Basic study on dynamic reliability of machinery and piping system supported by elasto–plastic supports

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Abstract

Recently, probabilistic evaluation has been required in the seismic design. In this study, a design method of piping system supported by elasto–plastic damper based on dynamic reliability of pipings was proposed. First, an analytical model of an L-type cantilevered piping system with weight at the top end subjected to seismic input was derived, considering the nonlinear characteristics of the elasto–plastic dampers. Installation of a lead extrusion damper (LED) was assumed as the elasto–plastic damper. The force–displacement relationship of the LED was given by a bilinear hysteretic curve. Seismic input was modeled as white Gaussian noise. The vibration behaviors were calculated for various seismic inputs, and the stress and the energy absorption were calculated. On the basis of the results, the evaluation indices, such as the dynamic reliability, the energy absorption ratio, and the balance of energy absorption, were calculated. Finally, optimization of the support locations was investigated on the basis of the viewpoint of the dynamic reliability. In addition, the effects of the capacities of the two supports on the evaluation index are also investigated. As a result, $J_{\text{piping}}$ was highest when Node 10 was supported at B. $J_{\text{energy}}$ was higher when Supports A and B were close to the weight but a little apart from each other. $J_{\text{balance}}$ was lower when Supports A and B were close to each other. Furthermore, it was obtained that the effect of Support B capacity on the response behavior of pipings is larger than that of Support A capacity.

Key words: Dynamic reliability, Piping systems, Elasto–plastic damper, Absorbed energy, White Gaussian noise, Optimization

1. Introduction

Large–scale earthquakes occurring around the world have increased the importance of designing earthquake–proof machines and structures. Conventional seismic design is based on deterministic theory, where the responses of structures are calculated assuming some types of seismic inputs. However, there is a risk that very large earthquakes may occur in the future that damage structures or cause them to fail. Hence, an earthquake–proof design based on the stochastic approach is required to evaluate the risk of failure or damage. Up to now, characteristics of probability density function based on the Fokker–Planck equation is derived and first passage destruction probability is derived analytically (Aoki et al., 1983; Aoki, 1992; Mochio, 1989; Mochio, 1993). However, it is not easy to derive the destruction probability of the nonlinear large–scale structures analytically.

On the other hand, various types of industrial plants such as chemical, thermal power and nuclear power plants contain numerous piping systems, which are generally supported by many supporting devices. Maintaining the structural integrity of such piping systems is very important to protect them against failure or damage in the event of a seismic disaster. Recently, various types of high damping supports that exhibit strong nonlinearity, i.e., elasto–plastic dampers, have been applied to large–scale piping systems to reduce plant construction costs. These elasto–plastic dampers are designed to absorb vibration energy effectively. Various researchers have considered the vibrational behavior of piping systems based on its energy absorption (Kobayashi, 1987; Fujita et al., 1991; Namita et al., 1995a; Namita et al., 1995b; Ito et al., 2003; Fujita et al., 2004). However, this energy absorption may cause fatigue or increase the temperature of the
elasto–plastic dampers. In the worst cases, excessive energy absorption may cause a loss in support functions owing to the failure or melting of support devices, which subsequently causes failure of the piping systems. Therefore, in the seismic design of piping systems supported by elasto–plastic dampers, the integrity of both the supporting devices and the piping systems must be considered. Previously, we investigated the optimal vibration–proof design for piping systems supported by elasto–plastic dampers subjected to a deterministic seismic input (Ito et al., 2009; Ito et al., 2010).

Furthermore, recently, seismic design methods using the probabilistic characteristics such as dynamic reliability are required by the simple numerical simulation. Hence, optimal vibration–proof design based on probabilistic theory considering probabilistic deviation in the seismic inputs and both the integrity of the I-type piping systems and the supporting devices were also investigated by simulation analysis (Shintani et al., 2013a; Shintani et al., 2013b).

In this study, this probabilistic seismic design method by the simulation was proposed to the L-type piping system supported by elasto–plastic dampers which moves in three directions. An analytical model of an L-type piping system supported by elasto–plastic dampers was constructed. A lead extrusion damper (LED) was used as the elasto–plastic damper. The responses of the piping system subjected to white Gaussian noise were calculated. We introduced three evaluation indices: dynamic reliability of piping, energy absorption ratio, and balance of energy absorption. Numerical simulations were performed to investigate the effects of the support position and the support capacity.

