Environ. Eng. Res. 2023; 28(3): 210639
https://doi.org/10.4491/eer.2021.639

pISSN 1226-1025
eISSN 2005-968X

Research

Experimental Evaluation of Water Supply Pipe Joints against Seismic Ground Deformation: A Four-point Bending Test

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Received December 24, 2021 **Revised** April 18, 2022 **Accepted** May 11, 2022

ABSTRACT

Due to permanent ground deformation (PGD) such as earthquakes and liquefaction, water supply pipes and connected joints may experience rotation and deflection through losing its function and complex water contamination. Since the specifications of joints are different in each country, evaluating joints are difficult to manage the functional maintenance of water network system. In this study, two metallic and three non-metallic pipe joints were selected through the joints commonly used in Korea. PGD simulation could be conducted through Four-point bending test which derives the result of deflection angle, moment, and strain value for damaged pipes. Each component showed above M-1 grade which resulted based on the grade of ISO 16134. To compare metallic pipe results, collar joint showed stronger binding force than the mechanical joint, but in deflection angle result mechanical showed higher value. In non-metallic pipe test, since its material contains large flexibility, strain value mainly affected its result. Based on this study, functional evaluation of water supply pipeline regarding the PGD was identified through comparing tendency of each joint characterization. Moreover, these data can be expected to be utilized as the basis of performance evaluation and critical component in piping design.

Keywords: Four-point bending test, Ground deformation, Seismic properties, Water supply pipe joint.

1. Introduction

Damage to urban infrastructure such as water supply and sewage pipe networks can cause serious socio-economic damage on supply of various water usage (drinking water, fire-fighting capacity and contamination of water resources and soil) [1-4]. Moreover, it is necessary to design the functional maintenance of water network system under critical risk assessment [5]. Since water supply pipelines are mainly buried in the lower part of the road or in filled up ground, bending deformation of a pipeline might occur due to many external factors (instability of the ground slope, landslides, liquefaction of the ground, floods, construction activities). In particular, ground deformation caused by external forces such as earthquakes is considered to be the most critical problem [6, 7]. In the 1994 Northridge earthquake-affected area of Los Angeles, USA, the installed pipelines were 72% cast iron (CI) and 8% ductile iron (DI) [8]. Also, Buried water supply pipes in the US with diameters of 200 mm or less account for 66% of the pipelines [9]. In Turkey, which is an earthquake-prone area, DI, polyethylene (PE), and polyvinyl chloride (PVC, 100-200 mm inner diameter) are mainly installed [10]. In the capital of South Korea, more than 86.6% DI and 9.7% non-metallic pipes are used in the domestic capital areas. The most commonly used pipes are regulated with a minimum diameter of 150 mm. In Japan, the Nikata earthquake in 2004 pipeline resulted in 150 km of pipeline breakages, which is 4.6% of the total pipeline length [11, 12]. For the great east Japan earthquake, of the 65,001 km of pipes, 642 km were broken of which about 90% was damaged by liquefaction [13]. Also, in Korea, based on the Pohang earthquake in 2017 and Gyeongju earthquake in 2016, which were the strongest domestic earthquakes measured in the last 50 years, there is no longer an earthquake-free zone [14, 15, 16]. Through these experiences, it was reported that most damaged pipelines bent when ground deformation occurred and the part that bent

