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Division V

NUMERICAL EXAMINATION ON SEISMIC RESPONSE BEHAVIOR OF A PIPING SYSTEM CONSIDERING PLASTIC DEFORMATION OF SUPPORTS

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ABSTRACT

Considering the mitigation of serious damage to important components under the beyond design basis event (BDBE), a concept of fracture control was proposed in the previous study. To apply this concept to the piping system, the effect of the elasto-plastic behavior of the piping support structure on the seismic response of the piping system was investigated through elasto-plastic time history response analyses on a piping system model having multiple support structures. In the numerical analyses, the elast-plastic behavior of supports and/or the inelastic characteristics of pipe material were considered. From the analysis results, it was confirmed that the response of piping system can be suppressed by introducing the inelastic behavior of support structures. The results show the possibility to realize the application of fracture control to piping systems.

INTRODUCTION

After the Fukushima Dai-ichi Nuclear Power Plant accident in 2011, the importance of consideration for beyond design basis event (BDBE) is widely recognized. Structures are designed to maintain their integrity under the design basis event (DBE). It means that any failure is not expected in the DBE condition. In contrast to the DBE, some minor failure may be acceptable in the BDBE, when it mitigates the serious damage of important structures and prevent the consequence of accident. Based on such idea, the concept of fracture control is proposed as the countermeasure for the BDBE (Kasahara, et al, 2020). Taking the piping systems as an example, boundary failure should be prevented under the BDBA condition, whereas the minor failure, such as support failure which does not affect the function of the piping system, can be acceptable.

The inelastic response behavior of piping systems under excessive seismic input have been intensively studied through experimental and numerical studies (Fujita et al. (1978), Tagart et al. (1990), Nakamura et al. (2010), Papatheocharis et al. (2013), Varelis et al. (2013), Ravikiran et al. (2015), Shibutani et al. (2015)). However, previous investigations mainly focused on the inelastic response characteristics of piping systems themselves, and the influence of behavior of supports were not so emphasized, though supports may affect the response characteristics of piping systems especially under severe seismic input which may invoke the inelastic behavior of supports. The effect of inelastic behavior of supports on the piping system's dynamic response have not yet been clarified.

As the first step of the investigation on the seismic response behavior of piping system with supports, numerical examination on a piping system by Finite Element Method (FEM) analysis were conducted. In this paper, the analytical results are described in which the elastic-plastic behavior of support structure as well as that of pipe material were considered.

ANALYSIS CONDITIONS

Piping System

The piping system configuration in this study was modelled on the piping system specimen for a shaking table test conducted by NUPEC (Nuclear Power Engineering Corporation) (Suzuki and Abe (2005)). Figure 1 shows the outline of the piping system in the NUPEC test. The piping system model included nine elbows and one tee, three anchors, five support position, and one additional mass. The category of the pipe was a carbon steel STS410 (Carbon steel pipes for high pressure service (Japan Industrial Standards (2016)), and the size was 200Asch40 (Outer diameter: 216.3 mm, wall thickness: 8.2 mm). The piping system model was filled with water in the test and pressurized up to 10 MPa.

ANSYS2021R1 was used as the FEM code in this study. In the analytical model, the configuration of piping system, support positions, and the material and size of the pipe were based on the NUPEC test. The weight of inner water was considered as the modified density of pipe material, and inner pressure was set as 1 MPa. Fig.2 shows the analytical model used in this study. The pipe except for tee was modelled by elbow element, ELBOW290. The tee was modelled by a quadratic three-node pipe element, PIPE289.

The material property for the inelastic analysis was modelled by bi-linear and applied a linear kinematic hardening rule. The minimum yield stress (S_y) provided by the JSME material code (The Japan Society of Mechanical Engineers (2013)) was 245 MPa for STS410, and the longitudinal elastic modulus (E) was 203000MPa. The yield stress (σ_y) and the second inclination of bi-linear model (E_2) was decided