2. Analytical Model

We used an analytical model to represent a two–dimensional L-type cantilevered piping system, as shown in Fig. 1. The piping system is represented by beam elements. A weight is attached to the free end of the beam to represent the valves, etc. The fixed end of the beam is subjected to the seismic input acceleration $\ddot{z}(t)$, which is subjected to the X axis, the out–of–plane direction of the L-type piping system. A piping system subjected to the input $\ddot{z}(t)$ moves in three directions because of the asymmetry of the piping. The piping is supported by two elasto–plastic dampers at two points of the piping. In this study, we adopted an LED as a typical elasto–plastic damper.

![Fig. 1 Analytical model of L-type cantilevered piping system with a weight. The fixed end of the beam is subjected to the seismic input acceleration $\ddot{z}(t)$, which is subjected to the X axis, the out–of–plane direction of the L-type piping system.](image)

The force–displacement relationship of an LED is expressed by the bilinear model shown in Fig. 2. In this study, we maintained the first and second stiffness coefficients $k_{1st}$ and $k_{2nd}$ of the elasto–plastic damper constant on the basis of...
3. Evaluation Index

Three types of evaluation indices were considered: (a) dynamic reliability of the piping systems based on stress, (b) energy absorption ratio, and (c) balance of energy absorption.

3.1. Evaluation of Dynamic Reliability of Piping Systems Based on Stress

The integrity of the piping systems was evaluated according to their dynamic reliability based on stress. We employ the first passage probability in the dynamic reliability. In the first passage probability, it is checked whether the response of the system exceeds the limit value such as the tolerance level of stress or not. If the response exceeds the limit value at least once, the system is regarded as destroyed. If not so, the system is regarded as healthy. The evaluation index of the stress of the piping systems $J_{piping}$ is defined as their reliability derived from the first passage probability when the tolerance level of stress $\sigma_{tol}$ is the proof stress of a high–pressure carbon–steel pipe STPG370 (i.e. 215 MPa). Concrete calculation method is described later. This evaluation index should be large because it represents the percentage of responses of healthy piping out of all the piping sample responses.
3.2. Evaluation of Energy Absorption Ratio

For structural damping, the elasto–plastic support should absorb as much seismic input energy as possible. This analytical model has two mounted support A and B, where A is the support closer to the fixed end. Higher energy absorption ratio $E_{ab}/E_{in}$ , where $E_{ab}$ is the absorbed energy and $E_{in}$ is the seismic input energy, means that the response displacement of the piping systems decreases significantly and that the supports work well. Thus, the ratio of energy absorption $E_{ab}$ to the seismic input energy $E_{in}$ should be increased. Because the absorbed energies at Supports A and B, $E_{abA}$, $E_{abB}$, and $E_{in}$ are strictly stochastic processes, we employed their mean values. The evaluation index of the energy absorption by the elasto–plastic dampers $J_{energy}$ is defined by Eq. (3), where $J_{energyA}$ and $J_{energyB}$ are given by Eqs. (4) and (5), respectively.

$$J_{energy} = J_{energyA} + J_{energyB} = \frac{\bar{E}_{abA} + \bar{E}_{abB}}{\bar{E}_{in}},$$

$$J_{energyA} = \frac{\bar{E}_{abA}}{\bar{E}_{in}},$$

$$J_{energyB} = \frac{\bar{E}_{abB}}{\bar{E}_{in}}.$$  

Here, $\bar{E}_{abA}$, $\bar{E}_{abB}$, and $\bar{E}_{in}$ are the mean values of $E_{abA}$, $E_{abB}$, and $E_{in}$, respectively. Furthermore, $E_{abA}$ and $E_{abB}$ are calculated by the following equations:

$$E_{abA} = \int_{0}^{t_e} F \left| |_{supportA} \right. dx = \int_{0}^{t_e} F \left| |_{supportA} \right. \ dt,$$

$$E_{abB} = \int_{0}^{t_e} F \left| |_{supportB} \right. dx = \int_{0}^{t_e} F \left| |_{supportB} \right. \ dt,$$

where $t_e$ is the earthquake duration. This evaluation index represents the ratio of the absorbed energy to the input energy, and therefore a large value is desirable.

