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DYNAMIC PROPERTIES AND SEISMIC RESPONSES OF INDUSTRIAL PLANT FACILITIES

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SUMMARY

The plant facilities in steel structures are classified into several types which have common structural features. The dynamic properties of representatives of each structural type were revealed by vibration tests. The seismic responses within specific parameters including the effects of newly developed aseismic devices, were investigated. The items that should be taken into account in the advanced seismic-resistant design of the industrial plant facilities are pointed out.

INTRODUCTION

Various shapes of steel structures were constructed in the industrialized areas. The general seismic design methods on the specific plant facilities are stipulated in the relevant seismic codes. However, in the practical design procedure, several subjects on the structural details are left to the structural engineers' discretion. Therefore, there is a need to provide valuable information concerning the particular dynamic properties and the seismic responses derived from the structural features.

From the engineering point of view, the plant facilities are classified into several types which have the following common structural features, for example, as tabulated in Table 1. In this study, much attention was focused on the representatives of each structural type except for the rigid body-supporting saddle or leg type, and the cylindrical vessel type.

DYNAMIC PROPERTIES

In order to reveal the dynamic properties of the industrial plant facilities, vibration tests were performed on cranes, a spherical gas storage tank, a steel stack, a coke dry quenching plant, and blast furnaces.

The natural vibrations of the 25t gantry crane and the 45t container crane are tabulated in Table 2, which were obtained through self-travelling and traversing of the trolley. The coupling motion of sway and torsion is significant in the direction of travelling.

Asymmetric vibrational modes were confirmed through a forced vibration test on the spherical gas storage tank. The asymmetric vibrational modes were first caused by random loosing of initial tensions in braces as pointed out in the seismic damage report on spherical vessels (Ref. 1).

The resonance curves, obtained through both tests and simulation analyses on the steel stack with the opening for equipment are compared in Fig. 1. The exciting direction was deviated by 30° from the principal axis. The dynamic properties of the steel stack are summarized in Table 3, and it suggests that the ordinal regression analysis may lead to overestimation of damping.

The results of the forced vibration tests on the coke dry quenching plant also emphasize the significance of torsional vibrations caused by asymmetric arrangement of the furnaces.

The comparison of the test and analytical results on the blast furnaces are summarized in Table 4. It is recognized that the effects of large-scale pipings on the lower natural vibration modes are not negligible, therefore a space structural model should be required in precise response analysis (Ref. 2).

SEISMIC RESPONSES

In order to arrive at widely applicable results, seismic response analyses on these structures within the extents of specific parameters were performed, based on the dynamic models of the real structures.

The shear forces in frames of container cranes subject to dynamic loads in the travelling direction are shown in Fig. 2, using an average spectrum of recorded motions (Ref. 3). When the parameter e_0/i_0 is small, the dynamic shear forces on one side of the frames are magnified compared with the static ones.

According to the response of spherical gas storage tanks, a pair of braces may buckle through excessive stresses caused by the torsional vibrations. Therefore, the magnification factor of shear forces was calculated in the condition without the pair of braces subject to perfectly flat spectrum loads. The results suggest the possibility of a progressive failure of the braces as shown in Fig. 3 (Ref. 4).

The distribution of shear force ratios in the furnaces was calculated on the coke dry quenching plant by substituting the foundation with a simple spring model with three levels of stiffness. The time histories of the El Centro, the Taft, the Kawanazaki and the Chiba earthquakes were used, the latter two were recorded at the bedrock of Ogishima(Ref. 5). As shown in Fig. 4, the relatively low stiffness of the foundation concentrates the shear forces at one side of the furnaces, and the more soft foundation makes the distribution uniform.

In Fig. 5, the simpified model of the blast furnace is illustrated. It may be used to obtain shear force ratios between the furnace and the supporting frame in the initial design stage. The calculated results were derived by averaging the responses subject to the four earthquake motions above, with and without dampers. When the parameter T_b/T_s is greater than 1.0, the dynamic shear forces concentrate more on the supporting frame compared to the static ones.

ASEISMIC DEVICES

As noted above, the dynamic properties and the seismic responses of the industrial plant facilities are very complex. To ensure satisfactory seismic performance of the structures, the next phase of research was directed to the development of aseismic devices.

The concepts and the test setups of the aseismic panel and the metal damper are shown in Figs. 6 and 7. Energy dissipation was achieved by utilizing hysteresis loops of the horizontal and vertical steel members, or through the web plate of H-shaped steel. The aseismic panel and metal damper's efficiencies were ascertained through these tests (Ref. 7).

