ground motion).

1. INTRODUCTION

NUPEC completed seismic proving test for 1/10 scaled model of a prestressed concrete containment vessel (PCCV) with steel liner installed inside the cylinder wall. All project tasks and evaluations have been completed by the end of March , 2000 through the eight- year project and most of the project results were already reported in several conferences ,such as on test planning [1], preliminary pushover test for curved shear walls to confirm the adequacy of liner anchor system[2], analytical evaluation[3] and so on.

As its final report ,a new restoring force characteristics is proposed compared with conventional JEAG[4] and seismic margins are evaluated considering both the capacity of leak-tightness and ultimate strength of a PCCV cylinder wall. The concept of cumulative energy input(CEI) proposed by the last author [5] is adopted for the evaluation.

2. RESTORING FORCE CHARACTERISTICS

Since PCCV is subjected to large prestressing force both in vertical and horizontal direction, it is estimated that it leads to shear failure after bending yield of reinforcing bars. An evaluation based on JEAG tends to predict restoring force characteristics of PCCV rather conservatively. Including the effect of the stiffness of steel liner plate and prestressing due to hoop tendons is emphasized in this evaluation. There are very few dynamic tests and their evaluations of a PCCV with the consideration of the effects of steel liner and prestressing by hoop tendons directly.

2.1 Analysis model

The evaluation is performed using a finite element model (shown in Fig.1) and beam models (shown in Fig.4 for horizontal and vertical dynamic analysis model ,respectively). The former model consists of solid elements except the PCCV cylinder portion composed of shell elements. The lower surface of basemat is assumed to be fixed. Beam model analysis is conducted calculating bending and shear deformation respectively, and rotational deformation due to pulling-out of vertical reinforcing bars at the utmost tension zone from the basemat is added to the bending deformation.

2.2 Maximum responses by analysis

Fig.2 shows the comparison on the relation between shear stress(τ) and deflection angle (R) obtained by above both analytical models and test result. Shear stress is calculated by dividing the shear force with half of the section area of PCCV cylinder wall. Both analyses agree quite well with the test result on the ultimate strength and its envelope curve .

Fig.3 also shows the comparison of bending and shear deformation between test and beam model analysis respectively. In this figure, both loading conditions including or neglecting the pressure due to LOCA is compared. It is clearly understood there is little change in bending stiffness compared with shear stiffness when subjected to pressure due to LOCA. Beam model analysis tends to overestimate shear stiffness a little than that obtained from the test, but on the whole , the behavior based on the analysis and test shows almost similar way.

Maximum responses (acceleration, displacement and shear stress) at the center of the top slab by test and beam model analyses are shown in Table 1 for each loading case , that is, RUN-1(S1(H)) to RUN-7(LOCA+S1(H+V)) corresponds to the design level ground motion , and the RUN-8(2S2(H)) to RUN-12(4S2(H) :ultimate condition) corresponds to the loading stage beyond S2 ground motion. Damping factors of the analysis are obtained by several sensitivity studies and in beyond design level, damping factor of 2% is allocated to RUN-8 and RUN-9 ,5% to RUN-12,respectively. Analysis results show a good agreement with test results. Especially, ultimate shear strength obtained from the elasto-plastic beam model analysis agreed quite well with the test results.

2.3 Acceleration time history waveforms

Fig.5 shows the comparison of test and beam model analysis with respect to horizontal acceleration and rotation time history waveform at the center of top slab under two representative loading cases RUN-6(S2(H+V)) and RUN-12(4S2(H)). Test and analysis indicates reasonably good agreement with each other in both cases.

