

## **AN EXPERIMENTAL INVESTIGATION ON FAILURE MODES OF PIPING COMPONENTS UNDER EXCESSIVE SEISMIC LOAD**

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### **ABSTRACT**

After the accident at Fukushima Dai-ichi Nuclear Power Plant in 2011, IAEA requires to consider the design extension conditions (DEC) for the safety management of nuclear power plants (NPP). In considering the DEC, it is necessary to clarify the possible failure modes of the structures and their mechanism under the extreme loadings. Because piping systems are one of the representative components of NPP, and there is a possibility to failure at seismic events, the authors conducted an experimental investigation on failure modes and mechanisms of piping systems under excessive seismic loads.

Conventional design and probabilistic risk assessment (PRA) considers collapse and ductile fracture due to peak ground acceleration as failure modes of piping systems. However a lot of experimental data shows the fatigue failure as the most possible failure mode under the seismic load. For considering the DEC, it is necessary to recognize the conditions to cause various failure modes. To clarify the failure modes under excessive seismic load, shaking table tests on different scale test specimens with different material or loading conditions were planned. The experiments are categorized into the fundamental plate tests and pipe component tests. The most of the observed failure modes were fatigue failure. Other failure modes such as ratchet deformation, collapse and the fracture appeared under extreme conditions of fundamental plate tests. In this paper, the outline of the experimental investigations and their results are described.

### **INTRODUCTION**

After the accident at Fukushima-Dai-ichi Nuclear Power Plant in the 2011 Great East Japan Earthquake, the importance of consideration for the design extension conditions (DEC) is widely recognized. Because the conventional design is established based on the thought to prevent damage to the nuclear power plants (NPPs) with certain safety margins, the knowledge on the ultimate strength, the process to failure and the failure modes are not necessarily required within the design basis accident. But in considering the DEC, it is necessary to understand the ultimate behaviour of structures under excessive loads and to take adequate countermeasures to prevent the fatal failure modes. With the aim of clarifying the failure modes and the ultimate structural strength under extreme loadings, a research project is conducted from 2012 to 2016 (Kasahara. et al (2014)). In this research program, the very high temperature, pressure, and excessive seismic loads are considered as the extreme loads.

In the investigation for seismic loads in this research program, piping systems are selected as the possible failure components in NPPs. In the conventional design rules (The Japan Electric Association (1987)), collapse is the postulated failure mode under a seismic load which is caused by the maximum peak acceleration. On the other hand, it is well known that the major failure mode of piping systems under large seismic loads would be the fatigue failure from several previous studies (Fujita, et al (1990), Tagart, et al (1990), Touboul, et al (1999), Yoshino, et al (2000), Varelis, et al (2013), Nakamura, et al (2010)). The fatigue failure is caused by large cyclic strain range. As a rare case of the failure mode, ratchet-buckling failure had been also reported (Tagart, et al (1990)). Though there are several postulated failure

modes of piping systems as just described, there are few experimental studies which aim to investigate and to categorize the possible failure mode related to the loading conditions under beyond design condition. In order to investigate the failure modes and to develop the evaluation methods under the DEC, a series of excitation tests using shaking tables has been planned and conducted. The excitation tests consist of mainly two campaigns; the pipe component tests and the fundamental plate tests. In this paper, the outline of the experimental investigations and their brief results are described.