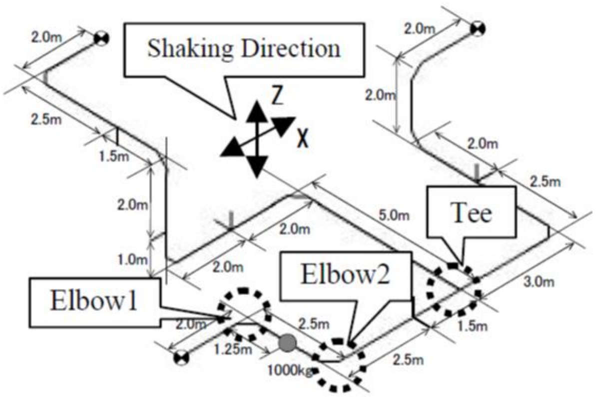
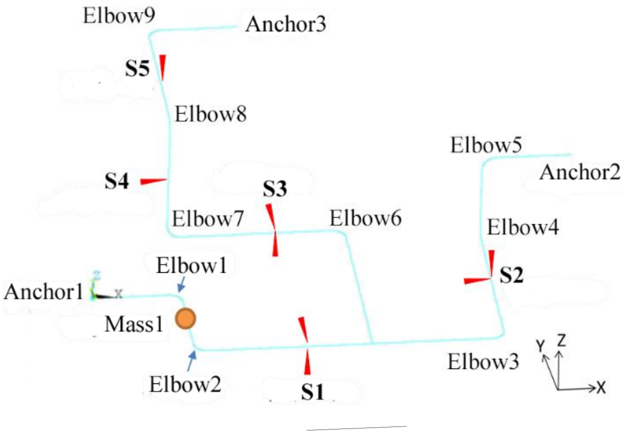


Figure 1. Configuration of the piping system model in the NUPEC test (Suzuki and Abe (2005))



Input motion direction in the analysis

Figure 2. FEM analysis model

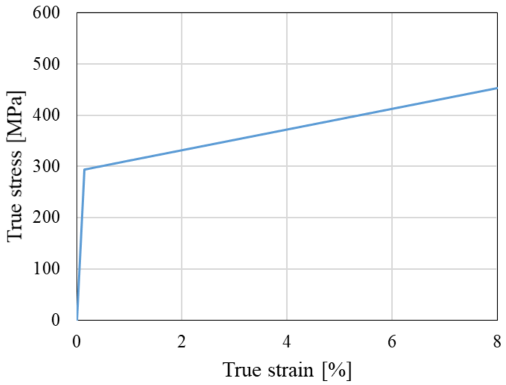


Figure 3. Stress-strain relationship of pipe material used in the FEM analysis

as follows, by reference to the recently developed inelastic analysis guideline in Japan (The Japan Society of Mechanical Engineers (2019), Morishita et al. (2019)).

$\sigma_y = 1.2\, S_y = 294$ MPa
$E_2 = E/100 = 2030$ MPa

Figure 3 shows the stress-strain relationship for pipe material.

Support of pipe

The piping system had three anchors (denoted as Anchor 1, 2, and 3 in Fig.2) and five support positions (denoted as S1 – S5 in Fig. 2). The constrained direction at each support points are summarized in Table 1. In this study, three kinds of supports were considered: Support-1, Support-1-P1, and Support-1-P2. The initial support stiffness (elastic stiffness) was set as 9.8×10^6 N/m for all supports. Plastic behavior was not considered in Support-1 (it remained in elastic region under large displacement), whereas Support-1-P1 and Support-1-P2 yielded under some specific displacement. The yield displacement of Support-1-P1 was set as 1 mm, and that of Support-1-P2 was set as 5 mm. In the case of Support-1-P1, the support was intended to yield prior to the pipe body's yielding, whereas Support-1-P2 was intended to yield posterior to the pipe

Table 1: Constrained direction at each support points

Support points	Constrained direction	Support points	Constrained direction
S1	Y, Z	S4	X
S2	X, Z	S5	Z
S3	Y, Z		

Table 2: Analysis specifications

Analysis code		ANSYS2021R1	
Pipe	Category	STS410 (Carbon steel pipes for high pressure service	
	Size	200Asch40 (Outer diameter: 216.3 mm, wall thickness: 8.2 mm)	
	Young's modulus	203 GPa	
	Poisson's ratio	0.3	
	Density	13704.36 kg/m^3	
	Yield stress	294 MPa	
	Secondary inclination modulus	2.03 GPa	
	Element type	Tee	PIPE289
		Pipe except for Tee	ELBOW290
		Additional mass	MASS21
Support	Initial stiffness	9.8×10^6 N/m	
	Secondary inclination modulus	9.8×10^4 N/m	
	Yielding displacement	Support-1	N/A
		Support-1-P1	1 mm
		Support-1-P2	5 mm
	Element type	COMBIN39	

body's yielding. Figure 4 shows the load-deflection relationship of these supports. These supports were modelled by a nonlinear spring element, COMBIN39.

