

THE DEVELOPMENT OF THE DESIGN METHOD OF NUCLEAR PIPING SYSTEM SUPPORTED BY ELASTO-PLASTIC SUPPORT STRUCTURES (PART 1)

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1. Introduction

The conventional aseismic design method of nuclear piping system is very conservative because of the accumulation of various safety factors in the design process, and nuclear piping systems are thought to have a large safety margin. Considering this situation, we promoted research to further rationalize nuclear power plants by reducing the amount of support structures and reducing the piping's seismic response through vibration energy absorption resulting from the elasto-plastic behavior of piping support structures.

The research has the following three stages. In the first stage, we select conventional piping support structures in Japanese light-water reactors that exhibit elasto-plastic behavior, and study the displacement dependency and the vibration frequency dependency on the stiffness and the energy absorption by testing their model. In the second stage, we make a piping test model with support structures whose characteristics have already been obtained, and perform vibration tests on a shaking table. In this way, we analyze the piping vibration characteristics by sinusoidal wave sweep tests and the piping response characteristics by seismic wave vibration tests, when the support structures are in an elasto-plastic condition. In the third stage, a general method is developed to evaluate the characteristics of the support structures obtained in the tests and it is applied to the evaluation of the characteristics of general support structures. A simplified analysis method is developed to evaluate the piping seismic response using the piping model test result.

To expand the results mentioned above, we are developing a seismic design method of piping systems that allows support structures to have elasto-plastic behavior. This paper reports the results of experiments conducted under the joint research program of Japanese electric power companies (The Japan Atomic Power Co., Hokkaido EPC, Tohoku EPC, Tokyo EPC, Chubu EPC, Hokuriku EPC, Kansai EPC, Chugoku EPC, Shikoku EPC and Kyushu EPC) and nuclear power plant makers (Hitachi Ltd., Toshiba Co., MHI Ltd., HEC Ltd., IHI Ltd. and MAPI Inc.) with support elements in the first stage and those with piping models in the second stage.

2. Support Element Experiments

2.1 Objective

The objective of these experiments is to obtain elasto-plastic characteristics of piping support structures currently used in Japanese light-water reactors that are expected to absorb vibration energy by their elasto-plastic behavior through their loading test.

2.2 Experiment Procedure

Test models were of the type that had the same configuration as the frame-type restraint support currently used in light-water reactors in Japan. The reason for the use of this type of support is that it has an appropriate structure and configuration and is expected to have elasto-plastic behavior. Test models were classified according to the support configuration, height-width ratio of the frame, cross-section of the support members, the size of the support members and whether they have braces or not.

The experiments themselves were classified by the method of loading into dynamic-load tests and static-load tests. In dynamic-load tests, a dynamic load was applied to test models, and the vibration frequency dependency on the stiffness and the energy absorption were examined. In the static-load test, applying a static load to test models, the displacement dependency on the load and the stiffness were examined.

The experimental conditions were classified according to the combination of support configuration, applied load, applied displacement, loading direction and applied frequency. The test matrix is summarized in Tab.1.

Fig.1 shows one of the test apparatus.

2.3 Experimental Results

The displacement-stiffness curve of the cantilever support, using $50 \times 50 \times 6$ angle, is shown in Fig.2. One example of hysteresis loops in the dynamic-load test is shown in Fig.3.

The result of the dynamic-load test with a $50 \times 50 \times 6$ angle cantilever support showed that energy absorption increased as the applied displacement increased. There were no major changes in the shapes of the hysteresis loops with various frequencies applied. This indicated that there was hardly any frequency dependency on the energy absorption. Furthermore, the stiffnesses that were obtained from the hysteresis loop failed to show any frequency dependency.

As far as these results were concerned, the same tendency was found in the other test models with other steel member sections and sizes. That is to say that it was confirmed that, as the applied displacement increased, the amount of energy absorbed by the supports increased and there was hardly any frequency dependency on the stiffness and the energy absorption.

The result from the static-load test with a $50 \times 50 \times 6$ angle cantilever support showed that, as the load moved to the higher side, the displacement grew larger and beyond the elastic range, there was a tendency for the increase ratio of the displacement to grow even larger. On the other hand, beyond the elastic range, the stiffness of the test model was confirmed to fall even more. Except for cases where braces were added, the results showed the same tendency with other test models with different member sections and sizes.

From the above results, except for cases where braces were used, it has become apparent that stable elasto-plastic behavior can be expected.