2.4 Modification on restoring force characteristics by JEAG

Based on the the test results, a new restoring force characteristics for PCCV is proposed herein. Conventional restoring force characteristics for PCCV is mainly derived from the pushover experiments of reinforced concrete shear walls in reactor buildings. Ultimate shear strength tends to be underestimated in case of shear failures within relatively small deformation region. Since a PCCV is subjected to a large prestressing force both in vertical and horizontal direction, it tends to lead to shear failure after bending yield of reinforcing bars. It is predicted that JEAG evaluates PCCV's restoring force characteristics consevatively. Therefore, the following three items are proposed to modify the JEAG

1) axial stress when calculating bending crack, bending yield and ultimate bending stress
   JEAG : Only membrane stress in vertical direction is considered.
   Proposed : Out-of-plane bending stress due to hoop tendons is deducted from the above stress.
2) axial stress when calculating shear crack stress
   JEAG : Only membrane stress in vertical direction is considered.
   Proposed : Horizontal membrane stress due to hoop tendons is also considered.
3) Ultimate average shear stress(τ 3) in $\tau \sim \gamma$ relationship (N/mm2)
   JEAG : $\tau 3 = 1.41\sqrt{Fc}$
   Proposed : $\tau 3 = 1.75\sqrt{Fc}$

2.5 Evaluation by proposed method

Relationship between shear force (Q) versus shear deformation (δ s) and total deformation (δ t) is shown in Fig.6 and Fig.7 ,respectively. In the figure ,the relationship based on beam model analysis is also plotted. From these figures, JEAG's results lie in safer side in design, and it is found that proposed method agrees well with the test result when considering the stiffness of liner plate.

3. EVALUATION of SEISMIC SAFETY MARGIN (SSM)

3.1 Survey procedures for seismic safety margin

SSM has to be investigated with the leak-tight function and ultimate strength of the PCCV. It is found out from the test result leak-tightness is maintained prior to structural failure. Therefore, ultimate strength is set to be the target item for SSM.

3.2 Definition of SSM

SSM is usually defined as the ratio of responses at failure versus those for design earthquake motion . But those responses such as acceleration ,velocity and displacement may differ in nonlinear region. In PCCV seismic proving test, design earthquake motion is different from failure motion in its spectrum and time history waveforms due to complex loading conditions. Here we adopted the ratio of intensity of input motion at failure versus that of design earthquake motion (S2) as SSM. Intensity is expressed by energy-equivalent velocity derived from CEI(Cumulative Energy Input) proposed by the last author.

3.3 Evaluaton method based on CEI

1) Calculation of CEI

Considering the pitching effect of the shaking table, CEI is derived as shown in Eq.(1).

$$E = -\int_0^{tend} m\,(b\ddot{X}(t) + b\ddot{\theta}(t)\,h)\,r\dot{X}(t)\,dt \qquad (1)$$

$$r\dot{X}(t) = r\ddot{X}(t)\,\Delta t + r\dot{X}(t-\Delta t)$$

$$r\ddot{X}(t) = t\ddot{X}(t) - (b\ddot{X}(t) + b\ddot{\theta}(t)\,h)$$

m: weight of top slab
$b\ddot{X}$: horizontal acc. at the top of basemat
$t\ddot{X}$: horizontal acc. at the top slab
h : length between top surface of basemat and top slab
$b\ddot{\theta}$: input acc. for pitching

2)Derivation of energy-equivalent velocity(V_E)

V_E is obtained by Eq.(2)

$$V_E = \sqrt{\frac{2E}{m}} \qquad (2)$$

3)Evaluation on the ratio of V_E

Fig.8 shows schematic illustration for evaluation of V_E ratio, where A,B and C corresponds to design earthquake motion, failure motion and magnified motion of A(amplification factor is α)

4) Analytical evaluation of SSM

Fig.9 shows analytical estimation of ultimate shear stress where ultimate shear strain is set γ=5.30/1000 considering the test result (γ=4.37/1000) and the behavior after reaching the ultimate strength. Magnification factor is obtained by step-by-step approach varying from 4.0 to 6.3 times of S2(H). In this analysis 5.4 times of S2(H) corresponds to ultimate strength and 6.1 times of S2(H) corresponds to failure state, respectively.