## EXPERIMENTAL STUDY USING SHAKING TABLES

### *Pipe Component Tests on Steel Elbows*

As an example of a realistic structural model, steel pipe elbow specimens were used in the pipe component tests in the first stage. It is assumed that piping systems in NPPs would remain mainly in the elastic region under the design based earthquake. But in consideration of the DEC, plastic strain would occur on the piping systems, and the dynamic response behaviour would be affected by the elastic-plastic effect. So the main purpose of the pipe component tests is to obtain the dynamic behaviour of pipe structures including the elastic-plastic region, and the failure modes under the excessive reversing dynamic load. The test specimen consisted of one steel pipe elbow, one weight, and two straight pipes. The configuration of the specimen is shown in Fig.1. The material used in the experiments are Carbon Steel JIS STS410 (Japanese Industrial Standards: carbon steel pipes for high pressure service) and Stainless Steel 304SS. These materials are widely used in the actual piping systems of NPPs. The in-plane bending deformation of the elbow is the target deformation by the excitation tests. The natural frequency of the in-plane bending mode of the specimen made of STS410 with 100kg weight was about 3Hz from the linear eigenvalue analysis. Five specimens in total were used in the pipe component tests (Four specimens made of STS410 and one specimen made of 304SS). The input motion used in the excitation tests was mainly constitutive sinusoidal wave as shown in Fig.2(a). The waveform, referred to as "30