3. Piping Model Experiments

3.1 Simple Piping Model

3.1.1 Objective

The purpose of the experiments on simple piping is to make the vibrational characteristics and seismic response characteristics clear when the supports go into elasto-plastic conditions. Based on the results of support elemental experiments, vibration tests using a shaking table were performed on simple two-dimensional piping models.

3.1.2 Experimental Procedure

In the test model of simple piping, two-dimensional piping was prepared so that the appropriate vibration could be applied within the capabilities of the shaking table. In order to simplify the responses of the pipe, a cantilever support with elasto-plastic characteristics was used. As for the support member, two types of materials were used: angle steel and rectangular steel pipe.

The experiments were classified into two tests: a vibration characteristics test and a seismic vibration test. In the vibration characteristics test, the sinusoidal wave sweep test was performed with the input acceleration as the parameter in order to obtain the vibration characteristics of the piping model. Also, in the seismic vibration test, three types of seismic waves were used: wave A has a dominant frequency that resonated at the natural frequency of piping system, wave B's dominant frequency is slightly higher than the piping's natural frequency, and wave C's is lower. The test was performed to obtain the response characteristics of the piping model in relation to the elasto-plastic behavior of the support structures.

The experimental conditions were classified according to the combination of support member, input wave type and input acceleration amplitude. Fig.4 outlines the experimental apparatus.

3.1.3 Experimental Results

Using a test model which uses rectangular steel pipes as support structures, the input acceleration dependency of the transfer characteristics near the primary natural frequency of the piping system is shown in Fig.5. Fig.6 shows an example of the hysteresis loops of the support structure when vibrations are caused by seismic waves resonating at the primary natural frequency of the piping system. Fig.7 and Fig.8 respectively show the relation between support displacement vs. input acceleration, and pipe stress vs. input acceleration.

In the vibration characteristic test, when the level of the input acceleration increased, the damping ratio of the piping increased because of the energy absorption of the support which showed elasto-plastic behavior and the response rate of the vibration transfer decreased. The maximum damping ratio was about 5%.

In the seismic wave vibration test, when the support was in an elastic condition, the responses of piping acceleration, support displacement, reaction force and pipe stress showed a linear increase as the seismic input acceleration level increased. However, when the support was in the elasto-plastic condition, due to the energy absorption of the support structure, the responses saturated since the damping ratio of the piping increased. It has become apparent that we can expect the response suppression effect in piping system. As for other waves with different frequency characteristics, we found no phenomena showing excessive displacement or unstable response. Also, the hysteresis loops of the support structure showed that the vibration energy was stably absorbed against random waves such as seismic waves.

The same tendencies were observed when using test models with angle steel as the support structures.

3.2 Three-Dimensional Scale Model

3.2.1 Objective

Experiments were performed on two three-dimensional piping systems, one with conventional supports, and the other with elasto-plastic ones. The objective of these experiments was to find the seismic response characteristics, and obtain basic data for the development of a simplified seismic response analysis method for piping with elasto-plastic supports.

3.2.2 Experimental Procedure

Two separate three-dimensional piping systems were used. The first one was a scale model of a piping system which had conventional support structures. This conventional supports were designed to provide rigid elastic characteristics. The second model had rationalized supports designed to have elasto-plastic behavior.

The use of two models allows a comparison of the difference in the models. First, the difference in damping ratios between each piping system can be found, and secondly the seismic response of the piping with elasto-plastic supports can be quantified.

Fig.9 shows the rationalized test model as mounted on the shaking table. In this model, elasto-plastic supports, made of $50 \times 50 \times 6$ angle steel, were used.

For each model, a sinusoidal wave sweep test was performed to find the vibration characteristics (natural frequency, mode shape, damping ratio, etc.). Next, a seismic wave vibration test was conducted to find the seismic response of the piping. Sufficiently high input acceleration levels were selected to ensure a nonlinear response in the system with elasto-plastic piping supports. Two types of seismic response time histories, which were wave A and wave B explained in 3.1.2, were used as input acceleration waveforms for the shaking table. The maximum acceleration was 2000 Gal with wave A.

3.2.3 Experimental Results

The primary and the secondary modes of the natural frequency of the rationalized model were found by the sinusoidal wave sweep tests. They were 8.5 Hz and 9.7 Hz respectively.

A nonlinear response was obtained in the seismic wave vibration tests. The damping ratios were calculated from the frequency transfer function shown in Fig.10, by the half power method. Fig.11 shows the hysteresis loop showing the relationship between reaction force and displacement in one of the supports. It was noted that during the vibration tests, some of the support brackets twisted elastically, and changed the boundary conditions of the piping system at those supports. This caused residual strain to be generated in the foundation of the supports. However, residual components were not found in the reaction forces and displacements. Substantial hysteresis was present, and the supports displayed stable energy absorption characteristics up to the maximum ductility factor of three. Due to these nonlinear effects, the natural frequencies were reduced by 10 % at an input acceleration level of 2000 Gal, and the damping ratios were increased to 3~4 % from the initial value of 1.2 %.

