The development of design method of nuclear piping system supported by elasto-plastic support structures (part2)

Endo, R.1, Murota, M.1, Kawahata, J-I.2, Sato, T.3, Hirose, J.4, Nekomoto, Y.4, Takayama, Y.5, Kobayashi, H.6
1) The Japan Atomic Power Co., Tokyo, Japan
2) Hitachi Works, Hitachi, Ltd., Ibaraki-ken, Japan
3) Toshiba Corporation, Yokohama, Japan
4) Mitsubishi Heavy Industries, Ltd., Nagasaki, Japan
5) Hitachi Engineering Co., Ltd., Ibaraki-ken, Japan
6) Ishikawajima-Harima Heavy Industries Co., Ltd., Yokohama, Japan

1. INTRODUCTION

The conventional seismic 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, research program was promoted to furthermore 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 had the following three stages. In the first stage, we selected conventional piping support structures in light-water reactors that exhibited elasto-plastic behavior, and studied the effect of displacement and the vibration frequency on the stiffness and on the energy absorption by testing these models. In the second stage, vibration tests were performed using piping models with support structures on shaking tables. The piping vibration characteristics were clarified by sinusoidal sweep tests and the piping response characteristics by seismic wave vibration tests when the support structures were in an elasto-plastic condition. In the third stage, a general method was developed to evaluate the characteristics of a variety of support structures in the tests. A simplified analysis method was also developed to evaluate the piping seismic response using the piping model test result. To expand the results mentioned above, we also established a new seismic design method of piping systems that allowed support structures to have elasto-plastic behavior.

This paper reports the newly developed seismic design method based on 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, Kyushu EPC) and nuclear plant makers (Hitachi Ltd., Toshiba Co., MHI Ltd., HEC Ltd. and IHI).

2. THE RESPONSE OF THE PIPING SYSTEM WITH RATIONAL SUPPORTS

2.1 Response characteristics of the piping system

Experiments using three dimensional piping system were performed to find the seismic response characteristics, and to obtain basic data for the development of a simplified seismic response analysis method for piping with elasto-plastic supports. Fig. 1 shows the rational test model as mounted on the shaking table. In this model, the elasto-plastic supports were made by using thin beams at three of the support points. These beams are L-angles with a thickness of 6 mm, and sides of 50 mm each.

A sinusoidal wave sweep test was performed to find the vibration characteristics. The first and second mode natural frequencies were 8.5 Hz and 9.7 Hz respectively, and the damping ratio was 1.2%. The next test was a random wave vibration test. Sufficiently high input acceleration levels were selected to ensure a nonlinear response in the system with elasto-plastic piping supports and the maximum acceleration was 2000 gal. During the vibration tests, the supports displayed stable energy absorption characteristics up to the maximum ductility factor of three. Due to these nonlinear effects, the natural frequency was reduced by 10% at the input acceleration level of 2000 gal, and the damping ratios were increased 3 ~ 4% up from the initial value of 1.2%. The relationship between support
reaction force and input acceleration is in Fig. 2. The response increase was proportional to the input accelerations for low inputs, however, in the high input range nonlinear behavior can be seen in the curve. This nonlinear phenomena is a feature of elasto-plastic response.

2.2 Comparison of the responses with a conventional piping system

Comparison of the responses was performed between two types of three dimensional piping system. One is the above rational scale model. The other is a conventional scale model with a support system based on a design providing rigid characteristics. Fig. 3 shows the conventional scale model mounted on a shaking table. This scale model has a support system including L-angles with a thickness of 10 mm, and sides of 100 mm each.

Sinusoidal wave sweep tests were performed to derive the vibration characteristics. The first natural frequency of the conventional scale model was 13.6 Hz, and that of the rational scale model was 8.5 Hz. Damping ratios of the conventional scale model were 0.5 ~ 1.4%, and those of the rational scale model were 3 ~ 4%.

Seismic vibration tests were performed with a random wave which had a dominant frequency to resonate at the natural frequency of the rational scale model. Seismic responses were compared at the input acceleration level 1000 gal as shown in Table 1.

In the rational scale model, response displacements and support reaction forces were higher than those of the conventional scale model, and supports displayed stable energy absorption characteristics up to ductility factor of one. Despite of this nonlinear behavior due to plasto-elastic supports, piping stress was found to be in elastic ranges.

Therefore, compared with the response of the conventional scale model, it was verified that the piping system including elasto-plastic supports was feasible for seismic design.

3. LIMITATION FOR SUPPORTS TO ALLOW THE ELASTO-PLASTIC BEHAVIOR

3.1 Support styles, materials and shapes of steel member section

Supports of following style are allowed to be in the elasto-plastic condition.