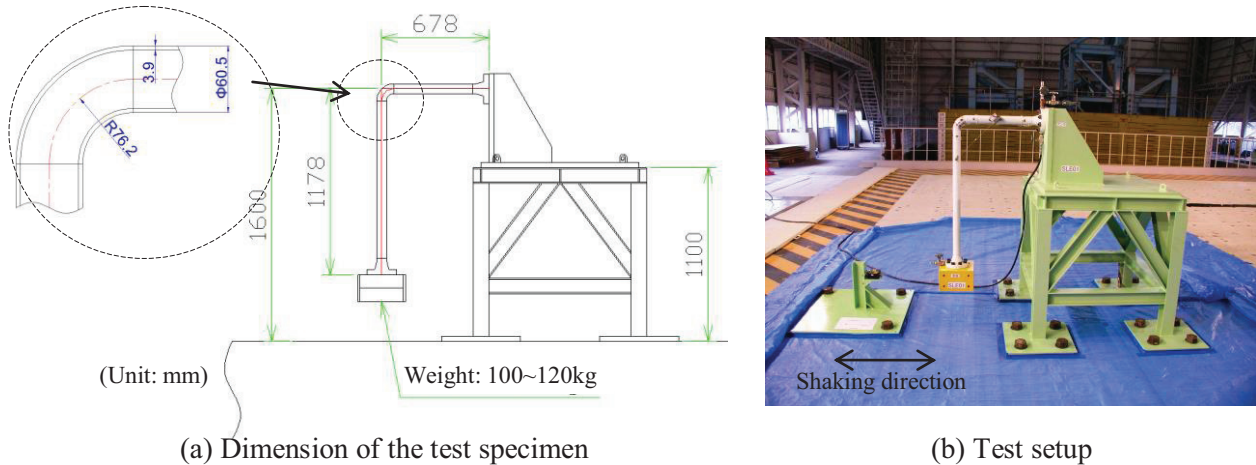


Figure 1. Configuration of the test specimen of the pipe component tests

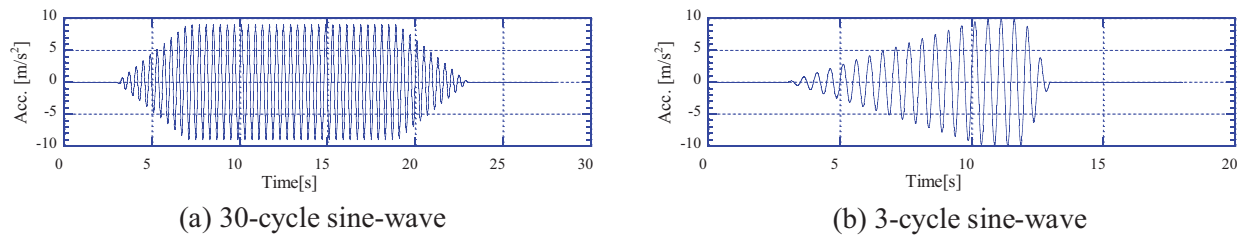


Figure 2. Input sinusoidal wave used in the pipe component tests

cycle sine-wave" in this paper, consists of 30 steady amplitude cycles part and 10 cycles transient parts at the beginning and the ending. The waveform of which the numbers of cycles at the steady amplitude parts changed from 30 to 60 was also used in the fatigue tests depends on the progress of the excitation tests. This waveform is referred to as "60-cycle sine-wave". Maximum input acceleration level was determined in consideration of the elastically calculated primary stress level at the elbow and the performance limit of the shaking table. As a result, mainly  $5.0\text{m/s}^2$  input acceleration was applied on the elbow specimens. When elastic behavior are assumed even against excessive load, which is supposed by the design procedure, the primary stress intensity caused on the elbow specimens by the  $5.0\text{m/s}^2$  input acceleration was about 20 times larger than the primary stress limitation in Japanese seismic design code (The Japan Electric Association (1987)). The excitation tests were conducted step by step increasing the maximum input acceleration up to  $5.0\text{m/s}^2$  for three specimens made of STS410 (the specimens' names are SLE01, SLE02, and SLE04) and one specimen made of 304SS (SLE03S). For one specimen made of STS410 (SLE05), the excitation tests by the  $9.0\text{m/s}^2$  input acceleration by another sinusoidal wave shown in Fig.2(b), which has less number of cycles than 30-cycle sine-wave and is referred to as "3-cycle sine-wave", was also conducted with the intention to cause the collapse failure.

The details of the tests are described in the other paper (Nakamura and Kasahara (2015)). The main finding from the pipe component tests on steel elbows is that the obtained failure mode by the shaking table tests was the fatigue failure as shown in Fig. 3. Though the input acceleration level was much larger than the primary stress limitation to prevent the collapse failure in the current design, the collapse did not occur on the specimens, and iteration excitations were necessary to cause failure on the specimens. One specimen was used for the excitation tests by 3-cycle sine-wave with the higher maximum input