In Fig. 8, the concept and the installation of the visco-elastic dampers to the plant tower model are shown. In this device, the high capacity of damping in shear displacement of acrylic polymers causes energy dissipation. From comparison of the resonace curves with and without dampers, a substantial decrease in the responses is clearly recognized through the shaking table tests and simulation analyses. In simulation analyses, the damper was substituted with springs with complex rigidity, and generally good agreements with the test results were obtained.

The visco-elastic dampers for the spherical gas storage tank are also shown in Fig. 9. The resonance curves obtained through the forced vibration test with and without the dampers indicate that efficiencies of the dampers are attained to the expected level of requirements (Ref. 4).

CONCLUDING REMARKS

1) In the boom-supporting frame type, torsional vibrations are apt to be coupled with swaying motions through the eccentricities. Magnified shear forces in the frames were drawn in design diagrams (Table 2, Fig. 2).
2) In the column-brace type, random loosing of initial tensions in braces may cause torsional vibrations with excessive stresses and may extend to a progressive failure of the braces (Fig. 3).
3) In the tower structure type, the opening for equipment may be negligible in the response analysis, but this makes two adjacent peaks in the response curve and it may lead to overestimation of damping through ordinal regression analysis (Fig. 1, Table 3).
4) In the furnace-supporting frame type, the base shear distribution may be non-uniform if the arrangement of the furnaces is asymmetric. The relatively low stiffness of the foundation compared with the upper structure furthers this tendency (Fig. 4).
5) In the furnace-piping-supporting frame type, the large-scale pipings affect lower natural vibrations in both frequencies and mode shapes (Table 4).
The shear force ratios between the furnace and the supporting frame were drawn in design diagrams (Fig. 5).
6) Aseismic devices to improve dynamic properties of plant facilities were developed and the efficiencies were ascertained through experiments and simulation analyses (Figs. 6-9).

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Table 1 Classification of Structural Types

Structural Type	Plnat Facility
boom-supporting frame	crane(container crane etc.) unloader
rigid·body-supporting saddle or leg	horizontal vessel,vertical vessel
column-brace	spherical gas storage tank, elevated water storage tank
cylindrical vessel	oil storage tank, LNG tank
tower structure	chimney·stack(self-standing), silo
furnace-supporting frame	chimney·stack(frame-supporting), coke dry quenching
furnace-piping-supporting frame	furnace (blast furnace etc.)

Table 2 Natural Vibrations 25t Gantry Crane

Mode No.	Period (sec)		Mode Shape
	Vibration Test	Calculation	
1	2.36	2.61	sway in X direction
2	1.87	2.43	torsion (C.R.; land side)
3	0.83	1.41	torsion (C.R.; sea side)
			45t Container Crane
1	—	1.63	sway in Y direction
2	1.46	1.37	torsion
3	0.97	0.75	sway in X direction

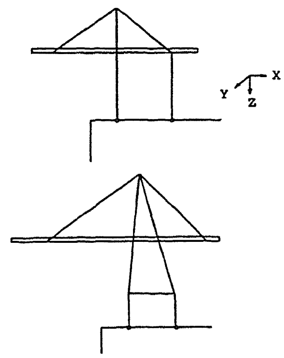


Table 3 Natural Vibrations Steel Stack ; before Lining

Mode No.	Freq. (Hz)	Critical Damping Ratio (%)	
		Regression Analysis	Simulation Analysis
1	1.104	0.63	0.30
2	1.125		
3	4.465	0.64	0.39
4	4.580		
		Steel Stack ; after Lining	
1	0.814	1.46	0.73
2	0.828		
3	3.555	0.72	0.56
4	3.655		

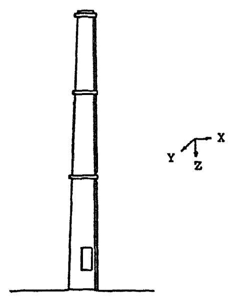
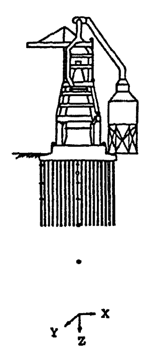