1. Support without brace
2. Support with the aspect ratio is greater than 0.4 and 1.2 (for gate type and frame type support, respectively)

By the experimental results, the force-displacement curve of supports with brace is generally complex by the buckling of compressed brace and their hysteresis loop is not stable in the seismic event. Therefore, the quasi-linear seismic analysis is not applicable for the piping system with such supports. The relationship between aspect ratio and stress ratio for frame type support is shown in Fig. 4. From this Fig., the aspect ratio may be greater than 1.2 in order to limit the elasto-plastic behavior within support anchor region and to prevent the permanent deformation at the horizontal and vertical beam connection.

The elasto-plastic behavior is allowed to the support with following material and shape of section.

1. SS400 and SM400A (JIS) for Angle steel, channel steel and H-steel
2. STKR400 (JIS) for square pipe

Supports of above material and shape of steel member section are used in the Japanese power plants and the elasto-plastic behavior was clarified by the support component test.

The support without above specified style, material and shape of section will be allowed to be in the elasto-plastic condition if it is stable, suitable to be used in the quasi-linear seismic analysis.

3.2 Estimation method of elasto-plastic behavior

The elasto-plastic characteristics (displacement dependency of stiffness and dissipation energy) of the support can be estimated for the quasi-linear seismic analysis by the following procedure.

1. Obtain the elasto-plastic behavior (static force-displacement curve) of the support by the elasto-plastic FEM analysis using beam or shell elements or the experiment.
2. Calculate the parameters of Ramberg-Osgood model which fit to the force-displacement curve obtained above.
3. Calculate the equivalent stiffness and the energy absorption for various displacement of the
support from the parameters of the best fit Ramberg-Osgood model.

The comparison of equivalent stiffness by the above mentioned analytical method and experimental results for cantilever type support is shown in Fig. 5. Good agreement is observed and this estimation method is confirmed to be applicable.

3.3 Limitation of support displacement at seismic event
In order to prevent the failure such by large deformation, buckling or fatigue of support in the seismic events, following displacement limitation was proposed from the experimental results of component test.

1. Max. support displacement is smaller than 2/3 of displacement when support stress reaches 1.0 Su.
2. The ductility factor (support displacement/yield one) is smaller than 3.0.

The limitation 1 still has the merit of elasto-plastic behavior of supports and has enough margin to support failure as shown in Fig. 6. The limitation 2 also has the margin of 5 in the strain, and of 14 in the cycle number for fatigue failure.

4. SEISMIC ANALYSIS METHOD
4.1 Establishment of an equivalent linear analysis method
As a simplified analysis method for nonlinear piping system with elasto-plastic characteristics in its supports, the equivalent linear analysis method based on the floor response spectrum modal analysis method was developed. It applies the response spectra corresponding to each mode’s damping ratio.

The equivalent linear analysis process is shown in Fig. 7. First, by using postulated displacements of elasto-plastic supports, equivalent stiffness*1 and every absorption of each support are calculated. Then eigen value analysis is conducted using the equivalent stiffness, and damping ratio of each mode is calculated using the energy absorption. Finally, floor response analysis is conducted using eigen value, mode vector, participation factor and floor response spectrum with damping ratio of each mode. The sequence of analyses is iterated until a calculated support displacement becomes equal to the postulated displacement.

*1 Equivalent stiffness: The tangent represented by load/displacement; where the load and the displacement are values at a certain point on load-displacement curve of an elasto-plastic support

4.2 Results of the equivalent linear analysis
To confirm the effectiveness of the equivalent linear analysis, the analysis results were compared with those of the seismic wave vibration test performed before.

The piping system model for the analysis is shown in Fig. 8. It is two-dimensional piping system which uses a square pipe as an elasto-plastic support. The input seismic wave has a dominant frequency that resonated at the natural frequency of piping system. The piping system, the input wave, and other conditions are the same as the test.

The comparison of response displacement-input acceleration curve of the test and the analysis is shown in Fig. 9. The analysis results have good agreement with the test results, so it is found that this analysis method is effective in predicting seismic response of piping system with elasto-plastic supports.

4.3 Condition for application
4.3.1 Condition of analysis method
The values of stiffness ratio of support to pipe*2 and damping ratio of each mode of piping system have an influence on errors in the equivalent linear analysis results. Therefore, limitations of the stiffness ratio and the damping ratio were studied by analyzing a simple beam with an elasto-plastic support in its center.

A study procedure is that both nonlinear analysis and the equivalent linear analysis of the beam are made, and ranges of the stiffness ratio and damping ratio, in which the difference of calculated displacements between two analyses is very small, are determined.