The pipe stress vs. input acceleration curve is shown in Fig.12, and the pipe response vs. input acceleration curve is shown in Fig.13. The maximum piping stress was found to be in the elastic range at all times in the tests. The response acceleration increase was proportional to the input accelerations for low input levels, however, in the high input range, nonlinear behaviour was found as in the curve. This nonlinear phenomena is a feature of the elasto-plastic response. The same characteristics were also found in the response accelerations and response reaction forces of the other elasto-plastic supports. Two of these three supports showed nonlinear responses at an input acceleration level of 1000 Gal, which corresponds to ductility factor of one.

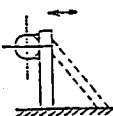
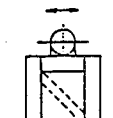
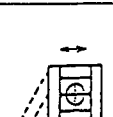
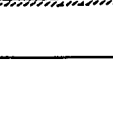
4. Conclusions

The following conclusions were obtained from the results of the support element experiments and the piping model experiments.

- (1)In the support element experiments, we obtained the displacement dependency and the frequency dependency of the stiffness and the energy absorption of the frame-type restraint.
- (2)In the piping model experiments, response reduction effects were found when the support structures exhibited elasto-plastic behavior. The damping ratio was 5 % in the simple piping system test and a maximum of 3~4 % in the three-dimensional piping system test. We also obtained data on the vibration level dependency on the natural frequency and the damping ratio of the piping system and data on the response characteristics of the piping system when shaking with seismic waves having different frequency characteristics.

Based on these experimental results, the method to evaluate the elasto-plastic characteristics of piping support structures will be developed and the aseismic design method for piping systems with piping support structures allowing elasto-plastic behavior will be established.

Tab. 1 Test matrix

Style	Form	Size	Condition
	Angle	50x6 100x10	Dynamic Static Static
	Square pipe	50x2.3	Dynamic Static
	Angle	50x6 100x10	Dynamic Static Static
	Square pipe	50x2.3 100x4.5	Dynamic Static Static

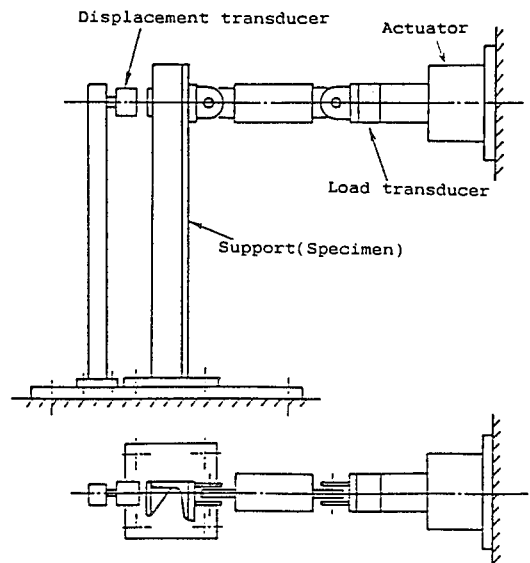


Fig. 1 Test apparatus (cantilever support of angle)

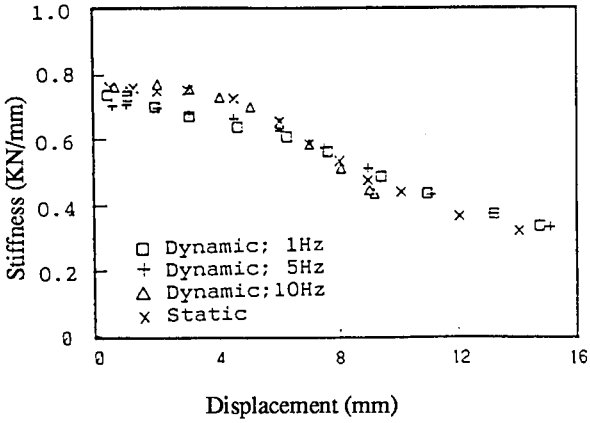


Fig. 2 Stiffness-displacement curve (cantilever support of angle)

