Evaluation Method of Seismic Safety of Interior Piping Using Single-Axis Shake-Table Test and Finite Element Analysis

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SUMMARY:
As a first step to establishing a reliable numerical simulation model for interior city-gas piping, some cases of shake-table tests for a partial-piping specimen were conducted. Static bending tests using almost the same supporting apparatus as the shake-table test were also conducted to obtain the mechanical characteristics of the clamp, the hanging bolt and the mechanical coupling, and simplified analytical models were investigated for the non-coupling specimen and for the with-coupling specimen. Finite element analyses (FEA) were then carried out for these models. The experimental data regarding the seismic response during the shake-table tests generally agreed with the FEA results. It was therefore inferred that the major structure of the analytical models proposed in this study is adequate to evaluate seismic safety for interior city-gas piping.

Keywords: interior city-gas piping, seismic safety, mechanical coupling, shake-table test, finite element analysis

1. INTRODUCTION

City-gas suppliers in Japan must be responsible for maintaining the integrity of pipeline networks, including interior city-gas piping. Earthquakes are one of the major threats that damage integrity, and it is therefore necessary for suppliers to establish a methodology for evaluating the durability of interior city-gas piping against an earthquake. In the evaluation, it is effective to build a reliable numerical simulation model by which to consider seismic safety, because various piping structures and earthquakes exist and there are a limited case of experiments that can actually be performed using real specimens. Furthermore, because the application of mechanical couplings in addition to conventional welding joints is expected to shorten the construction period and to increase the safety of construction work, an analytical model which can simulate both types of joints is required to be established.

In the past, experiments using a shake-table to evaluate the seismic response of the interior piping for a sprinkler system (Ohsakaya et al. 2010, Suwa et al. 2011) and the seismic durability of the interior piping with a mechanical coupling for water supply (Kiuchi et al. 1991, Kitagawa et al. 1991) were conducted in Japan. However, there is very little research discussing numerical models for the evaluation of the seismic response of interior piping, and almost no reports have been presented discussing the above issue for the city-gas piping system.

In this study, as a first step to establishing a reliable numerical simulation model, some cases of shake-table tests for a partial-piping specimen were carried out to obtain the seismic response for real interior city-gas piping, and finite element analyses (FEA) were then performed on specimens having both types of joints in order to discuss the applicability of the FEA, resulting in appropriate design of the interior city-gas piping. In the shake-table tests, the amplification of seismic motion due to the difference of the ground and the response of buildings was taken into account as an input seismic wave for the tests.

2. UNDERSTANDING OF SEISMIC RESPONSE FOR INTERIOR PIPING USING SHAKE-TABLE TESTS

2.1. Test Specimens

The test specimens in this study were a horizontal mild-steel pipe hung from the ceiling, which was based on Japan Industrial Standard (JIS) G3452 SGP type of steel pipe, having 114.3 mm in nominal outer diameter and 4.5 mm in nominal thickness. According to the design standard of interior piping in Japan, the maximum span between weight supports is 4 m and one support within three times the distance between the weight supports must be a fixed seismic support in case of the piping having more than 50 mm in diameter and more than 300 mm in horizontal hanging length. Because the dominant vibration mode in this case is shown as the dotted curve in Fig. 1 and the three spans is the shortest length by which to show the phenomena, they were chosen as the subject of the evaluation in this study.

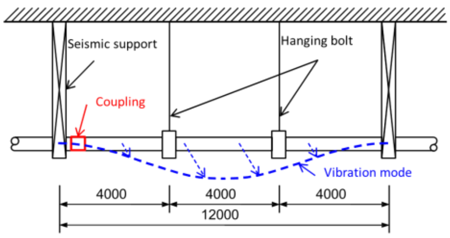
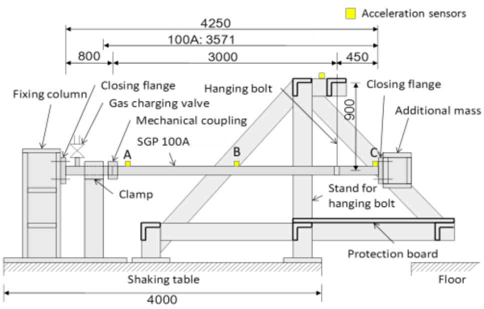


Figure 1. Illustration of the dominant vibration mode in the three spans

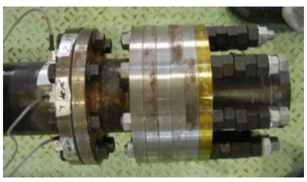
Fig. 2 shows an overview of the test apparatus in this study, including a partial-piping specimen, which was chosen as the specimen for the shake-table tests due to the limitation of the shake-table area of 16 square meters. Fig. 3 shows the additional mass attached to the end of the test pipe in order that the resonance frequency of this specimen should be the same as the real three spans shown in Fig. 1. In the test apparatus, a steel clamp and a hanging bolt were used as the seismic support and the weight support respectively. The distance between the hanging bolt and the clamp was determined as 3.1 m due to the limitation of the shake-table size. The distance was shorter than 4 m, but the influence of this was considered to be negligible because the vibration response of the piping can be controlled using the additional mass.