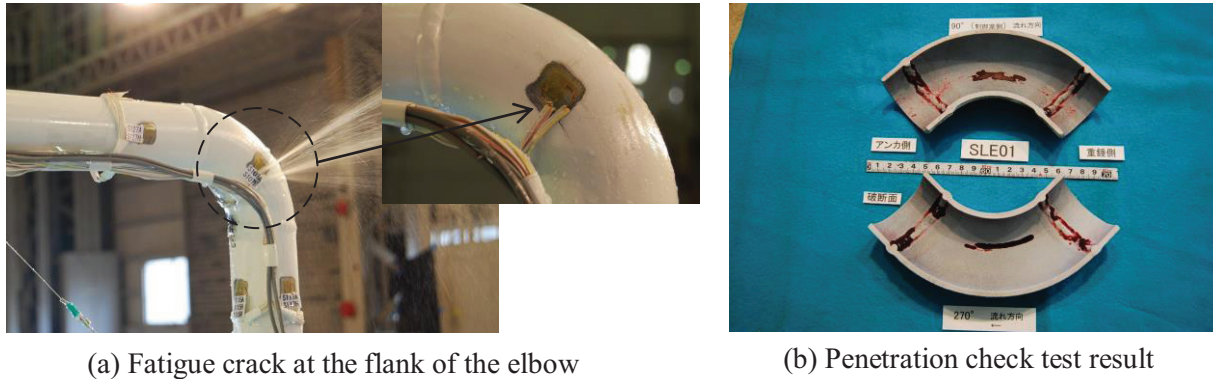


Figure 3. Typical failure mode obtained in the pipe component tests

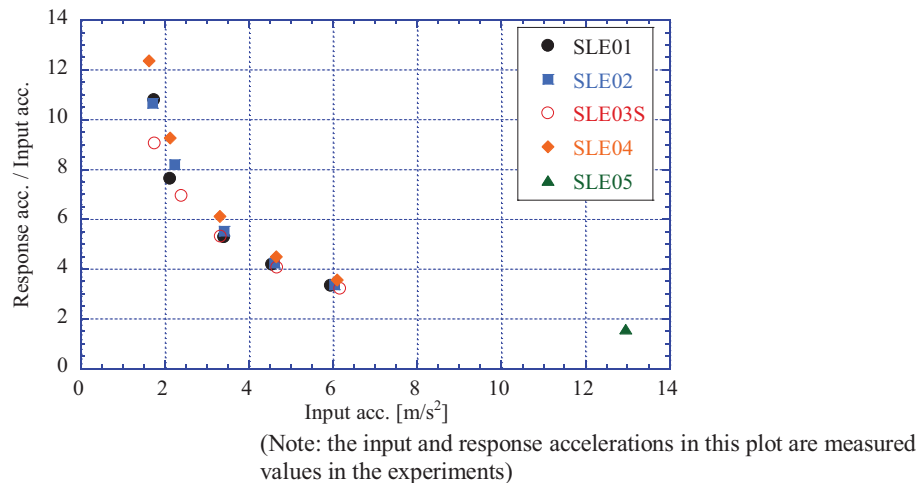
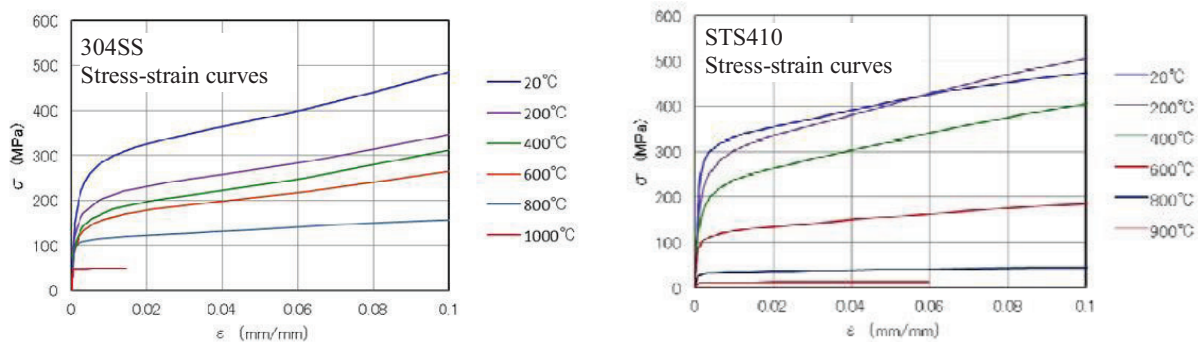


Figure 4. Relation between the maximum input acceleration and the amplification ratio under the sinusoidal wave input

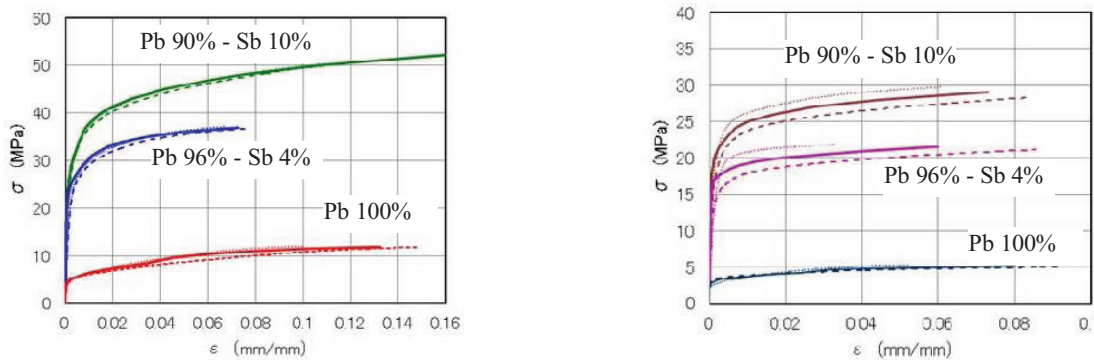
acceleration ( $9.0\text{m/s}^2$ ), but the collapse failure did not occur even in this case. One reason of such result is thought due to a large hysteresis damping under the elastic-plastic region. Figure 4 shows the relation between the maximum input acceleration and the response amplification ratio under the sinusoidal wave input. Here, the response amplification ratio is determined as the ratio of the response acceleration to the input acceleration. The labels in the graph legend, SLE01~SLE05, are the specimens' names. As shown in Fig.4, the amplification ratios were remarkably reduced as the input acceleration level increased. The specimens exceeded the elastic region in these excitations, and it is considered that the large hysteresis damping due to the plastic deformation affected the dynamic response behavior of the specimens. The reversing characteristics of the input motion may also work so as not to cause collapse failure. The experimental results showed that the fatigue failure would be most likely to occur on steel pipes though the reversing dynamic load is up to 20 times larger than the primary stress intensity limitation, and the collapse failure is unlikely to occur.