Table 2 summarizes the analysis specifications of piping system and support, and Table 3 shows the relationship of analytical model names and the combination of the condition of pipe's material and supports.

Figure 5 shows the modal analysis result. The first mode was the translational mode to the X direction in Fig.2, and this mode was focused to be excited in the time history analysis.

Input Motion

In the time history analysis, a uniaxial excitation to the X direction in Fig.2 by a seismic input was conducted. Figure 6 shows the time history of input acceleration and the response acceleration spectrum of

Table 3: Analytical model name and condition of pipe's material and support type

Analytical model name	Support type	Pipe's material condition
SEPE1a	Support-1 (Elastic)	Elastic
SEPP1a		Elastic-plastic
SNPE1a1	Support-1-P1	Elastic
SNPP1a1		Elastic-plastic
SEPE1a2	Support-1-P2	Elastic
SNPP1a2		Elastic-plastic

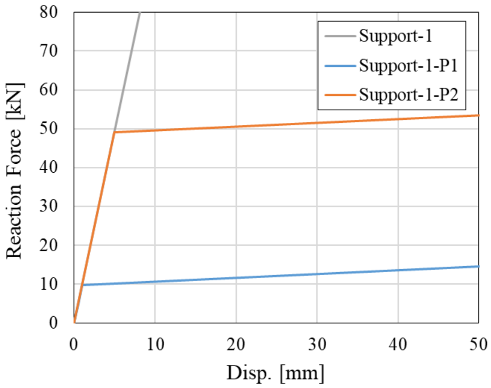
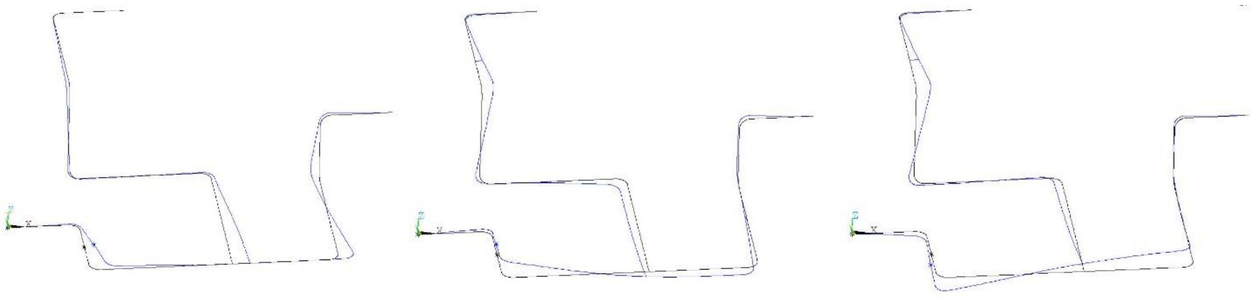