5) Comparison of SSM between test and analysis

Fig. 10 shows the comparison between test and analysis on the magnification factor of seismic safety margin tests in terms of V_E compared with S2(H)incrementally. It is understood SSM of PCCV is approximately 6 times of S2(H).

4. CONCLUSIONS

1) A new restoring force characteristics for a PCCV is proposed considering the effects of steel liner plate stiffness and stresses due to hoop tendons.
2) Based on the Cumulative Energy Input(CEI) concept ,seismic safety margin (SSM) of the PCCV turned out to be approximately 6 times of S2(H) considering cyclic loading effect.
3) Among many indices ,CEI is validated to be most appropriate for the SSM evaluation.

Acknowledgment

Since 1980,NUPEC has conducted a series of seismic proving tests of nuclear power plant facilities and components under the sponsorship of Ministry of Economy,Trade and Industry(METI) of Japan. This test of PCCV is carried out as one of those tests. The authors would like to acknowledge the advice of the Steering Committee of NUPEC.

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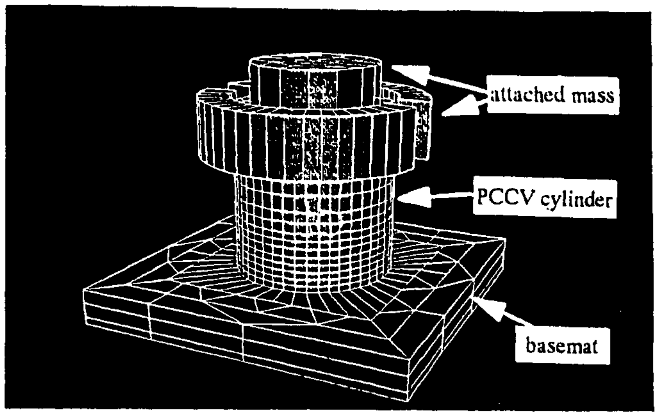
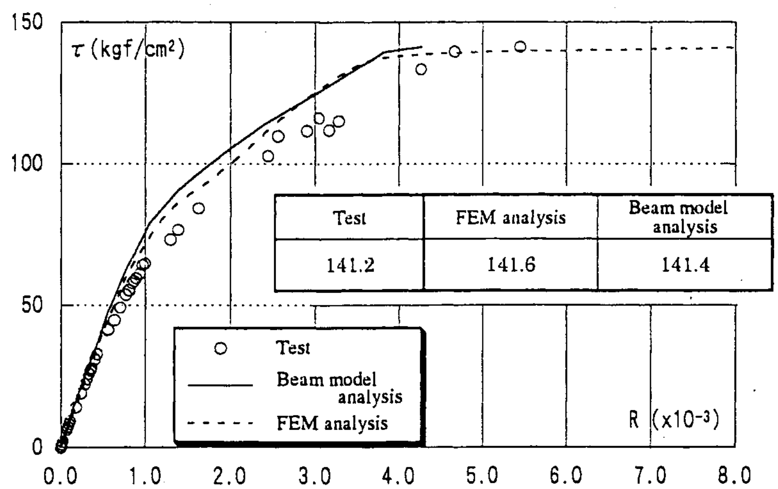