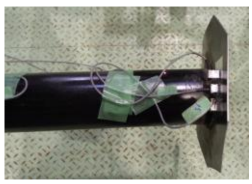
(a) Schematic

(b) Photo

Figure 2. Shake-table test apparatus and partial-piping specimen



(a) Non-coupling specimen (33.9 kg)



(b) With-coupling specimen (1.2 kg)

Figure 3. Overview of the additional mass

In the tests, the specimen with no coupling, hereafter the non-coupling specimen, was used to evaluate conventional weld-jointed piping. The steel piping specimen with a commercial mechanical coupling for the water supply piping in Japan, hereafter the with-coupling specimen, was applied to evaluate piping having a mechanical joint. The appearance of the coupling applied to the tests is shown in Fig. 4. Table 1 shows the major conditions of the shake-table tests. For the with-coupling specimen, the gap width between the pipes in the coupling was almost 4 mm. The coupling was tightened under standard conditions at a range of the torque from 50 Nm to 120 Nm.

Figure 4. Applied mechanical coupling

Table 1. Major conditions of shake-table tests

	Test case	Additional mass weight	Seismic wave	Subsurface soil	Layer thickness	Building grade	Pipe installation position
Non-coupling specimen	1	33.9 kg	Kobe	Cohesive	10 m	Grade 2	Hung from ceiling of RF of a seven-storey building
	2	33.9 kg	Hachinohe	Cohesive	10 m	Grade 1	
With-coupling specimen	3	1.2 kg	Kobe	Cohesive	10 m	Grade 2	
	4	1.2 kg	Hachinohe	Cohesive	10 m	Grade 1	

2.2. Test Method

2.2.1. Method of the resonance test

The resonance test can clarify the resonant frequencies of the objects. In this study, a single-axis sinusoidal wave from 1.0 to 10.0 Hz was applied to the test specimens in steps to determine their resonant frequencies. The target maximum amplitude of the input waves was 0.1 m/s^2, which was set to be lower to avoid damage to the objects. The resonance tests were carried out before and after the seismic response tests to understand whether the seismic motion influenced the test specimens or not.

2.2.2. Method of the seismic response test

For the purpose of the understanding of the seismic response of the interior piping, the shake-table tests were carried out under the wave conditions with consideration of the difference of the ground and the response of buildings during an earthquake. This is also indicated in Table 1. The seismic wave which could cause the largest bending moment at the position of the mechanical coupling was chosen from the seismic wave database obtained by the following method for the shake-table tests.

First, seismic response analyses of ground using the equivalent linear method were performed under condition of different kinds of surface soil, soil layer thickness and buildings for two types of earthquake: the ‘Level 1’ earthquake ground motions at engineering bedrock outcrop, which were based on the design acceleration response spectrum defined in the Notification No. 1461 of the Japanese Ministry of Construction in 2000, with the two types of phase characteristics of JMA Kobe 1995 NS, which was an inland earthquake, and Hachinohe 1968 NS, which was a trench-type earthquake. These earthquakes are adopted as a typical seismic motion used in a seismic design in Japan. Then, response analyses of buildings under the evaluated ground motions were carried out. Fig. 5 shows the schematic of the seismic response analyses. The conditions of the analyses are shown in Table 2. The assumed properties for the simulation of the seismic grade 1 type of reinforced concrete buildings were a natural period of 0.02 s × building height / 1 m, a bilinear type of restoring force characteristics and *Ds*, a factor representing structural resistance, of 0.8, and a stiffness given as an Ai distribution. The damping coefficients for the three-story building and the other buildings were 0.03 and 0.02, respectively. In addition to the above, a simulation was performed for grade 2 buildings with a stiffness and *Ds* of 1.25 times greater than those of the grade 1 buildings.