Figure 4. Load-deflection relationship of supports



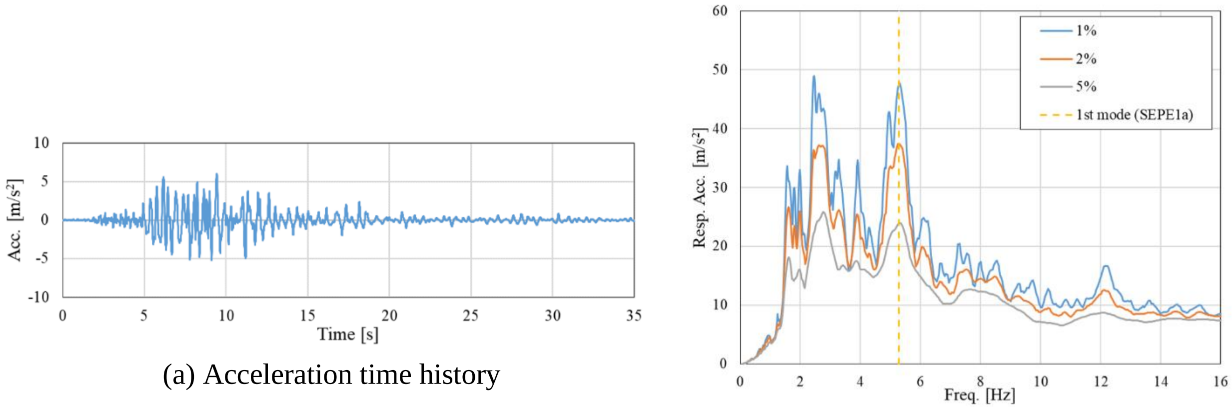
(a) 1st mode: 5.29 Hz

(b) 2nd mode: 6.55 Hz

(c) 3rd mode: 6.81 Hz

Figure 5. Modal analysis result

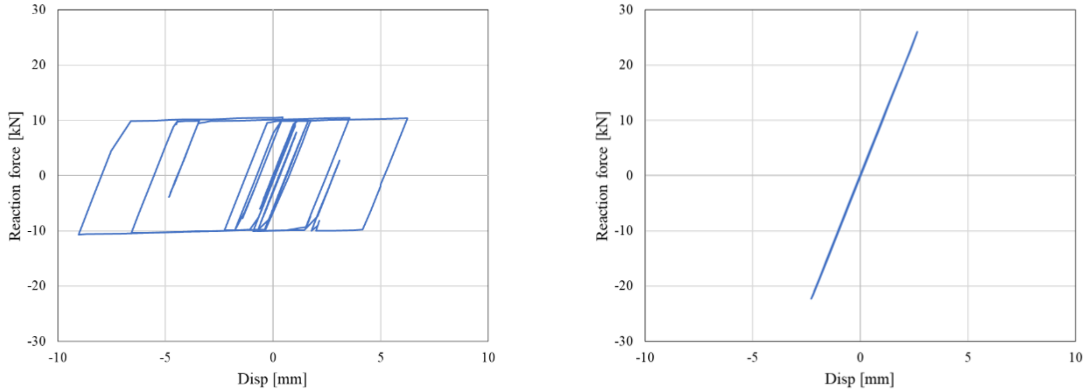
the seismic motion used in the analysis. In Fig.6(b), the first natural frequency of the piping system model is indicated by the dashed line. The waveform of the input motion is originally from the recorded seismic motion at HKD125 station of K-NET in the 2018 Hokkaido Eastern-Iburi Earthquake (National Research Institute for Earth Science and Disaster Resilience, 2018), and scaled the time axis by 0.8 so that the



(a) Acceleration time history

(b) Acceleration response spectra

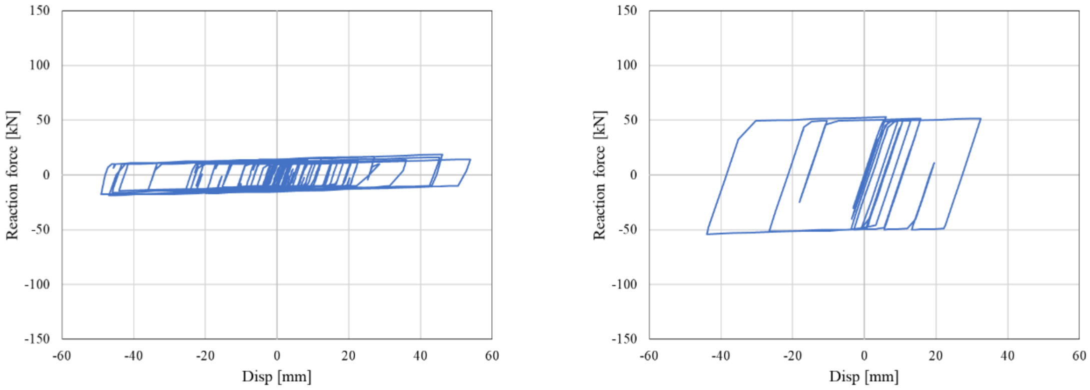
Figure 6. Input motion in the FEM analysis



(i) SNPE1a1

(ii) SNPE1a2

(a) Input acceleration: 6 m/s^2



(i) SNPE1a1

(ii) SNPE1a2

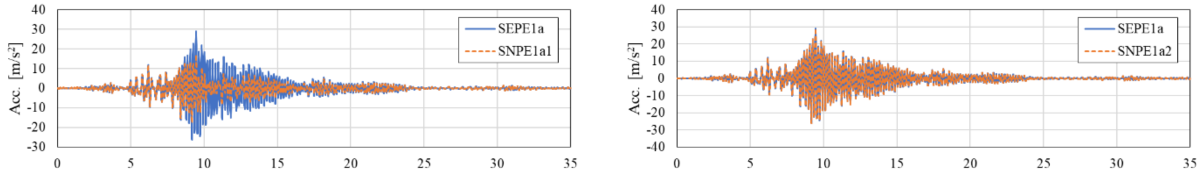
(b) Input acceleration: 30 m/s^2

Figure 7. Load-deflection relationship in the X direction of S2

dominant frequency of the input motion was almost coincident with the piping system model's first natural frequency. The amplitude of input motion in the time history analysis was equal to the original wave or was amplified to 5 times of the original as necessary. The maximum input acceleration was approximately 6 m/s^2 when the magnification of input acceleration was 1, and it was approximately 30 m/s^2 when the magnification of input acceleration was 5.