Fig. 1 FEM Analytical Model



Test	FEM analysis	Beam model analysis
141.2	141.6	141.4

Fig. 2 Comparison of Ultimate Strength

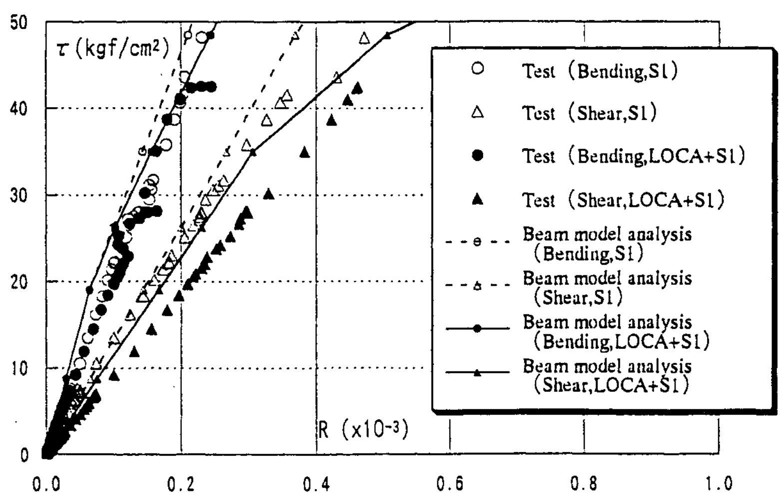


Fig. 3 Comparison of Bending and Shear Deformation between Test and Analysis (Pressure due to LOCA considered)

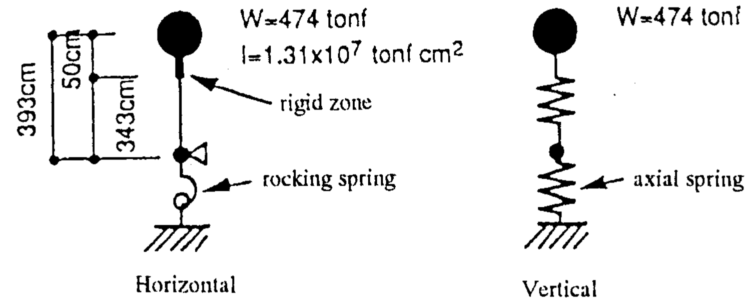


Fig. 4 Models for Dynamic Analysis

Table. 1 Comparison of Maximum Responses

Test name	Test case		Test Acc. (cm/s²)	Test Disp. (mm)	Test Shear stress (kgf/cm²)	Analysis Damping factor (%)	Analysis Acc. (cm/s²)	Analysis Disp. (cm/s²)	Analysis Shear stress (kgf/cm²)	Test／Analysis Acc.	Test／Analysis Disp.	Test／Analysis Shear stress
RUN −1	S1(H)	H	981	2.20	41.4	1.0	1136	2.30	48.1	0.86	0.96	0.86
RUN −2	S1(V)	V	354	0.08	7.48		335	0.09	7.12	1.06	0.89	1.05
RUN −3	S1(H+V)	H	1162	2.78	49.2		967	1.92	41.0	1.20	1.45	1.20
		V	347	0.08	7.35		413	0.11	8.75	0.84	0.73	0.84
RUN −4	S2(H)	H	1362	3.34	57.6		1437	2.98	60.9	0.95	1.12	0.95
RUN −5	S2(V)	V	784	0.18	16.59		787	0.20	16.63	1.00	0.90	1.00
RUN −6	S2(H+V)	H	1529	3.94	64.8		1686	3.63	71.4	0.91	1.09	0.91
		V	786	0.17	16.63		786	0.20	16.59	1.00	0.85	1.00
RUN −7	LOCA + S1(H+V)	H	1012	2.73	42.6		1027	2.60	43.5	0.99	1.05	0.98
		V	600	0.16	12.69		421	0.12	8.92	1.43	1.28	1.42
RUN −8	2.0 S2(H)		2650	12.60	112.0	2.0	2760	10.20	116.11	0.96	1.23	0.96
RUN −9	3.0 S2(H)		3300	19.60	139.6	2.0	3060	13.61	128.51	1.08	1.44	1.09
RUN −12	4.0 S2(H)		3340	21.9	141.2	5.0	3610	17.69	147.07	0.92	1.24	0.96