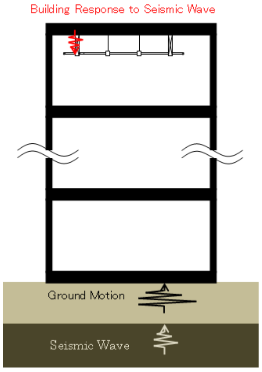


Figure 5. Schematic of seismic response analyses

Table 2. Analytical conditions to obtain seismic-wave database

Items	Conditions
Type of subsurface soil	Sandy soil, loam and cohesive soil
Thickness of soil layer	0 m, 0.5 m and 10 m
Height of building	3, 7, 11 and 15 storeys (height by one storey of 4 m)
Seismic grade of building	Grade 1 and grade 2

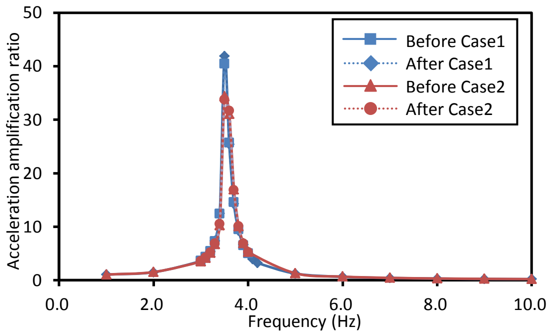
2.2.3. Measurements

Strain-gauge acceleration sensors were attached to each test specimen at the three positions A, B and C shown in Fig. 2, and the acceleration in the horizontal direction was measured at a sampling rate of 200 Hz.

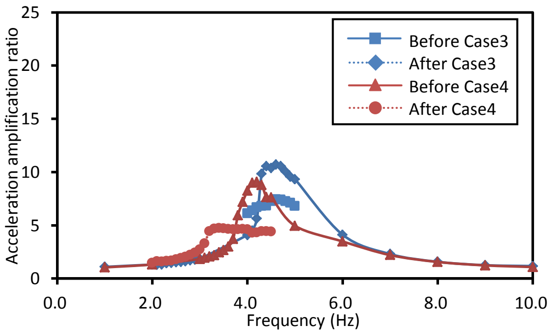
2.3. Test Results

2.3.1. Resonance test results

Fig. 6 shows the results of resonance tests for the four test cases shown in Table 1. For the non-coupling specimens, the amplification ratio of the acceleration was approximately 42 for Case 1 and 32 for Case 2 respectively. Frequency response characteristics are almost the same between Cases 1 and 2, and before and after the seismic response test. The resonance frequency was 3.5 Hz. Meanwhile, frequency response characteristics obviously changed before and after the seismic response tests for the with-coupling specimens of Cases 3 and 4. This indicates that the characteristic could change for interior piping having mechanical coupling due to a fairly large earthquake.



(a) Non-coupling specimen



(b) With-coupling specimen

Figure 6. Results of the resonance tests using the shake-table

2.3.2. Seismic response test results

The acceleration responses during the seismic response tests measured at the three positions for each case are shown in Fig. 7. Acceleration response C at the location near the additional mass for the with-coupling specimen was greater than that for the non-coupling specimen. This means that the inertial load due to the earthquake is larger for the piping having the mechanical coupling than that for the non-coupling piping; this is because the input motions were selected from the seismic wave database so that the coupling of the specimen could undergo the largest bending moment.