### ***Fundamental Plate Tests with Simulated Materials***

Because the failure mechanisms under the DEC are still unclear, it is necessary to conduct extensive investigations to find out the different kinds of failure modes and the conditions to cause each failure mode under the DEC. But as shown in the results of the pipe component tests on steel elbows, it is difficult to cause failure except for the fatigue on the actual pipe structures made of steel by the excitation input, because applying higher input accelerations on the steel elbow specimens was practically difficult in both aspects of the safety problem in the experiment, and the performance limit of the test facility. In order to investigate the failure modes under excessive seismic load extensively in safe experimental condition, fundamental plate tests has been conducted using plate-type test pieces made of a Pure lead (Pb) and Alloys of lead and antimony (Sb). The main object of the fundamental plate tests is to survey the



(a) Stress-strain curves of typical structural materials



(i) Room temperature

(ii) 100°C

(b) Stress-strain curves of Pb-Sb alloys

Figure 5. Stress-strain curves of typical structural materials and simulated materials (Pb-Sb alloys)

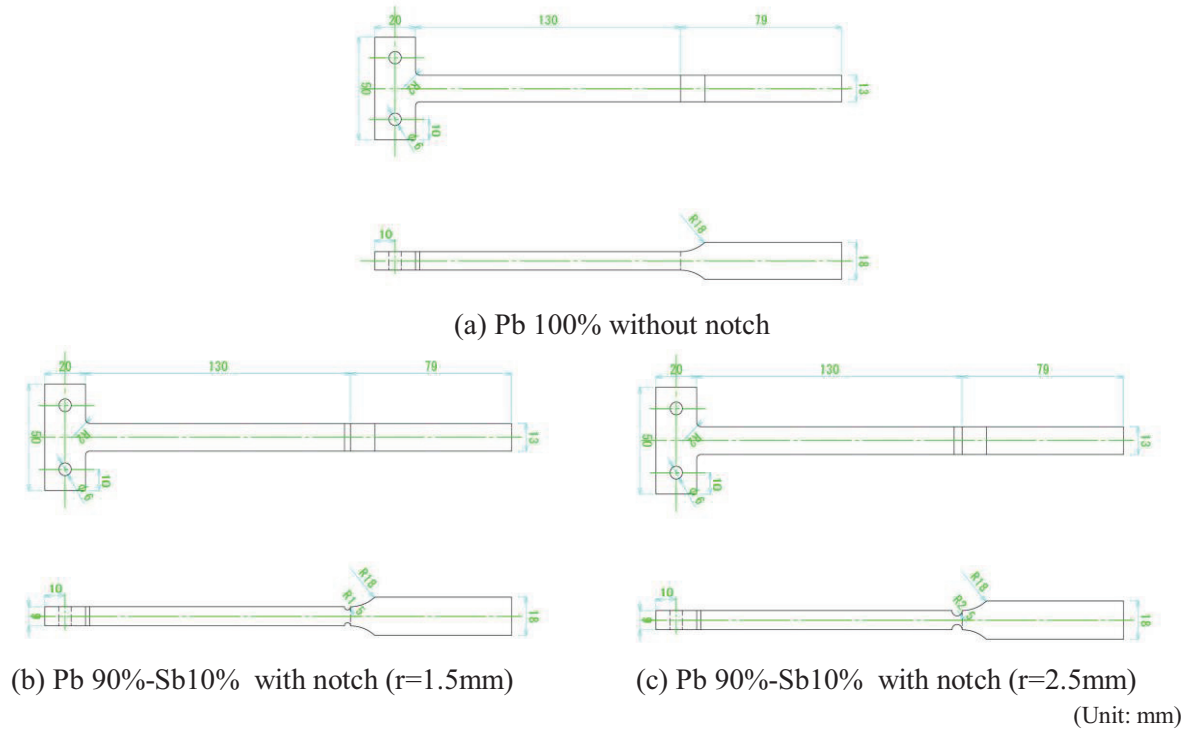


Figure 6. Configuration of the plate type test pieces for the fundamental plate tests