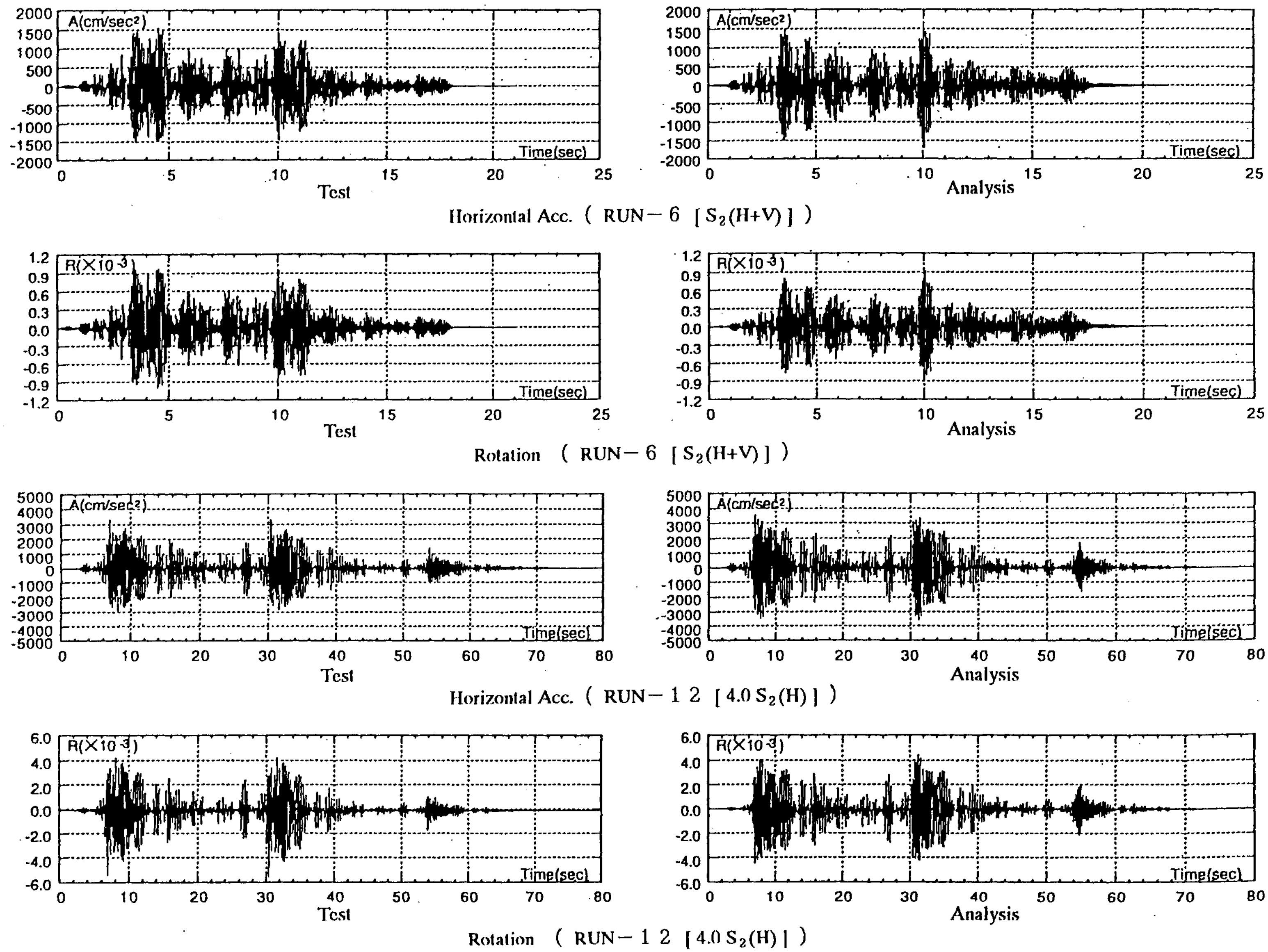


Fig. 5 Comparison of Response Waveforms at Top Slab

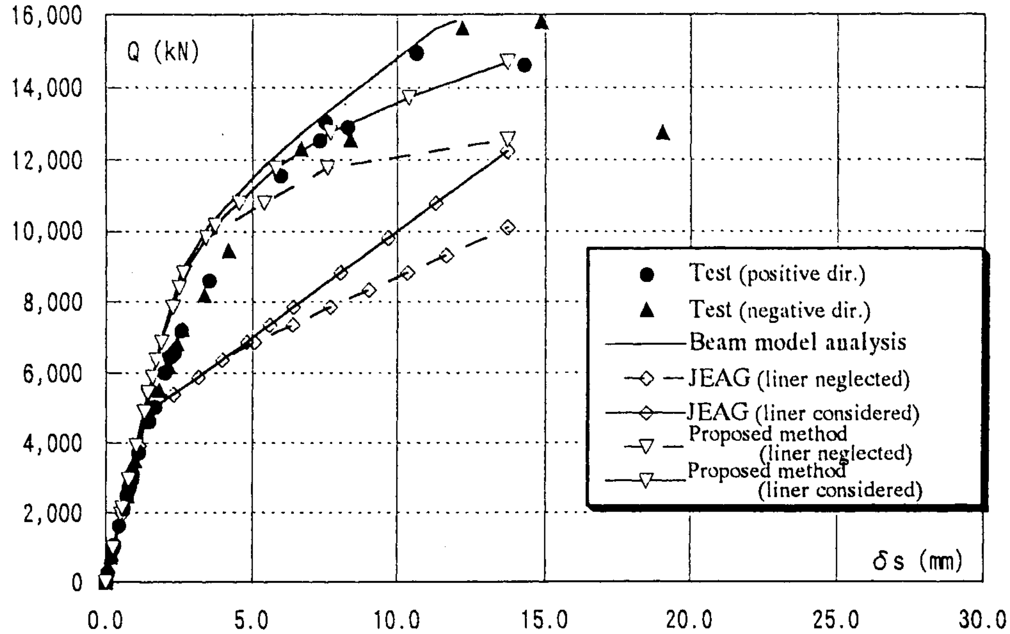