Table 4 Natural Vibrations Ogishima No.2 Blast Furnace

Mode No.	Vibration Test		Calculation			
			piping included		piping ignored	
	freq.	mode shape	freq.	mode shape	freq.	mode shape
1	0.92	torsion+sway in Y	0.80	torsion+sway in Y	0.77	torsion+sway in Y
2	1.33	sway in X	1.12	sway in X	1.12	sway in X
3	1.39	(sway in X)	1.18	(sway in X)	1.20	(sway in X)
4	1.44	torsion+sway in Y	1.32	torsion+sway in Y	1.33	torsion+sway in Y
						Fukuyama No.2 Blast Furnace
1	0.91	torsion+sway in Y	0.88	torsion+sway in Y	1.13	sway in X
2	1.26	sway in X	1.29	sway in X	1.27	torsion+sway in Y
3	1.47	torsion+sway in Y	1.39	torsion+sway in Y	1.77	torsion
4	1.62	torsion	1.78	torsion	1.79	sway in X



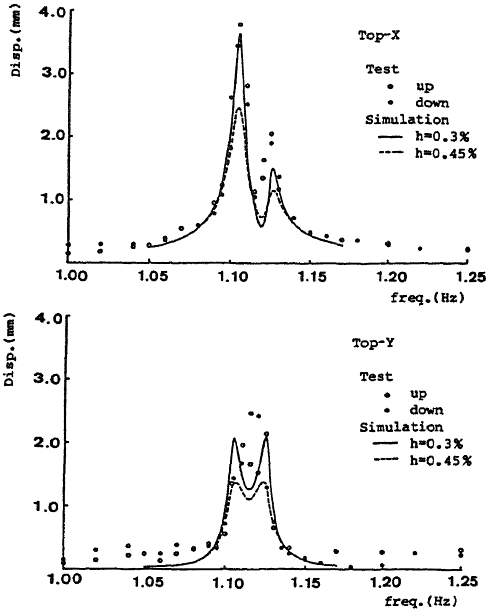