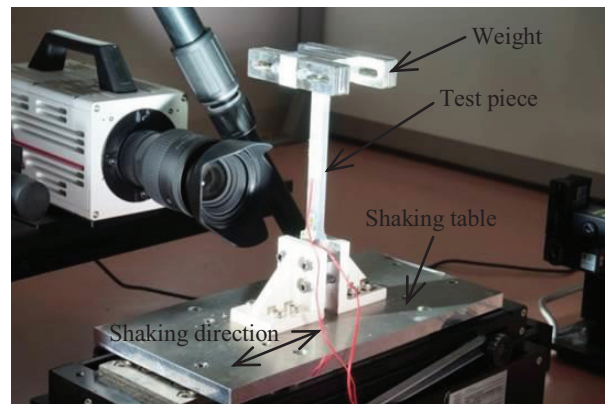


Figure 7. Test setup of the fundamental plate tests

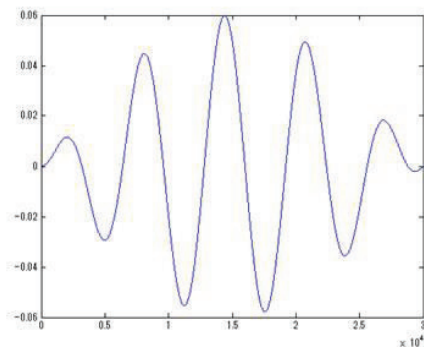


Figure 8. Pulse-like sinusoidal wave

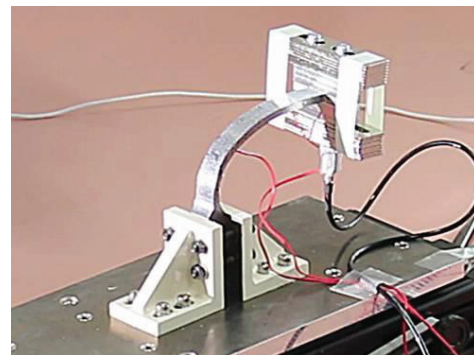


Figure 9. Ratchet-collapse failure mode of the plate-type test piece

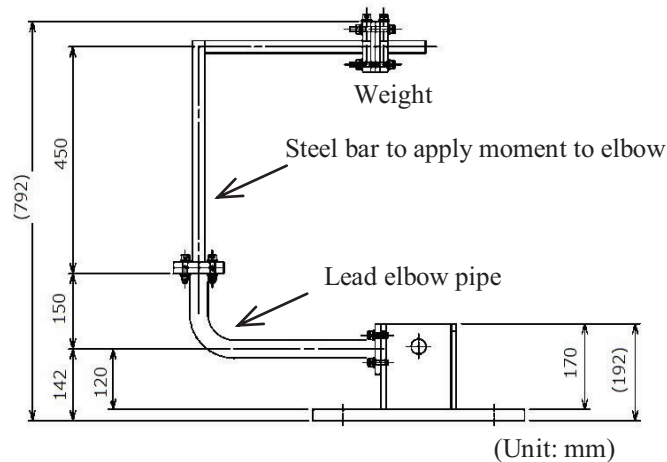
tendency and transition of failure modes under wide range of loading conditions in a qualitative manner. Figure 5 shows the stress-strain curves of steel (the typical structural materials) and Pb-Sb alloys. Solid and chained lines for Pb-alloys mean variations among specimens. As shown in Fig.5, yield stress of alloys is less than 10% of steel. It means that the required external force to cause failure would be reduced less than 10% of the steel structures and it is expected that the failure modes under the excessive seismic loads would be obtained by the existing testing facility in safe condition. Furthermore, the material ductility can be varied for Pb-Sb alloy by controlling the Sb ratio in alloy. For example, a pure lead (Pb 100%) is very ductile (about 50% ductility), and it can simulate the very high temperature conditions of structural materials. Alloys of Pb 96% -Sb 4% and Pb 90% - Sb 10% have the similar trend stress-strain curves to typical structural materials. Alloy of Pb 80% - Sb 20% exhibits brittle behaviour (less than 1% ductility).

Figure 6 shows the configuration of the plate-type test pieces. The test pieces set on a shaking table with weights at the top as shown in Fig.7. Some test pieces have a notch at their bottom parts. The input waveform mainly used in the fundamental plate tests is a pulse-like sinusoidal wave as shown in Fig. 8 or constitutive sinusoidal wave. The mass of the weight was 820g, and the input frequency at the excitation tests was 15.625Hz. The maximum peak ground acceleration is about  $100\text{m/s}^2$

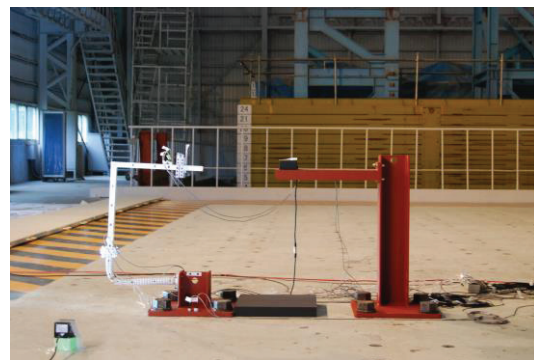