Fig. 6 Shear Force (Q) ～ Shear Deformation (δs) Relationship

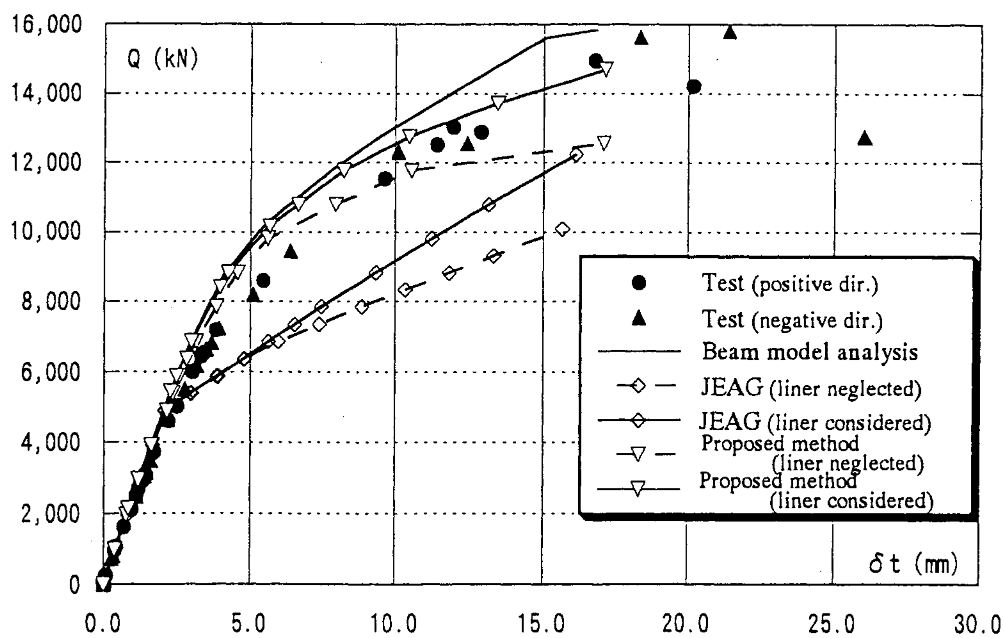
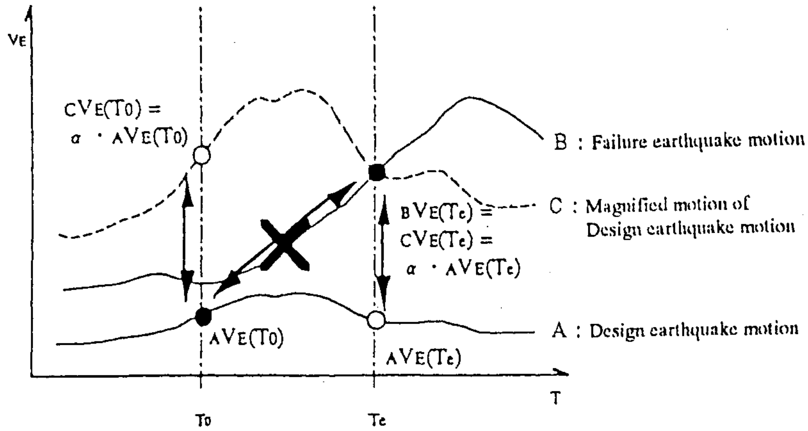