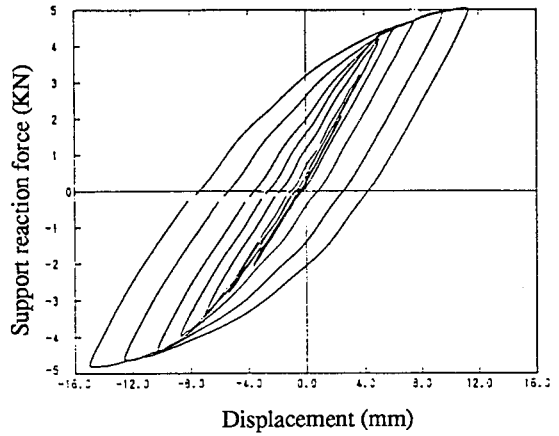


Fig. 3 Hysteresis loop (cantilever support of angle)

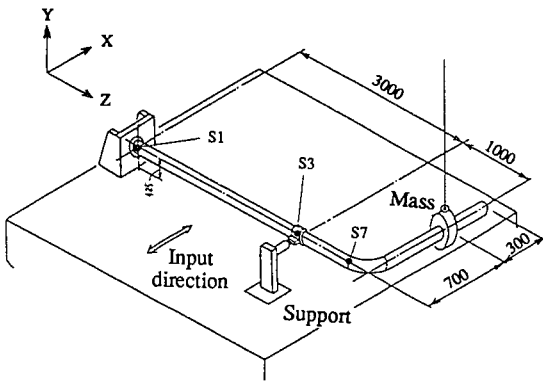


Fig. 4 Simple piping system

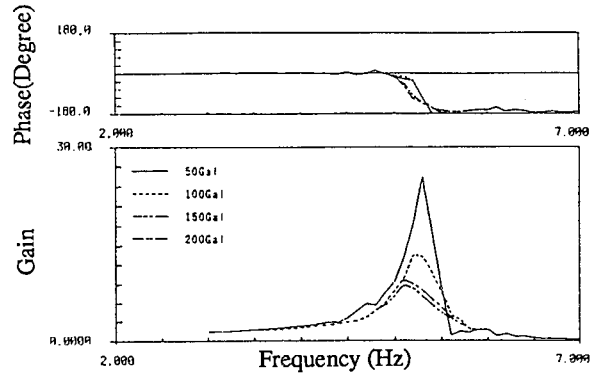


Fig. 5 Frequency transfer function of piping system

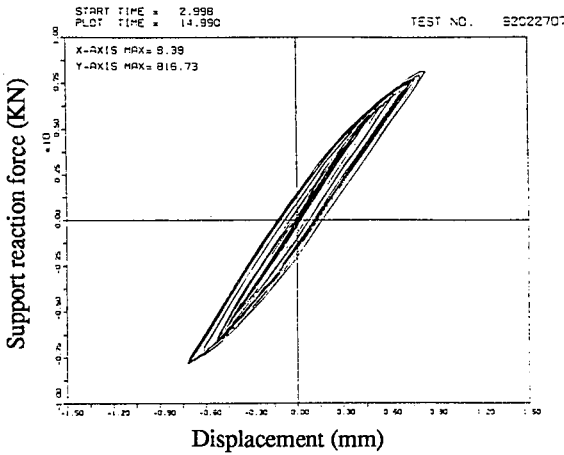


Fig. 6 Hysteresis loop (seismic wave A, 600Gal)

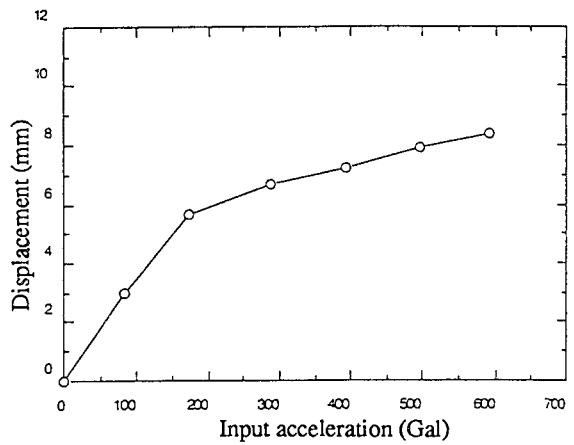


Fig. 7 Displacement - input acceleration curve (seismic wave A)

