Seismic Simulation Test of a Fire Protection Riser Pipe with Fixed Groove Joints

S W Kim¹*, B G Jeon¹, S W Ahn² and S W Wi²

¹ Seismic Research and Test Center, Pusan National University, 49 Busandaehak-ro, Mulgeum, Yangsan, Kyungnam 50612, Republic of Korea
² Korea Testing Certification, 27 Heungan-daero, Gunpo, Gyeonggi, 15809, Republic of Korea

*Corresponding author: swkim09@pusan.ac.kr

Abstract. In this study, seismic simulation tests were conducted on a stainless steel pipe with fixed groove joints for fire protection systems using cyclic loading. When a seismic load occurred, the deformation of the specimen and the response by the relative displacement between the elements were analyzed. To examine the behavior of the tee joints and elbow (vulnerable elements of the specimen) in the range higher than the ±1° minimum deformation angle in the event of an earthquake, the deformation angle was measured using an image processing method. The von Mises stress was also measured at the tee joint and elbow using a 3-axis strain gauge, and the result was compared with the allowable stress criterion to confirm the seismic performance.

1. Introduction

With the improvement of living standards and the continued industrial development, the importance of air-conditioning machinery, industrial machinery, and piping materials has been recognized. Pipes are used as applications in all industrial fields, such as machinery, electricity, electronics, fibers, refrigeration air conditioning, and plants, and they are also widely utilized in areas related to fire protection, chemistry, and safety, thereby increasing the importance of the piping area by day. Although pipes are connected to major structural sections, they do not support external loads and perform their own given functions. Thus, they can be classified as non-structural elements.

The trend of earthquake occurrence, among natural disasters, shows that earthquakes with magnitudes between 5.0 and 5.9 are increasing worldwide. Owing to this trend, studies for securing the seismic safety of non-structural elements are being conducted mainly in countries with frequent earthquakes [1,2]. Verification criteria for evaluating the mechanical performances of piping-related products, such as vibration, bending, and internal pressure, have been presented. Studies on seismic performance evaluation that consider the characteristics that may occur due to the behavioral difference between two supports in the event of a seismic load as well as the characteristics of pipes that exhibit the damage trend of low-frequency fatigue failure due to repeated displacement, however, are required. In the U.S., the National Fire Protection Association (NFPA) suggests the seismic design criteria of fire protection facilities, including piping [3].

In this study, a piping system with fixed groove joints was constructed by referring to NFPA13, and seismic simulation tests were conducted using cyclic loading. The behavior of the specimen due to
the displacement-dominant behavior caused by the deformation of the structure or the relative displacement between the structural elements in the event of a seismic load was analyzed.

2. Test Conditions and Method

In this study, a riser pipe system was selected as the test facility, and a steel frame was designed and fabricated to implement side sway using the relative displacement between the structural elements. The test facility was a riser pipe system with two tee joints and one 90° elbow. It was constructed to have pipe connectors within 305 mm from the floor and 610 mm from the ceiling, in accordance with NFPA13.

To consider the actual operating conditions, the pipe was filled with water, and a 2 MPa internal pressure was applied using a booster. For the allowable side sway suggested by the International Building Code (IBC) as shown in Table 1, ten static cyclic loading tests were conducted [4]. $h_{xx}$ represents the floor height of the corresponding floor.

| Table 1. Allowable side sway of IBC |
|-----------------------------------|
| Risk category | I or II | III | IV |
|----------------|--------|-----|-----|
| $0.020 h_{xx}$ | 0.015 $h_{xx}$ | 0.010 $h_{xx}$ |

**Figure 1. Riser pipe system with fixed groove joint**

Figure 1 shows the riser pipe with fixed groove joints obtained using the image measurement system for measuring the deformation angle [5,6]. Table 2 shows the major components and subassembly lists of the specimen. The height of the specimen was 3 m (3.04 m including the plate for connecting the load cell).