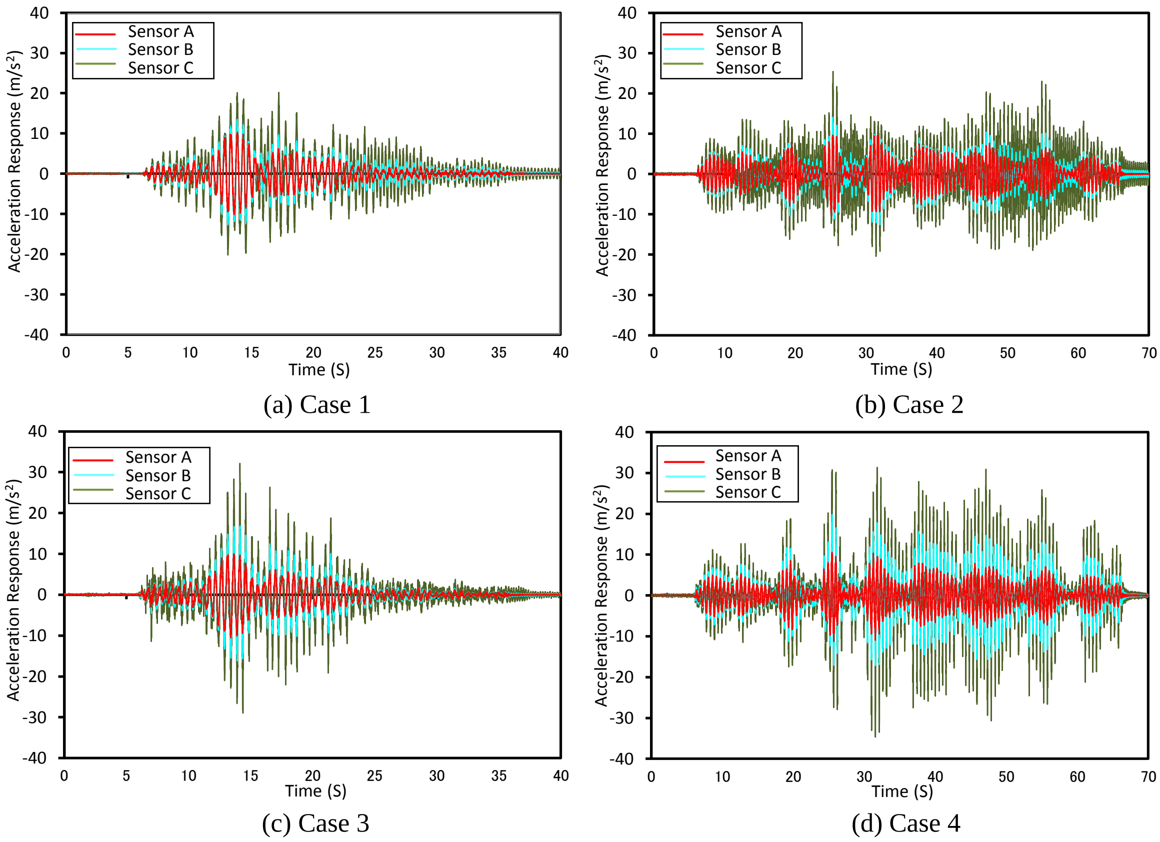


Figure 7. Results of the seismic response tests using the shake-table

3. EVALUATION OF SEISMIC RESPONSE OF INTERIOR PIPING USING FINITE ELEMENT ANALYSIS

3.1. Static Bending Test

In order to obtain the deformation characteristics of the clamp, the hanging bolt and the mechanical coupling in the shake-table tests, a static bending test was carried out for almost the same supporting apparatus as that of the shake-table test. Fig. 8 shows the overview of the bending test. The static displacement was alternately loaded using a hydraulic jack located at the end of the piping. In the bending tests, the rotational angle of the pipe axis was controlled and the alternate displacement was gradually increased to be an angle from 1 to 5 degrees. The target loading program during the bending test is shown in Fig. 9.

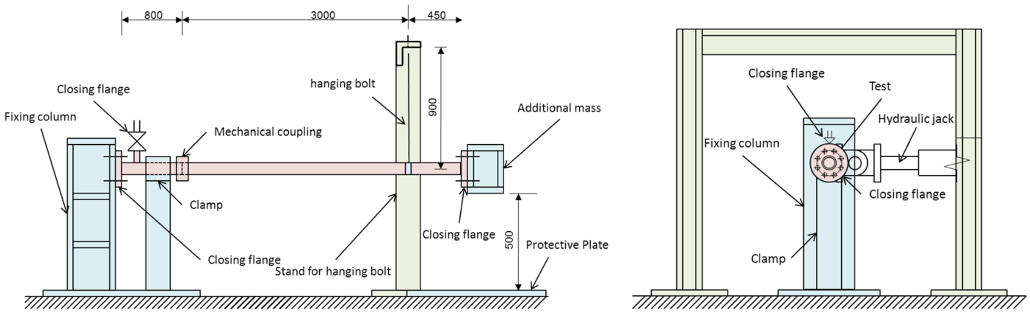


Figure 8. Schematic of the static bending test apparatus

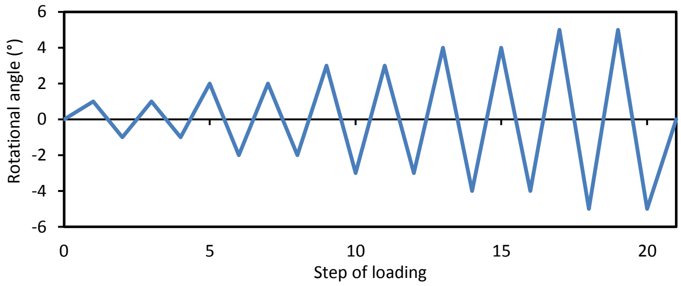


Figure 9. Target alternative loading program in the static bending test

3.2. Simplified Analytical Model for FEA

3.2.1. Modelling of the hanging bolt and the clamp

Since the rotation of the pipe specimen at the clamp, which was used as a seismic support, was observed in the static bending test, the clamp was modelled as a linear rotational spring. The load vs. displacement curve obtained from the bending test for the non-coupling specimen is shown in Fig. 10. This curve was transferred to the stiffness of the rotational spring, K_c, vs. the maximum experienced rotational angle, θ_{Cmax}, as shown in Fig. 11. The K_c value was calculated from the following equation:

$$K_c = \frac{(P - P_0)L^2}{\delta - (P - P_0)\dfrac{L^3}{3EI}} \tag{3.1}$$

where L is the length between the clamp and the loading point, δ is the displacement at the loading point, which includes elastic and plastic deformation and rigid body rotation of the pipe, and P and P_0 are the load corresponding to δ and the latest load when δ passes through zero, respectively. For the seismic response tests in this study, the averaged rotational angle during the test was almost 0.0017 radians (0.1 degrees), and the K_c value for FEA was determined as 1058 kNm/s^2 from this figure.

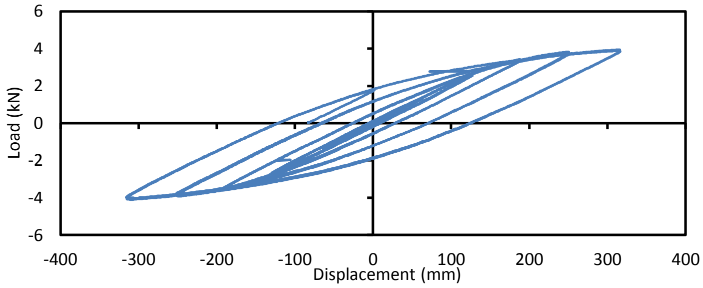


Figure 10. Result of the static bending test for the non-coupling specimen

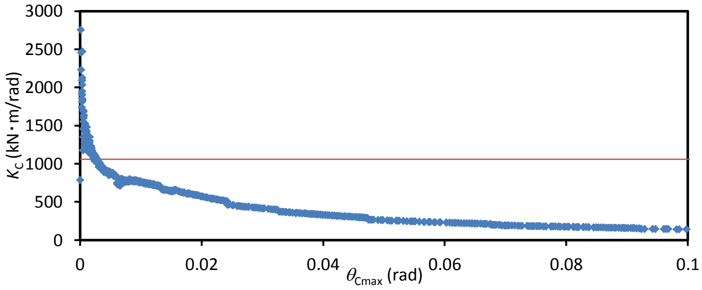
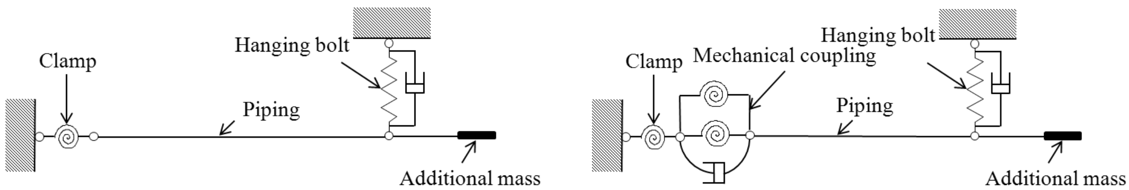


Figure 11. Stiffness of the rotational spring vs. the maximum experienced rotational angle

The hanging bolt, which was used as a weight support, was modelled as a linear spring with a damper. The stiffness of the spring was determined from the difference between the loads with and without the hanging bolt in the static bending test. The damping coefficient was decided so as to agree with the resonance test results. From the above, a simplified analytical model of the seismic tests for the non-coupling specimen was assumed as shown in Fig. 12 (a). The characteristic values of each component are indicated in Table 3 respectively. Here, the pipe was modelled as an Euler beam having the characteristics of typical mild steel.



(a) Non-coupling specimen (b) With-coupling specimen

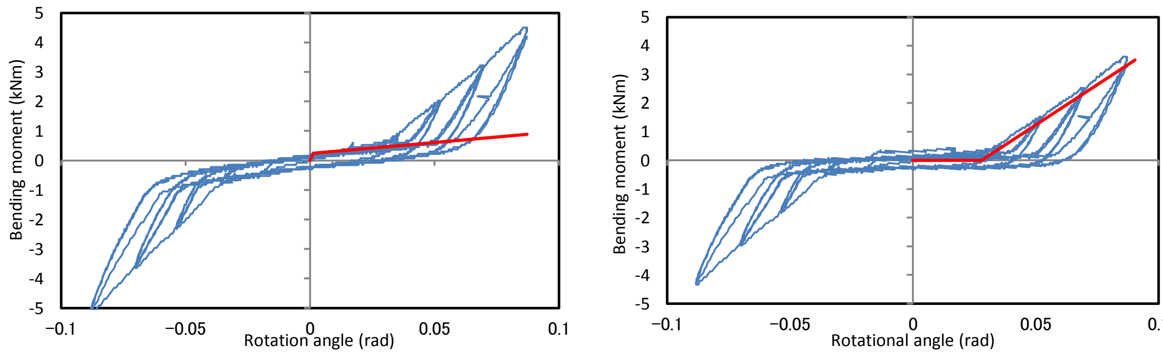
Figure 12. Proposed simplified analytical models