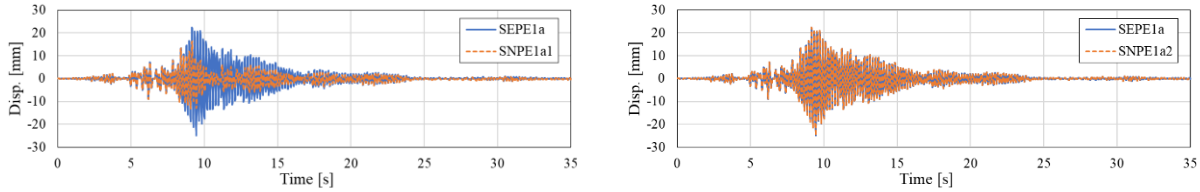
ANALYTICAL RESULTS

Figure 7 shows the load-deflection relationship in the X direction of S2 of SNPE1a1 and SNPEa2. Figure 8 shows the time history of the response acceleration and displacement at Mass1 of SNPE1a1 and SNPE1a2 in comparison with those of SEPE1a. The difference of these analytical cases is the support condition; SEPE1a is the model with Support-1 (elastic support), SNPE1a1 is the model with Support-1-P1, and SNPE1a2 is the model with Support-1-P2. The pipe material is considered as elastic material. As shown in