3.3. Evaluation of Balance of Energy Absorption

When two supports are used, a large load may be concentrated on a specific support. The specific support may then become damaged, leading to decreased functionality, and the other support does not act most of the time. Therefore, a safe design prevents a large load on a particular support. The evaluation index for the balance of energy absorption $J_{balance}$ is defined by Eq. (8):

$$J_{balance} = \left| J_{energyA} - J_{energyB} \right|.$$  

This evaluation index should be small, in contrast to the other evaluation indices, because a small difference between the energy absorption ratios at the two supports is desired.

4. Simulation Conditions

4.1. Parameter Dimensions

The parameters of the analytical model were the following values: the length of the cantilever piping systems $L = 8.0 \ (= 4.0 + 4.0)$ m, the length of the beam elements $l = 0.8$ m, the cross–sectional area $A = 1.445 \times 10^{-3}$ m², the diameter of the beam elements $d = 89.1 \times 10^{-3}$ m, Young’s modulus $E = 1.920 \times 10^{11}$ Pa, the modulus of rigidity $G = 7.39 \times 10^{10}$ Pa, the second moment of area $I = 1.27 \times 10^{-6}$ m⁴, the torsional constant $K_t = 2.54 \times 10^{-6}$ m⁴, density $\rho = 7850$ kg/m³, the mass of the attached weight $M_{at} = 100$ kg, the moment of inertia of the attached weight in the X-direction $I_{WX} = 0.94$ kg·m², the moments of inertia of the attached weight in the Y and Z directions $I_{WY} = 0.27$ kg·m² and $I_{WZ} = 0.94$ kg·m², respectively. The first and second natural frequencies without support (in X-direction) are $f_1 = 0.64$ Hz and $f_2 = 3.59$ Hz, and the first and second damping ratios without support are $\xi_1 = 0.008$ and $\xi_2 = 0.008$. The first and second mode shapes for an L-type piping system without supports are shown in Fig. 3. The free end vibrates largely in the first mode. The corner at the center vibrates largely in the second mode. The first and second stiffness coefficients are $k_{1st} = 6.817 \times 10^6$ N/m and $k_{2nd} = 3.158 \times 10^5$ N/m, respectively.
4.2. Input Wave

In this study, 50 samples of white Gaussian noise with a narrow band 0–10 Hz and a power spectral density of 0.1 were used as the seismic acceleration input wave. The duration of the input excitation $t_e$ is 30 s. Figure 4 shows a sample time history. Because white Gaussian noise contains a wide range of frequency components, it is considered that the piping subjected to white Gaussian noise will show worse results than that subjected to an seismic waves that have a predominant frequency component, such as an actual seismic wave. Therefore, we employed narrowband white Gaussian noise in this study.

![Fig. 4 Input acceleration. White Gaussian noise contains waves with a narrow band 0–10 Hz and a power spectral density of 0.1.](image)

4.3. Calculation Method of Dynamic Reliability

It is difficult to calculate the reliability $J_{piping}$ analytically in the nonlinear system. Hence, in this study, the following calculation is carried out: responses of stress for 50 inputs are calculated. Letting the limit value as the tolerance level of stress $\sigma_{\text{tol}}$, we investigate whether the response of stress exceeds the tolerance level of stress. If the response does not exceed the tolerance level, we make a decision that the piping is not destroyed or is healthy. If the response exceeds the tolerance level, we investigate the time instant when the response exceeds the tolerance level first. We make a decision that the piping is destroyed after that time instant. From this result, we define the ratio of the number of cases in which piping is healthy out of all cases of the piping responses as $J_{piping}$.

5. Simulation Results

5.1. Effects of Support Locations on Each Evaluation Index

In this subsection, the effect of the support location on each evaluation index is presented. The support capacities of Supports A and B were each fixed as 300 N.

5.1.1. $J_{piping}$: The dynamic reliability of the piping was evaluated. The effect of the support locations on $J_{piping}$ was investigated. Figure 5 shows the effect of the locations of Supports A and B on $J_{piping}$. We consider only the half plane on the Support A-B plane because Support A is set closer to the fixed end than Support B is. Table 1 presents the optimized results.

The figure shows that $J_{piping}$ was highest when Support B is at Node 10. In this simulation, the attached weight (100
kg) had a larger weight than the piping (90 kg) itself. Hence, the displacement of the piping decreased when Support B was located at Node 10.