As a result, the limitations for application of the equivalent linear analysis are set up as below.
• Stiffness ratio of support to pipe < 30
• Damping ratio of each mode < 30%

Stiffness ratio of support to pipe : Elastic stiffness of the elasto-plastic support/stiffness of the piping system at the supporting point

4.3.2 Environmental condition
Environmental condition for the application of the analysis method shall be under the condition of Japanese light-water reactors now in use. Temperature condition shall be below 93°C which is the long-term temperature after loss of coolant accident in PCV (PWR: 60°C, BWR: 93°C), since it is the highest temperature in operating condition combined with earthquake.

5. RESTRICTION TO PIPING SYSTEM
5.1 Stress evaluation
Stress evaluation of piping is performed by “MITI Notification 501” and “Technical Guideline for Aseismic Design of Nuclear Power Plant. JEAG-4601 Supplement-1984”.

5.2 Restriction
a. Natural frequency and response of piping system
• The lower limit of natural frequency for piping system should be no less than 1 Hz.
• Response displacement and reaction force to components should be less than the allowable limits specified in design.

b. Scope of the application for elasto-plastic support
Elasto-plastic support is not allowed to use for the following piping system.
• Piping system where flow induced vibration will be anticipated.
• Piping system where mechanical load such as water hammer will be presumed.

c. Load limits of elasto-plastic support
Load limits of elasto-plastic support is as follows.
• Seismic inertia load: $F_p \ldots F_p > F_y$
• $F_y$ : Load where support stiffness will initiate to reveal nonlinearity.
• Load the other than seismic load : $F_1 \ldots F_1 < F_y$

6. CONCLUSIONS
The following conclusions were obtained from the results of experiments and analysis of piping systems that allow support structures to exhibit elasto-plastic behavior.

(1) We clarified typical support styles, shapes of steel member section and sizes of support structures that exhibit elasto-plastic behavior. We also established the evaluation method of elasto-plastic behavior for support elements by using Ramberg Osgood model.

(2) The equivalent linear analysis method and nonlinear time history analysis method were applied to evaluate piping seismic response for dynamic seismic waves. We confirmed that the elasto-plastic analysis method was applicable to the piping systems by comparing analytical results with experimental results.

(3) We established the strength limit of elasto-plastic piping supports concerning support failure modes (large displacement, buckling, fatigue, etc.).

7. REFERENCE
R. Endo et. al., The development of design method of nuclear piping system supported by elasto-plastic support structure (part 1), Transaction of the 12th international conference on structural mechanics in reactor technology, K20/1, P193–198, Aug., 1993.
Table 1 Comparison of the maximum responses

<table>
<thead>
<tr>
<th>ITEM</th>
<th>CONVENTIONAL SCALE MODEL</th>
<th>RATIONAL SCALE MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>POINT (DIRECTION) VALUE</td>
<td>POINT (DIRECTION) VALUE</td>
</tr>
<tr>
<td>DISPLACEMENT</td>
<td>DS (X) 2.1mm</td>
<td>DS (X) 11.4 mm</td>
</tr>
<tr>
<td>SUPPORT REACTION FORCE</td>
<td>F3 (X) 232N</td>
<td>F1 (X) 469N</td>
</tr>
<tr>
<td></td>
<td>F4 (X) 276N</td>
<td>F3 (X) 363N</td>
</tr>
</tbody>
</table>

Fig. 1 3 dimensional piping system (Rational Model)

Table 2 Displacement limitation to prevent the break of support

<table>
<thead>
<tr>
<th>Support size and type</th>
<th>Yield (mm)</th>
<th>1.0%Es (mm)</th>
<th>Allowable 1.0%Es/1.5 (mm)</th>
<th>Max. of test (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Cantilever</td>
<td>3.5 – 4.0</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>100</td>
<td>Cantilever</td>
<td>5.2</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>50</td>
<td>Frame</td>
<td>3.9 – 4.5</td>
<td>42</td>
<td>28</td>
</tr>
<tr>
<td>100</td>
<td>Frame</td>
<td>3.5</td>
<td>29</td>
<td>19</td>
</tr>
<tr>
<td>Square pipe</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>Cantilever</td>
<td>2.5 – 3.0</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>100</td>
<td>Cantilever</td>
<td>3.0</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>50</td>
<td>Frame</td>
<td>2.4 – 3.0</td>
<td>25</td>
<td>19</td>
</tr>
<tr>
<td>100</td>
<td>Frame</td>
<td>2.2</td>
<td>25</td>
<td>19</td>
</tr>
</tbody>
</table>

Fig. 2 Relationship between reaction force and input acceleration

Fig. 3 3 dimensional piping system (Conventional model)

Fig. 4 Relationship between stress ratio and aspect ratio for the frame type support
Fig. 5  Relationship between stiffness and displacement

Fig. 6  Force - displacement curve for cantilever type support

Fig. 7  Equivalent linear analysis process

Fig. 8  Piping system model for the analysis

Fig. 9  Response displacement - input acceleration curve