Figure 2 shows the specimen installed for the side sway test of the riser pipe system as well as the installation locations of the sensors. As for the sensors, a 3-axis load cell (MC63-3A, Dacell) was fastened to all the ends of the riser pipe with bolts to measure the drawing force. Previous studies reported that the damage to piping caused by earthquakes is low-frequency fatigue failure, and that damage caused by displacement-dominant behavior may occur at the fittings, such as the tee joints and elbows, where the nonlinear behavior is concentrated [6]. Therefore, a 3-axis strain gauge (FRA-5-11-5L, Tokyo Sokki) was attached to the center of the tee_2 joint (3SG-1) and to the crown location of
the upper elbow (3SG-2). For cyclic loading, two actuators were connected to the upper slab of the steel frame. In addition, a frame connected with hinges was used so that the load could be applied only to the pipe system when cyclic loading was performed using the actuators. The loading displacement and the load were measured using the load cells of the actuators and an LVDT (linear variable differential transformer; SDP-300D, Tokyo Sokki).

Table 2. Major components and subassembly lists

| Part name          | Specifications                         | Quantity |
|--------------------|----------------------------------------|----------|
| Pipe               | KS D 3507 SPP, 100A 4.5T               | -        |
| Elbow              | KS D 3507 SPP, 100A 4.5T, 90° elbow    | 1        |
| Tee                | KS D 3507 SPP, 100A 4.5T, 100A         | 1        |
| Angle check valve  | L-type                                 | 1        |
| Hammerless valve   | Hammerless valve                       | 1        |
| Joint              | Groove joint (fixed), steel, manufacturer C | 11       |

Figure 2. Side sway test of the riser pipe system

The fixed groove joints must endure an at least ±1° deformation in the event of an earthquake. Moreover, according to the results of previous studies, leakage occurs in tee joints with groove joints due to the gradually amplified cyclic loading at the lower than 1.15° deformation angle [7]. For this reason, for the seismic safety evaluation of pipe connectors, which are major piping elements vulnerable to earthquakes, it is necessary to consider the deformation angles of major piping elements. Therefore, the displacement responses were measured at each point of Figure 1 using the image processing method, and the deformation angles were measured using the measured displacement responses.

3. Test Results and Analysis

Ten cyclic loading tests were conducted for the allowable side sway (0.02 $h_{xx}$, ±60 mm) suggested by IBC. After the seismic simulation tests, test facility deformation, leakage, cracking, parts separation, and damage did not occur. In this study, the deformation angles were measured using the image processing method, and the displacements were measured at the tee joints and elbow, the riser pipe
elements vulnerable to earthquakes. Figure 3 shows the deformation angles measured at the tee_2 and elbow points, and Table 3 shows the maximum and minimum deformation angles measured from the cyclic loading test. As can be seen from Table 3, the maximum deformation angle range of the specimen was $3.83^\circ$ for the upper elbow, $1.38^\circ$ for the tee_1 joint, and $1.68^\circ$ for the tee_2 joint (angle check valve). Therefore, when a structure with a 3 m floor height is loaded with a $0.02 \ h_0$ magnitude, the maximum deformation angle range applied to the elbow of the riser pipe is more than $1^\circ$, resulting in a higher than $1^\circ$ deformation angle, the minimum deformation criterion of fixed groove joints, in the event of an earthquake.

Table 3. Deformation angle at vulnerable components of the riser pipe

| Position           | Target  | Maximum deformation angle (Degree) | +  | -  | Max. range |
|--------------------|---------|------------------------------------|----|----|------------|
| Tee_1              | 1~4     | 0.55 -0.83                         | 1.38|
| Tee_2 (angle check valve) | 4~6     | 0.57 -1.11                         | 1.68|
| Upper elbow        | 7~10    | 1.88 -1.95                         | 3.83|

Figure 3. Deformation angles measured at the tee_2 joint and elbow

Figure 4. Strain responses measured at the tee_2 joint and elbow

Figure 4 shows the responses measured at the tee_2 joint and elbow of the specimen using the 3-axis strain gauges. Table 4 shows the measured maximum strain values and confirms that the strain values measured at the tee_2 joint and elbow were relatively small.
Table 4. Maximum strain responses

| Location name | Orientation | Measured strain (μm/m) |
|---------------|-------------|------------------------|
|               |             | Max.   | Min.   |
| SG3-1         | X           | 309.0  | -124.2|
|               | 45°         | 286.3  | -142.2|
|               | Y           | 201.9  | -124.2|
| SG3-2         | X           | 270.1  | -147.9|
|               | 45°         | 306.2  | -158.3|
|               | Y           | 233.2  | -100.5|