As a result, the failure mode was the fatigue failure in most cases of the fundamental plate tests. But different failure modes were also observed in some cases. Ratchet deformation and subsequent collapse (hereinafter this type of the failure mode is called as "ratchet-collapse") was observed in the Pb 100% test pieces under a high-level pulse-like sinusoidal wave (more than 30 times larger than the yield stress level). As for the test pieces with notch made of the alloy Pb 90% - Sb 10% resulted in the ductile fracture. Figure 9 shows the test results of the Pb 100% test pieces under a high-level pulse-like sinusoidal wave. As the pulse-like sinusoidal wave applied to the test pieces repeatedly, the lean deformation occurred and accumulated in one side, and finally collapse after fifth excitation by the pulse-like sinusoidal wave.

### *Pipe component Tests on Lead Elbows*

From the fundamental plate tests, it seems that the experimental approach to use test specimens made of the simulated material is useful to investigate the failure behaviour under the excessive reversing dynamic load qualitatively. The kinds of failure modes obtained by the fundamental plate tests were the fatigue, the ratchet-collapse, and the ductile fracture. The next step to investigate the failure modes of the piping system is to clarify whether such failure modes would occur on a pipe structure, which is more realistic structural model. In order to investigate the occurrence of such failure modes on a pipe structure, the excitation tests on pipe elbows made of pure lead were planned as the next structural tests. In



(a) Dimension of the test specimen



(b) Test setup

Figure 10. Configuration of the test specimen of the lead elbow tests

considering the condition of the fundamental plate tests, the inverted configuration of the elbow specimen was adopted. The configuration of the specimen is shown in Fig.10. As a preliminary result, the ratchet-collapse failure occurred by a few repetition of the large pulse-like sinusoidal input. The obtained failure mode is shown in Fig.11. The lead elbow tests are currently underway, and the detail of the experimental results would be described in near future.