Fig.1 Comparison of resonance curves in a steel stack ; before lining

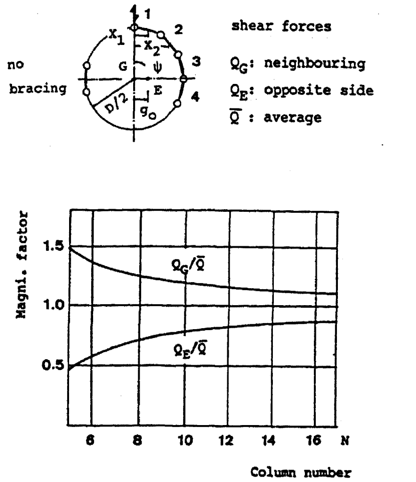


Fig.3 Magnification factor of shear forces without a pair of braces

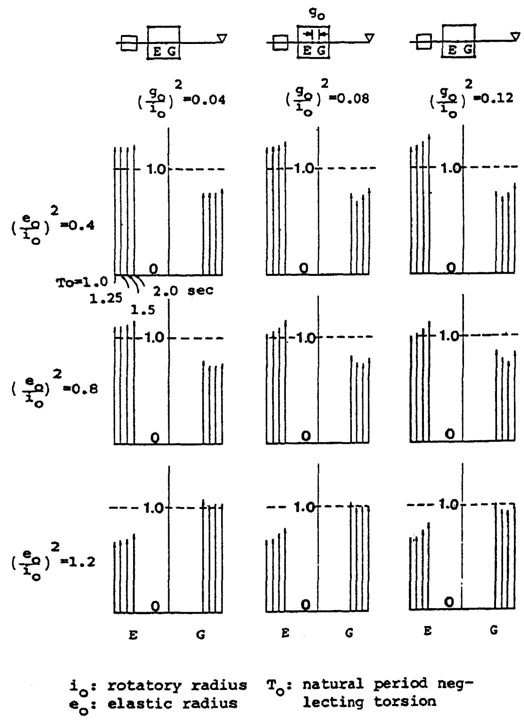


Fig.2 Shear forces in frames ; dynamic/static

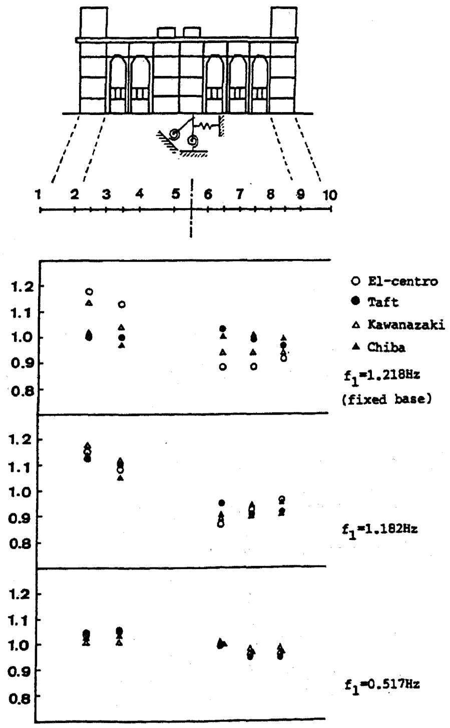


Fig.4 Distribution of shear force ratios

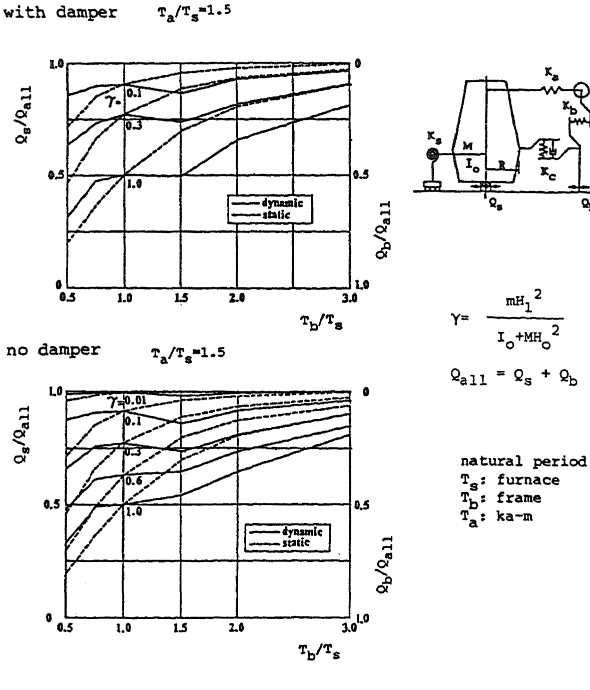


Fig.5 Shear force ratios ; furnace and frame

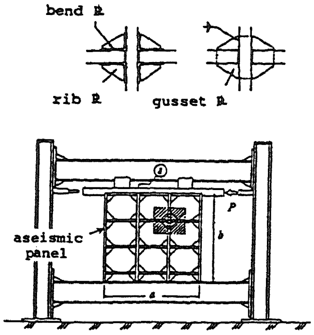


Fig.6 Test setup of aseismic panel

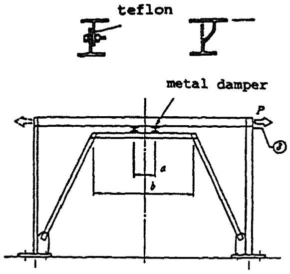


Fig.7 Test setup of metal damper

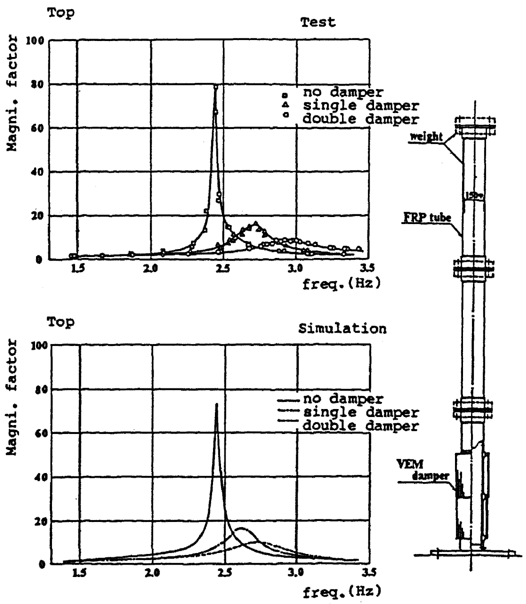


Fig.8 Comparison of resonance curves ; tests and simulation

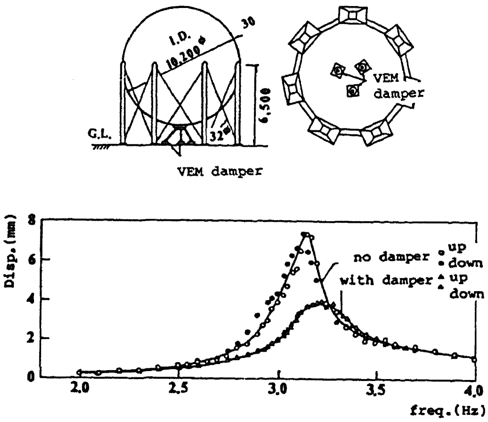


Fig.9 Resonance curves by tests