(1) Response acceleration

(1) Response acceleration



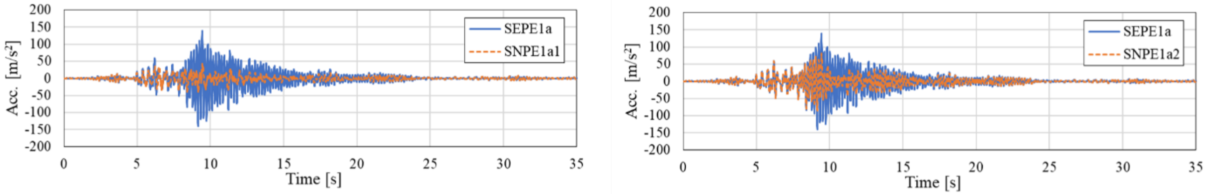
(2) Response displacement

(2) Response displacement

(i) SNPE1a1

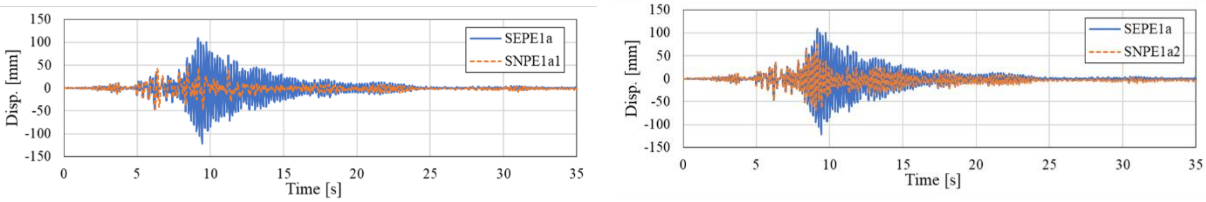
(ii) SNPE1a2

(a) Input acceleration: 6 m/s^2



(1) Response acceleration

(1) Response acceleration



(2) Response displacement

(2) Response displacement

(i) SNPE1a1

(ii) SNPE1a2

(b) Input acceleration: 30 m/s^2

Figure 8. Response acceleration and displacement at Mass1

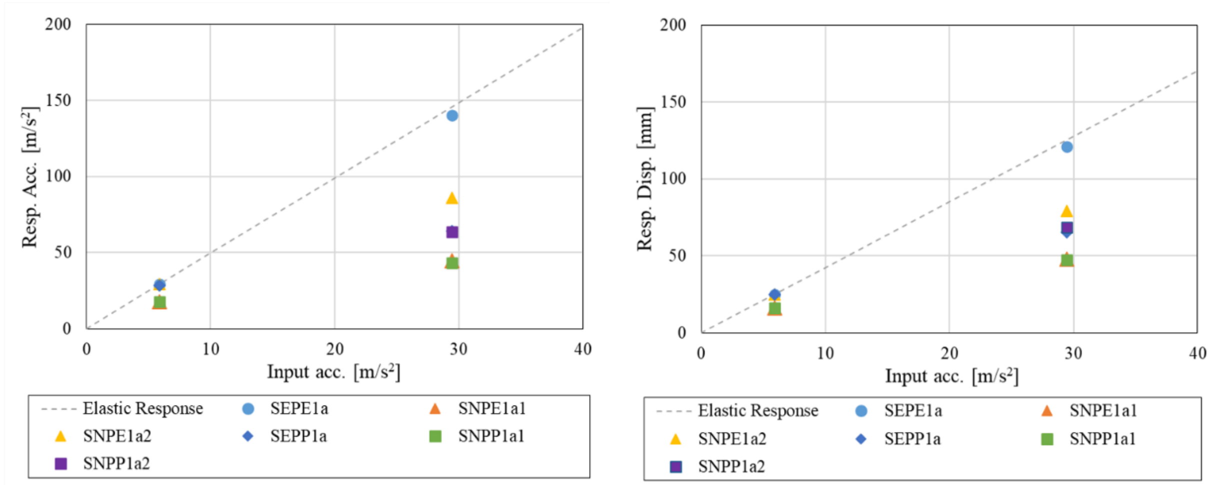
Fig.7, S2 of SEPE1a1 showed a remarkable elastic-plastic behavior under 6 m/s^2 input, whereas S2 of SEPE1a2 remained in elastic behavior under this input level. S2 of SEPE1a2 reached to the inelastic region under 30 m/s^2 input. Figure 8 shows that the piping system's response acceleration was reduced effectively when the inelastic characteristic of support was considered. The reduction of the response was mainly due to the energy dissipation at support. The similar tendency was confirmed for the response displacement at Mass1.

Figure 9 shows the relationship between the input acceleration and the response acceleration / displacement at Mass1 for all analytical cases. The response of SEPE1a, in which neither inelastic behavior of pipe material nor support structure was considered, is expressed by circle mark in Fig.9. The gray-dashed line denotes the elastic response. The diamond marks denote the analytical conditions in which the inelastic characteristic of support is not considered and that of pipe material is considered. The triangle marks denote the analytical conditions in which the inelastic characteristic of support was considered and that of pipe material was not considered. The square marks denote the analytical conditions in which both the inelastic characteristics of pipe material and support were considered. As shown in Fig.9, the responses at Mass1 were reduced by considering the inelastic behavior of support and/or pipe material.

Comparing the triangle marks with circle marks (or gray-dashed line) in Fig.9, the difference of analytical conditions was the consideration of support inelasticity. The response acceleration and displacement were effectively suppressed by considering the support inelasticity, as described above.

When considering the pipe material's elastic-plastic behavior, most of the piping system remained in elastic region under 6 m/s^2 input, though a slight plastic strain was confirmed at Elbow2 (approximately 0.1%). Several elbows reached to plastic region under 30 m/s^2 input acceleration if the supports would not yield under large input motion. Comparing the diamond marks with circle marks (or gray-dashed line) in Fig.9, it is confirmed that the response of piping system also suppressed under large input acceleration. The response of the piping system was reduced in return for the plastic behavior of pipe itself.

The analytical results show that the piping system's response could be reduced by considering the inelastic behavior of pipe material or supports; however, from the viewpoint of importance of the structure, the failure at support which is relatively minor failure for the plant safety is appropriate. The analytical results shows that the support failure could mitigate the failure of pipe body, which may cause the boundary failure.



(a) Input Acceleration and response acceleration

(b) Input Acceleration and response displacement

Figure 9. Relationship between input acceleration and response at Mass1

Though the numerical examinations described in this paper are somewhat ideal and how to design and to realize the appropriate support inelastic characteristics is remained as a future task, the analytical results suggest the feasibility of fracture control concept on piping system.

CONCLUSION

Numerical investigation on seismic response behavior of piping systems with supports were conducted. The analysis results indicate that the response acceleration and displacement of piping systems can be reduced effectively when the inelastic characteristic of support is considered. The results show the possibility to realize the application of fracture control to piping systems.

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