As demonstrated in the table, the sample mean of the maximum stress generated in the piping for 50 inputs under the optimal condition (Support A: Node 8, Support B: Node 10) (182 MPa) was less than the stress tolerance level of 215 MPa, which is the proof stress of a high-pressure carbon–steel pipe STPG370.

5.1.2. \( J_{\text{energy}} \): \( J_{\text{energy}} \) is the ratio of the absorbed energy to the input energy. Here, the effect of the support location on \( J_{\text{energy}} \) is shown in Fig. 6. The optimized results are presented in Table 2. The figure shows that \( J_{\text{energy}} \) was highest when Support B is at Node 10.

On the basis of the results in Tables 1 and 2, the ratio of the absorbed energy to the input energy \( J_{\text{energy}} \) (= \( E_{\text{ab}}/E_{\text{in}} \)) was higher when Supports A and B were close to the weight but a little apart from each other.

5.1.3. \( J_{\text{balance}} \): \( J_{\text{balance}} \) is the difference between the ratios of the absorbed energy by the two supports. Figure 7 shows the effect of Supports A and B on \( J_{\text{balance}} \). Table 3 presents the optimized results. \( J_{\text{balance}} \) should be small, in contrast to the other evaluation indices, because a smaller difference between the energy absorption ratios by the supports is preferable for the supports in order that the two supports works equally and the specific support does not become

<table>
<thead>
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<th>Item</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of Support A</td>
<td>—</td>
<td>Node 8</td>
<td>—</td>
</tr>
<tr>
<td>Location of Support B</td>
<td>—</td>
<td>Node 10</td>
<td>—</td>
</tr>
<tr>
<td>Absorbed energy of supports</td>
<td>( E_{\text{ab}} )</td>
<td>1008</td>
<td>J</td>
</tr>
<tr>
<td>Seismic input energy</td>
<td>( E_{\text{in}} )</td>
<td>1143</td>
<td>J</td>
</tr>
<tr>
<td>Maximum stress</td>
<td>( \sigma_{\max} )</td>
<td>182</td>
<td>MPa</td>
</tr>
<tr>
<td>Reliability of piping</td>
<td>( J_{\text{piping}} )</td>
<td>0.87</td>
<td>—</td>
</tr>
<tr>
<td>Energy absorption ratio</td>
<td>( J_{\text{energy}} )</td>
<td>0.88</td>
<td>—</td>
</tr>
<tr>
<td>Balance of absorption</td>
<td>( J_{\text{balance}} )</td>
<td>0.07</td>
<td>—</td>
</tr>
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</table>
damaged. As shown in Fig. 7, \( J_{\text{balance}} \) was lower when Supports A and B were close to each other. This is because the piping behaviors at the two supports are similar when they are located close to each other. Under the optimal conditions (Support A: Node 3, Support B: Node 7), Support A absorbed 148 J, and Support B absorbed 151 J on the basis of Eqs.(6) and (7), respectively. Thus, the supports absorbed energy almost equally. However, the maximum stress when \( J_{\text{balance}} \) was considered (310 MPa) was higher than the stress tolerance level (215 MPa). The reliability of the piping is not guaranteed when only \( J_{\text{balance}} \) is considered. Further, the ratio of energy absorption at the two supports when only \( J_{\text{balance}} \) was considered as the evaluation index (\( J_{\text{energy}} = \frac{299}{647} = 0.46 \)) was less than that when only \( J_{\text{energy}} \) was considered as the evaluation index (\( J_{\text{energy}} = \frac{825}{904} = 0.91 \)). Therefore, considering only \( J_{\text{balance}} \) cannot guarantee the reliability of the piping system or increase the absorption ratio at the two supports. When only one index was considered, all of the individual reliabilities of the piping, energy absorption ratio, and balance of energy absorption were not optimized. Hence, the three indices should be considered simultaneously. A composite evaluation index is desirable to solve this problem.

In the reference (Ito et al., 2010), the optimization of the support location and support capacity for the L-type piping system subjected to the various type of seismic input is performed on the basis of the deterministic approach. In this method, the two supports are set apart from each other after optimization (one is the fixed end side and the other is the free end side). In our proposed method, similar piping system are employed, however after optimization the two supports are set close to the free end comparing to reference’s method. Since the optimization of the support capacity is not performed in this proposed method, it is difficult to compare two methods simply. However, it is considered that in the proposed method, two supports are set on free end side relatively by putting a high priority on supporting the attached weight when supporting the piping system subjected to various input wave.