Fig. 7 Shear Force (Q) ～ Total Deformation (δt) Relationship



T_0 : Elastic Natural Period T_e : Equivalent Period at Failure

Fig. 8 Schematic Illustration for Evaluation of V_E Ratio

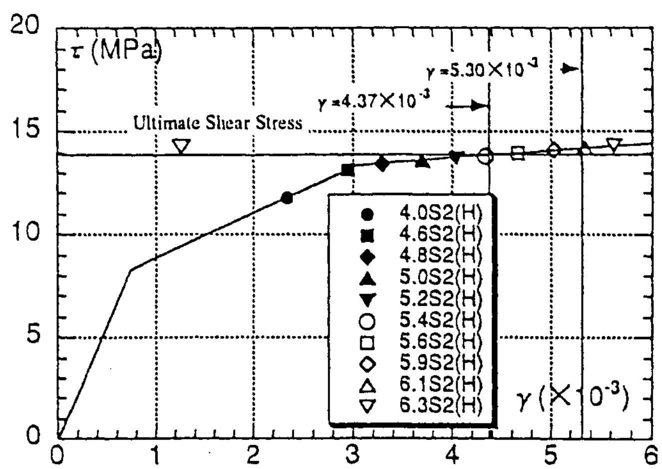


Fig. 9 Analytical Estimation of Ultimate Shear Stress

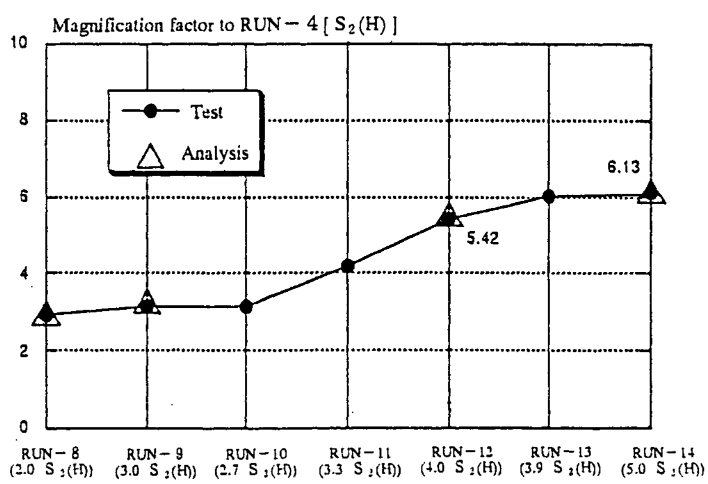


Fig. 1 0 Magnification Factor of Seismic Margin Tests in terms of V_E