The minimum tensile strength (0.2% offset) of SUS 304 stainless steel, the piping material used in this study, is 205 MPa, and its allowable stress is 137 MPa because it accounted for 2/3 of the tensile strength [8]. The stress criterion of the Class 1 piping of a nuclear power plant under the Level D service loading condition suggested by ASME Boiler & Pressure Vessel Code, SEC III, DIVISION I, Subsection NB, NB-3656 is less than a third of the allowable stress. The Level D service loading condition is a load combination that occurs with an extremely low probability, and includes seismic loads [9]. Therefore, if the von Mises stress measured from the specimen is lower than 410 MPa, the specimen is considered safe against earthquakes. Figure 5 shows the von Mises stress values measured at the tee_2 joint and upper elbow of the specimen using the 3-axis strain gauges. In Table 5, the measured von Mises stress is compared with the allowable stress, and based on this, it was found that the measured stress was lower than the allowable stress criterion. When construction was performed according to the method suggested by NFPA13, as shown in Figure 5 and Table 5, the strain and von Mises stress that occurred to the pipe with fixed groove joints were low, and the margin was high compared to the allowable stress criterion.

Figure 5. von Mises stress measured at the tee_2 joint and elbow

Table 5. Comparison of the measured and allowable stress values

| Location | Measured max. stress (S, MPa) | 3Sm (MPa) | S/3Sm |
|----------|-------------------------------|-----------|-------|
| SG3-1    | 74.82                         | 410       | 5.35  |
| SG3-2    | 73.34                         | 410       | 5.45  |
4. Conclusion
In this study, for the evaluation of the seismic performance of a riser pipe with fixed groove joints, cyclic loading tests were conducted using the pipe installation method suggested by NFPA13 and the allowable side sway of IBC. After the seismic simulation tests, test facility external deformation, leakage, cracking, parts separation, and damage were not observed through visual inspection, and infinitesimal deformation of the components was not found as well. Moreover, the von Mises stress values of the tee joints and elbow, the vulnerable elements of the riser pipe, were lower than the allowable stress, and it was confirmed that the margin of the riser pipe with fixed groove joints for the seismic performance was high.

Acknowledgments
This work was supported by the Technology Innovation Program (or Industrial Strategic Technology Development Program) (10078266, National Standard Technology Improvement program) funded by the Ministry of Trade, Industry & Energy (MOTIE, Korea). Moreover, the authors would like to thank the KOCED Seismic Research and Test Center for their assistance with the test equipment.

References
[1] Oh SH and Shin SH 2016 Correlation analysis of Gyeongju Earthquake waveform and structural damage scale Journal of the Architectural Institute of Korea Structure & Construction 32(12) pp. 33-44
[2] Yoon BI 2018 Nonstructural elements resulting from Pohang Earthquake and direction of future seismic design nonstructural elements Review of Architecture and Building Science 62(4) pp. 23-28
[3] NFPA 13 standard for the installation of sprinkler systems
[4] IBC 2012 International Building Code International Code Council
[5] Kim SW, Choi HS, Jeon BG, Hahm DG, Kim MG 2018 Strain and deformation angle for a steel pipe elbow using image measurement system under in-plane cyclic loading Nuclear Engineering and Technology 50(1) pp. 183-195
[6] Kim SW, Choi HS, Park DU, Baek ER, Kim JM 2018 Water level response measurement in a steel cylindrical liquid storage tank using image filter processing under seismic excitation Mechanical Systems and Signal Processing 101 pp. 274-291
[7] Bursi OS, Reza MS, Abbiati G, Paolacci F 2015 Performance-based earthquake evaluation of a full-scale petrochemical piping system Journal of Loss Prevention in the Process Industries 33 pp. 10-22
[8] ASME Section II Part D
[9] ASME 2007 Boiler & Pressure Vessel Code, SEC III Division I Subsection NB NB-3656