Table 3. Mechanical properties of each component for FEA

Element	Model	Parameter	Value
Piping	Euler beam	Second moment of area, I (m^4)	2.343×10^{-6}
		Elastic modulus, E (N/m^2)	2.06×10^{11}
		Poisson's ratio	0.3
		Density (kg/m^3)	7850
Clamp (Seismic support)	Linear rotational spring	Stiffness (kNm/rad)	1058
Hanging bolt (Weight support)	Linear spring	Stiffness (kNm/rad)	520.0
	Damper	Damping coefficient (Ns/m)	28.8
Mechanical coupling	Bilinear elastic-plastic rotational spring	Stiffness of the first branch (kNm/rad)	181
		First folding point (rad)	0.0014
		Stiffness of the second branch (kNm/rad)	7.46
	Hardening-type bilinear elastic rotational spring	Stiffness of the first branch (kNm/rad)	0
		First folding point (rad)	0.029
		Stiffness of the second branch (kNm/rad)	52.1
	Rotational damper	Damping coefficient (Ns/m)	50

3.2.2. Modelling of the mechanical coupling

The bending moment vs. rotational angle curve in the static bending test for the with-coupling specimen is shown in Fig. 13. From this figure, it was inferred that the mechanical coupling is modelled as a parallel following two springs; a bilinear elastic-plastic rotational spring and a hardening-type bilinear elastic rotational spring. The properties of the former spring were determined from Fig. 13 (a) and those of the latter spring were determined from Fig. 13 (b), which was obtained from the difference of the bending moment between the static bending test result and the determined properties of the bilinear elastic-plastic rotational spring. It was also decided from the resonance test results that the rotational damper should also be in parallel to these springs. The assumed simplified analytical model of the seismic tests for the with-coupling specimen is shown in Fig. 12 (b) and the determined characteristic values for the springs are also shown in Table 3.

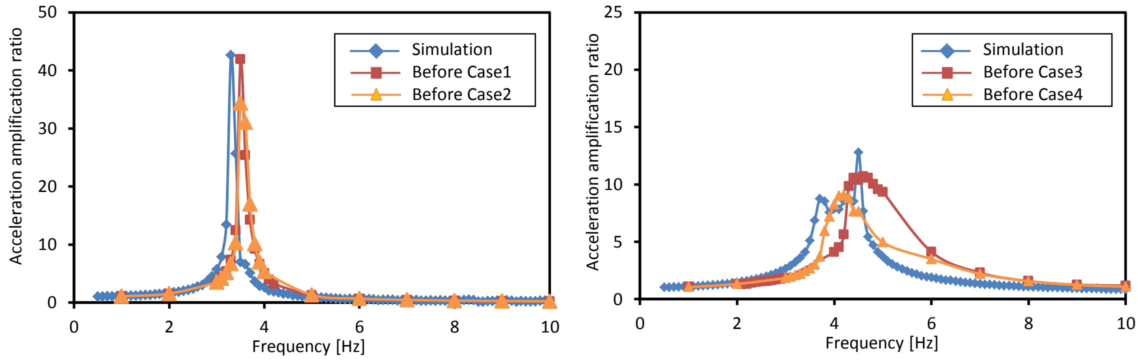


(a) Bilinear elastic-plastic rotational spring (b) Hardening-type bilinear elastic spring

Figure 13. Result of the static bending test for the with-coupling specimen and the determined characteristics of the two bilinear springs (shown as red lines)