If the characteristics of the input wave are assumed preliminary, the optimization can be achieved in the reference’s method. However, to assume the type of the seismic input preliminary is difficult. In our proposed method, optimization can be achieved without assuming the input wave type because the various waves are considered as the input (in this case 50 samples), and dynamic reliability derived from the probability and the mean value of the absorbed energy ratio are used as the indices.

5.2. Effect of Support Capacity

In this subsection, we consider the effects of the support capacity on each evaluation index.

5.2.1. Effect of Support A

We fixed the capacity of Support B as 500 N and consider the two cases of 100 and 500 N for Support A. The results of the reliability of piping \( J_{\text{piping}} \) are shown in Fig. 8. Comparing Figs. 8(a) and (b), when the support capacity of A increases, the reliability slightly increases.

An example of the stress distribution is shown in Fig. 9 in the case of Support A attached to Node 9, Support B attached to Node 10, where the difference between Figs. 8(a) and (b) is largest. From this figure, when the support capacity increases, the maximum stress acting on the pipings becomes small. This is because the piping is fixed solidly at Node 9 by Support A. At Node 9, the vibration amplitude is large and Support A is located close to the weight. As a result, the reliability increases.

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of Support A</td>
<td>—</td>
<td>Node 3</td>
<td>—</td>
</tr>
<tr>
<td>Location of Support B</td>
<td>—</td>
<td>Node 7</td>
<td>—</td>
</tr>
<tr>
<td>Absorbed energy of supports</td>
<td>( E_{\text{ab}} )</td>
<td>299</td>
<td>J</td>
</tr>
<tr>
<td>Seismic input energy</td>
<td>( E_{\text{in}} )</td>
<td>647</td>
<td>J</td>
</tr>
<tr>
<td>Maximum stress</td>
<td>( \sigma_{\text{max}} )</td>
<td>310</td>
<td>MPa</td>
</tr>
<tr>
<td>Reliability of piping</td>
<td>( J_{\text{piping}} )</td>
<td>0</td>
<td>—</td>
</tr>
<tr>
<td>Energy absorption ratio</td>
<td>( J_{\text{energy}} )</td>
<td>0.46</td>
<td>—</td>
</tr>
<tr>
<td>Balance of absorption</td>
<td>( J_{\text{balance}} )</td>
<td>0.01</td>
<td>—</td>
</tr>
</tbody>
</table>
Fig. 8  Effect of capacity of Support A on $J_{pipe}$. $F_y$ is fixed as $F_y = 500$ N. When the support capacity of A increases, the reliability slightly increases.

Fig. 9  Effect of capacity of Support A on piping stress in the case of Support A attached to Node 9, Support B attached to Node 10. When the support capacity increases, the maximum stress acting on the pipings becomes small.

The results of the absorbed energy ratio $J_{energy}$ are shown in Fig. 10. Comparing Figs. 10(a) and (b), large differences in the distribution of $J_{energy}$ cannot be seen. The accumulated absorbed energy slightly decreases (or slightly increases) when the support capacity increases. Furthermore, when the support capacity increases, the input energy also decreases (or increases) similarly. Hence, it is considered that the absorbed energy ratio remains almost constant.

Fig. 10  Effect of capacity of Support A on $J_{energy}$. $F_y$ is fixed as $F_y = 500$ N. Large differences in the distribution of $J_{energy}$ cannot be seen when the support capacity increases.

The results of the balance of the absorbed energy $J_{balance}$ are shown in Fig. 11. Comparing Figs. 11(a) and (b), when the support capacity of A increases, there are two cases; one where the difference in the absorbed energy becomes large and the other where the difference becomes small.

We consider the case of Support A attached to Node 4, Support B attached to Node 10 (hereafter, we call this Case 1) where $J_{balance}$ largely decreased from 100 to 500 of $F_y$. The time evolution of the accumulated absorbed energy is shown in Fig. 12. The green and red lines show the absorbed energies at Supports A and B. When the support capacity at A increases, the absorbed energy by support at A increases and the absorbed energy by support at B decreases, the absorbed
energies at two supports become similar, and as a result, $J_{\text{balance}}$ becomes small.

Fig. 11  Effect of capacity of Support A on $J_{\text{balance}}$. $F_{yB}$ is fixed as $F_{yB} = 500$ N. When the support capacity of A increases, there are two cases; one where the difference in the absorbed energy becomes large and the other where the difference becomes small.