### ***Failure Modes from the Excitation Tests***

From the experiments on steel elbow pipes and specimens made of Pb / Pb-Sb alloys, the possible failure modes under excessive seismic loads are mainly thought to be 1) fatigue failure, 2) ratchet-collapse, and 3) ductile fracture in the case of low ductile materials. The most likely failure mode is the fatigue failure both in the pipe component tests and the fundamental plate tests. In some cases of the excitation tests on the specimens made of Pb, the ratchet-collapse failure mode was observed both on the plate-type test pieces and the pipe elbow specimens. This failure mode was observed under the condition that the specimen was a top-heavy configuration, and was excited by a high-level pulse like sinusoidal wave. Once a lean deformation occurs on the top-heavy configuration specimen, the collapse failure would be accelerated by the gravity effect. The ductile failure was obtained in one case in the fundamental plate tests on the test piece with a notch made of Pb90%-Sb10% alloy. From these results, the relation between the intensity of the input motion and the strength of the piping specimen is of course one important factor, furthermore it seems that other factors, such as the configuration of the specimen, the material property, the existing stress concentration part and so on also affect the occurrence of a specified failure mode. In the next step, the effect of the relation between the frequency of the input motion and the natural frequency of the specimen, the effective numbers of cycles in the input motion to cause the fatigue failure, the failure mode by the random wave such as seismic motions, etc., are still necessary to investigate to clarify the failure mechanism under excessive seismic loads.

### **CONCLUSION**

In order to clarify failure modes under excessive seismic load, a series of excitation tests were conducted. The excitation tests consist of mainly two sections; the pipe component tests and the fundamental plate tests. In the pipe component tests, the shaking table tests on steel elbow specimens were conducted. In the fundamental plate tests, the experimental approach to use the simulated materials (a Pure lead (Pb) and Alloys of lead and antimony (Pb-Sb) ) was proposed to obtain failure modes under excessive seismic load in a safe manner. Because the experimental approach to use the simulated material was useful for extensive investigation of the failure behaviour qualitatively, the shaking table tests on lead elbow pipe were also conducted.

The possible failure modes under excessive seismic loads are mainly thought to be 1) fatigue failure, 2)

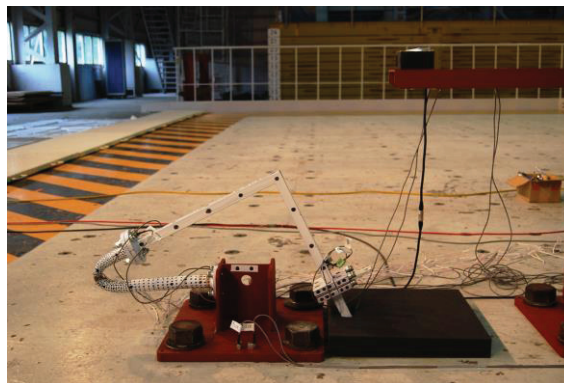


Figure 11. Ratchet-collapse failure mode of the lead elbow pipe

ratchet-collapse, and 3) ductile fracture from the experimental results. The most likely failure mode is the fatigue failure both in the pipe component tests and the fundamental plate tests. In some cases of the excitation tests on the specimens made of Pb, the ratchet-collapse failure mode was observed both on the plate-type test pieces and the pipe elbow specimens. The ductile failure was obtained in one case in the fundamental plate tests.

At the current moment, the qualitative tendencies of the failure mechanisms are obtained by the series of excitation tests. Further experimental investigations with the simulated material as well as the analytical approach would be conducted to elucidate the failure mechanism of piping structures under the excessive seismic load.

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