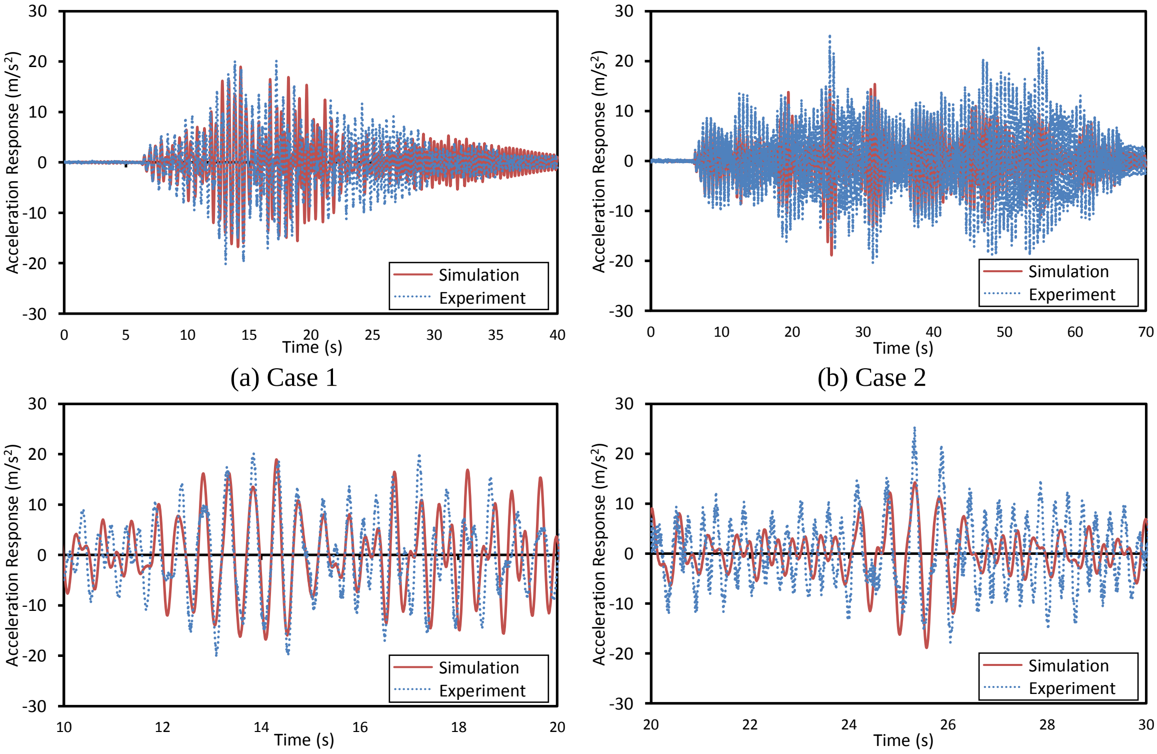
3.3. Comparison of the FEA Results with the Experimental Results

Using the FEA code of Matlab, the amplitude response from the resonance tests and that during the seismic response tests using the shake-table was calculated, and the FEA results were compared with the experimental results. Fig. 14 shows the comparison of the experimental data with the analytical results for the resonance tests. The comparisons for the seismic response tests are shown in Figs. 15 and 16 for the non-coupling specimen and for the with-coupling specimen, respectively. The acceleration response from the FEA generally agreed with the measured data from the experiments. It was therefore inferred that the proposed simplified models shown in Fig. 12 are applicable to evaluate the seismic response of the interior piping. Meanwhile, the accuracy of the FEA for the with-coupling specimen was lower than that for the non-coupling specimen. As described in 2.3.1, the resonance characteristic of the with-coupling specimen changed between before and after the seismic response tests. This could cause the difference of accuracy in the FEA results. While further work is needed to obtain more reliable FEA results, the fact that the FEA results in this study generally agreed with the experimental data could indicate that the major structure of the proposed simplified analytical models was adequate for evaluation of the seismic safety of interior city-gas piping.