Figures 13 and 14 show the hysteretic curves of Supports A and B. From these figures, when the support capacity increases, Support A works effectively; from Fig. 14, it is noted that large difference in the hysteretic curve of Support B cannot be seen.

Fig. 13  Effect of capacity of Support A on hysteretic curve of Support A (Case 1). When the support capacity increases, Support A works effectively.

On the other hand, consider the case of Support A attached to Node 6, Support B attached to Node 10, where $J_{\text{balance}}$ largely increased from 100 to 500 of $F_{yA}$ (we call this Case 2). Figure 15 shows the time evolution of the accumulated energies. The green and red lines show the absorbed energies at Supports A and B, respectively. When the support capacity of A increases, the absorbed energy at A does not change, and hence the absorbed energy at B increases. As a result, $J_{\text{balance}}$ increased.
5.2.2 Effect of Support B We fixed the capacity of Support A as 100 N and consider two cases on Support B capacity; 100 and 500 N. The results of the reliability of piping $J_{pipe}$ are shown in Fig. 16. Comparing Figs. 16(a) and (b), when the support capacity at B increases, the reliability increases. An example of the stress distribution is shown in Fig. 17 in the case of Support A attached to Node 9, Support B attached to Node 10. From Fig. 17, it is found that the piping stress for the capacity $F_{yB} = 500$ N is smaller than that for $F_{yB} = 100$ N. The reason why the reliability of the piping at $F_{yB} = 100$ N is smaller is that Support B close to the weight attached to the free end cannot sufficiently support the piping and the attached weight by the capacity of 100 N.

![Diagram](image_url1)

Fig. 14 Effect of capacity of Support A on hysteretic curve of Support B (Case 1). Large difference in the hysteretic curve cannot be seen.

![Diagram](image_url2)

Fig. 15 Effect of capacity of Support A on accumulated energy (Case 2: the case of Support A attached to Node 6, Support B). When the support capacity of A increases, the absorbed energy at A does not change, and hence the absorbed energy at B increases. As a result, $J_{balance}$ increased.

![Diagram](image_url3)

Fig. 16 Effect of capacity of Support B on $J_{pipe}$. $F_{yA}$ is fixed as $F_{yA} = 100$ N. When the support capacity at B increases, the reliability increases.
The results of the absorbed energy ratio $J_{\text{energy}}$ are shown in Fig. 18. Comparing Figs. 18(a) and (b), the ratio of the absorbed energy increases when the capacity at Support B increases. The time evolution of the accumulated absorbed energy is shown in Fig. 19 in the case of Support A attached to Node 2, Support B attached to Node 10. From this figure, it is evident that when the capacity at Support B increases, the accumulated energy of Support A decreases slightly; however, because the accumulated energy of Support B increases significantly, the total accumulated energy of the two supports increases.

The results of the balance of the absorbed energy $J_{\text{balance}}$ are shown in Fig. 20. Comparing Figs. 20(a) and (b), when the capacity of Support B increases, the difference in the absorbed energies increases. This is because similar to the case of $J_{\text{energy}}$, the absorbed energy at Support B increases significantly, when the capacity of Support B increases. From these results, we conclude that the effect of Support B capacity on the response behavior of pipings is larger than that of Support A.
A capacity, and hence Support B is more important than Support A.

6. Conclusion

The vibrational behavior of piping systems supported by elasto–plastic dampers subjected to white Gaussian noise was considered. The seismic design method was proposed on the basis of the dynamic reliability. We introduced and calculated three evaluation indices $J_{\text{piping}}$, $J_{\text{energy}}$, and $J_{\text{balance}}$. $J_{\text{piping}}$ was highest when Node 10 was supported at B. $J_{\text{energy}}$ was higher when Supports A and B were close to the weight but a little apart from each other. $J_{\text{balance}}$ was lower when Supports A and B were close to each other. However, when only one index was considered, all of the individual reliabilities of the piping, energy absorption ratio, and balance of energy absorption were not satisfied. Hence, a composite evaluation index of these is desirable to solve this problem. Furthermore, it was concluded that the effect of Support B capacity on the response behavior of pipings is larger than that of Support A capacity. In proposed method on the basis of the dynamic reliability, optimization can be achieved without assuming the input wave type. Such stochastic approach will become more needed.

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