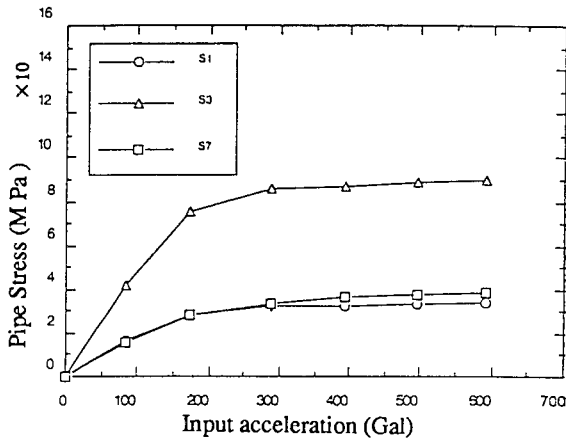


Fig. 8 Pipe stress - input acceleration curve (seismic wave A)

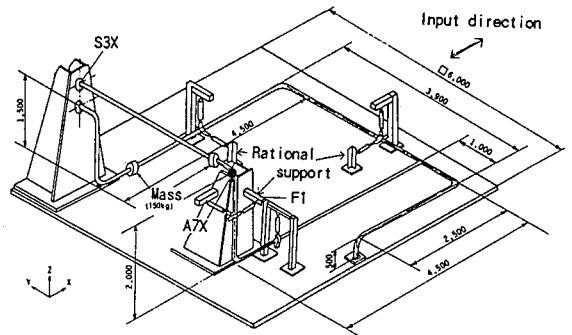


Fig. 9 Three dimensional piping system (rationalized model)

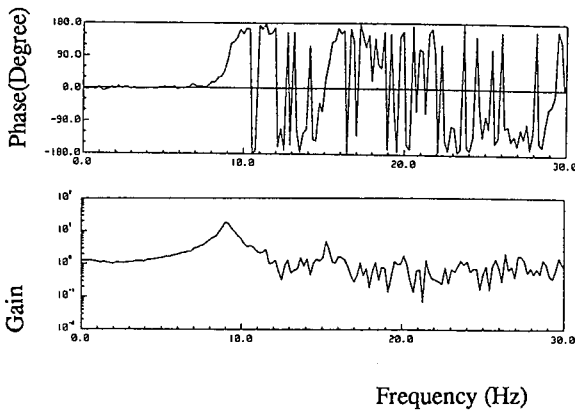


Fig. 10 Frequency transfer function of piping system (point A7X, 2000Gal)

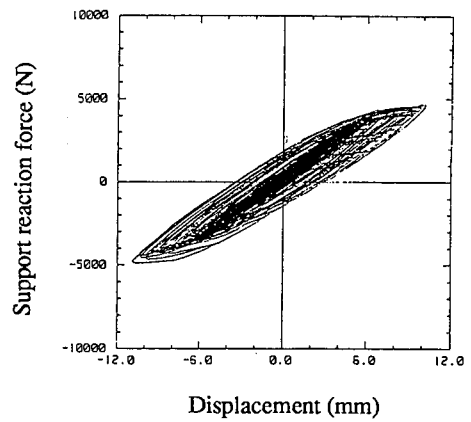


Fig. 11 Hysteresis loop (support F1)

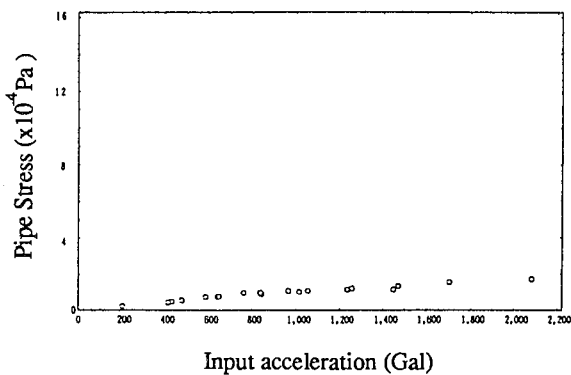


Fig. 12 Pipe stress - input acceleration curve (point S3X)

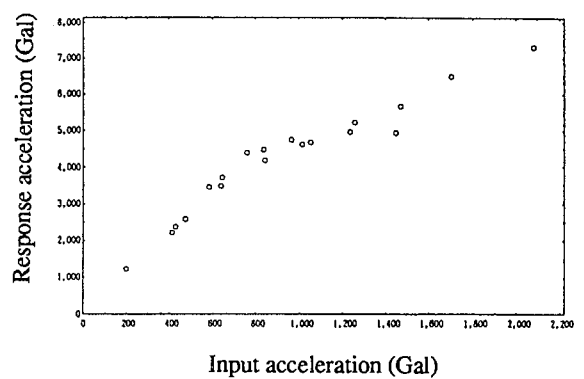


Fig. 13 Pipe response - input acceleration curve (point A7X)