(a) Non-coupling specimen (b) With-coupling specimen

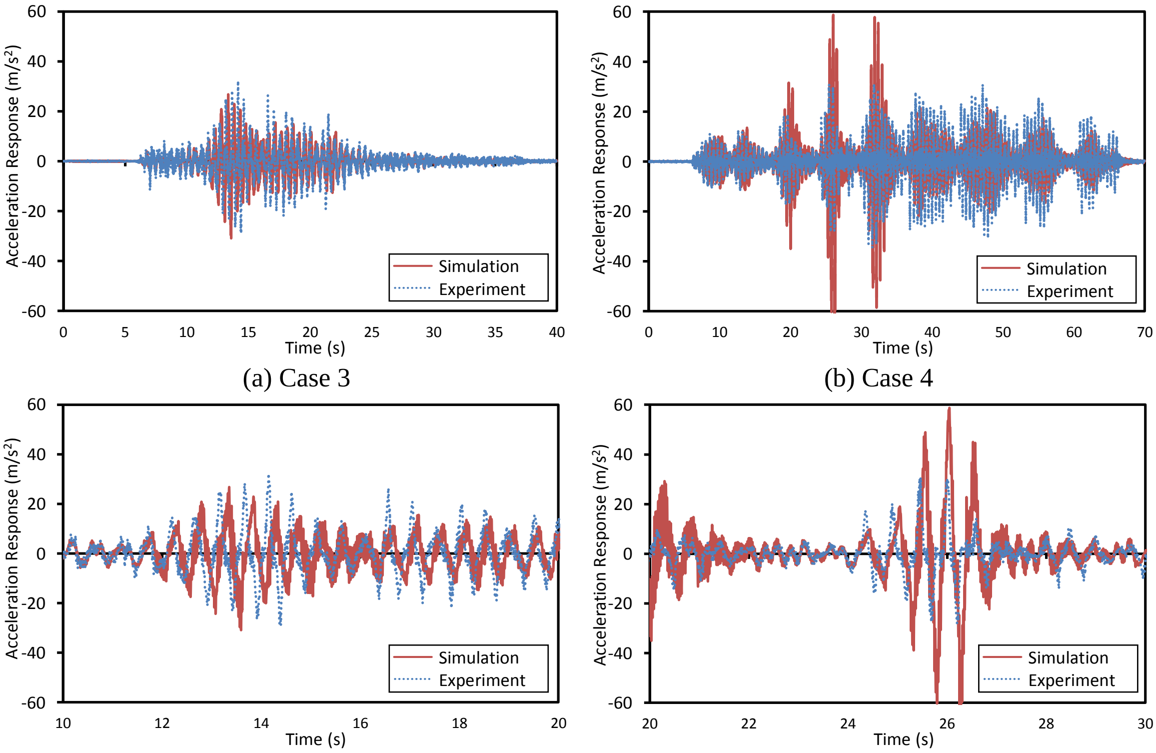
Figure 14. Comparison of the experimental results with the FEA results in the resonance tests



(a) Case 1 (b) Case 2

(c) Case 1: expansion of (a) (d) Case 2: expansion of (b)

Figure 15. Comparison of the experimental results with the FEA results in the seismic response tests for the non-coupling specimens



(a) Case 3 (b) Case 4

(c) Case 3: expansion of (a) (d) Case 4: expansion of (b)

Figure 16. Comparison of the experimental results with the FEA results in the seismic response tests for the with-coupling specimens

4. PROPOSAL OF FRAMEWORK TO EVALUATE SEISMIC SAFETY

The use of FEA should contribute to a more precise evaluation of the seismic safety of city-gas piping systems, because FEA can be used for evaluation in addition to full-scale experiments using a shake-table if reliable analytical models are established. In this situation, the framework shown in Fig. 17 can be applied as the evaluation methodology for seismic safety. This framework indicates concrete steps to obtain the appropriate design scheme and guideline based on full-scale experiments and simulation.

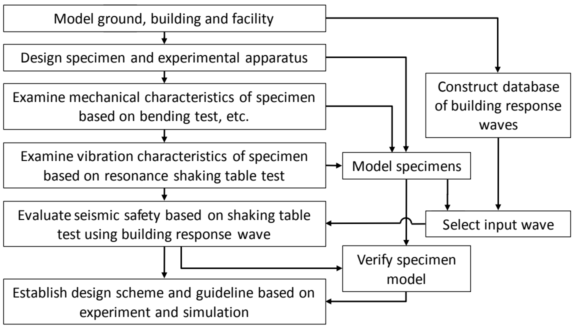


Figure 17. Proposed framework for the method of evaluation of seismic safety for the interior-piping

5. CONCLUSIONS

The major results obtained in this study are the following:

1) The seismic response tests using the shake-table for the partial-piping specimens clarified their real behaviour during an earthquake. The frequency response characteristics obviously changed before and after the seismic response tests for the with-coupling specimens.
2) From the static bending tests, the non-coupling specimen was modelled consisting of an Euler beam, a linear rotational spring for the clamp, a linear spring with a damper for the hanging bolt, and the with-coupling specimens was modelled consisting of two paralleled bilinear-type rotational springs with a rotational damper in addition to the non-coupling specimen model.
3) It was inferred that the major structure of the simplified analytical models proposed in this study is adequate to evaluate the seismic safety for the interior city-gas piping because the experimental data regarding the seismic response during the shake-table tests generally agreed with the FEA results.

ACKNOWLEDGEMENTS

The authors thank to Mr. Takao Ohashi of Japan Open System Co. and Mr. Shin Uchiki of Tokyo Rigaku Kensa Co. for their help in the shake-table tests. The authors also acknowledge Ms. Nanako Miura of Keio University for her support in the construction of the seismic wave database.

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