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the most was the joint part. As a result, it is necessary to evaluate the deflection limit of the joint. In damage to buried pipelines due to ground deformation, it has been noted that permanent ground deformation (PGD) has resulted in severe loss of lifeline functions, as in the case of Canterbury in New Zealand [17, 18]. In addition to the American Lifeline Alliance (ALA) [19], many engineers commonly use PGD as a major factor in the vulnerability of buried pipeline structures related to ground deformation [20, 21, 22]. Moreover, most pipelines function as a tunnelling-type structure with joints. In relation to PGD, it has been reported that the joint connections of pipes greatly affect the tensile and compressive forces applied in the axial direction (pull-out) in addition to the rotation of the joint [23]. In this regard, there are cases of tensile, compression, four-point bending, and ground fault simulation tests for DI [23, 24, 25, 26, 27] and PVC [28, 29] socket-type joints used in the US. For the four-point bending test, limit deflection of the pipeline at the time of leakage of water was specifically evaluated. Regarding the pipeline deflection angle, the seismic performance standard of DI material is available for component grades in ISO 16134 [30]. However, there is less guidance for the sockets or joints of non-metallic pipes. Thus, there are very few regulations on the durability of pipe joints in each country, where the frequency of disasters and specifications of the basic pipe products used are different in each country. Therefore, it is necessary to review the seismic performance of the PGD joints of piping materials used in each region. Only the socket types of DI and PVC pipes have been reported for the bending performance of joints against ground deformation, but it is necessary to evaluate other materials and joint types. In this study, DI, PVC, and PE material pipes, which are the most commonly used in Korean water supply pipelines, were tested. For testing under the same conditions as the PGD-related four-point bending test, a specimen with an inner diameter of 150 mm was evaluated. For DI and PVC, an external detachable socket with a mechanical joint and HP joint that tighten the rubber gasket were used. For PE, fusion bonding was used to evaluate the bending limit performance against leakage. Through the four-point bending test assuming PGD, the performance against leakage of the pipeline was compared with the results of previous studies. Moreover, in this study, we reviewed the functional maintenance level of various type of joints.

2. Materials and Methods

2.1. Materials

The 150 mm DI pipes evaluated in this study (Knuckle Pin (KP) Mechanical joint, Collar connection joint) frequently used in Korean water distribution systems were manufactured by Ill-san Steel Co., Ltd. Moreover, 150 mm HI-VP (High Impact Vinyl Pressure) pipes (with one rubber-ring socket, two rubber-ring socket) and HDPE (High Density Polyethylene) pipe (with fusion-bonding) were provided by Shin Woo Co., Ltd. Each pipe was equipped with separation restraint material, commonly used in each joint, and manufactured in accordance with the Korean Standards association [31, 32, 33, 34]. A summary of the test specimens is provided in Table 1 and Fig. S1. The required sensors for the tests were strain gauges and a wire displacement gauge (maximum measuring length: 500 mm), which was manufactured by the Tokyo measuring instrument lab (Type: Flab-5-11-5LJC-F, DP-E). In Table S1, the purpose and significance of each test specimen are summarized.

2.2. Composition and Four-Point Bending Test Method

The four-point bending test was conducted for all samples at the Myung-ji University Hybrid Structure Testing Center, which satisfies international ISO 17025 quality requirements, as shown in Fig. S2. For the four-point bending test, the test specimen was installed under a 250 kN (MTS Co., LTD) actuator with designed pressing and supporting frames. Before putting each test specimen together, lubricant was applied to the inside surface of the joint spigot following the manufacturer's installation guide [18]. The displacement and load were measured using a displacement meter and load sensor installed in the MTS Co., LTD software. The description of the test specimen and sensor locations are shown in Fig. 1 and Table 2.

The axial strain was measured by using strain gauges and the vertical displacement was measured using displacement gauges in each selected location. Moreover, for each support and load point, all pipes were covered with clamps to prevent the occurrence of deformation. The maximum capacity of the MTS actuator used in the four-point bending test was 200 kN with a maximum displacement of 600 mm. To perform the four-point bending test, points

Table 1. Characteristics of the Pipes Evaluated by the Four-Point Bending Test (Inner Diameter of 150 mm)

Specimen name.	Type		Components	Out diameter (mm)	Length (m)	Company
	property	Pipes type				
FDK_1	Metal	DI (2^{nd} type)	1. KP mechanical joint 2. Separation restraint wheel	170	6	Ill-san Steel Co., Ltd.
FDC_2	Metal	DI (2^{nd} type)	1. Collar connection joint 2. Separation restraint wheel	170	6	Ill-san Steel Co., Ltd.
FHS_3	Non-metal	HI-VP	1. Socket joint (one rubber-ring) 2. HP separation restraint	165	4.5	Shin Woo Co., Ltd.
FHS_4	Non-metal	HI-VP	1. Socket joint (two rubber-ring) 2. HP separation restraint	165	4.5	Shin Woo Co., Ltd.
FPF_5	Non-metal	HDPE	1. Fusion bonding	160	4.5	Shin Woo Co., Ltd.

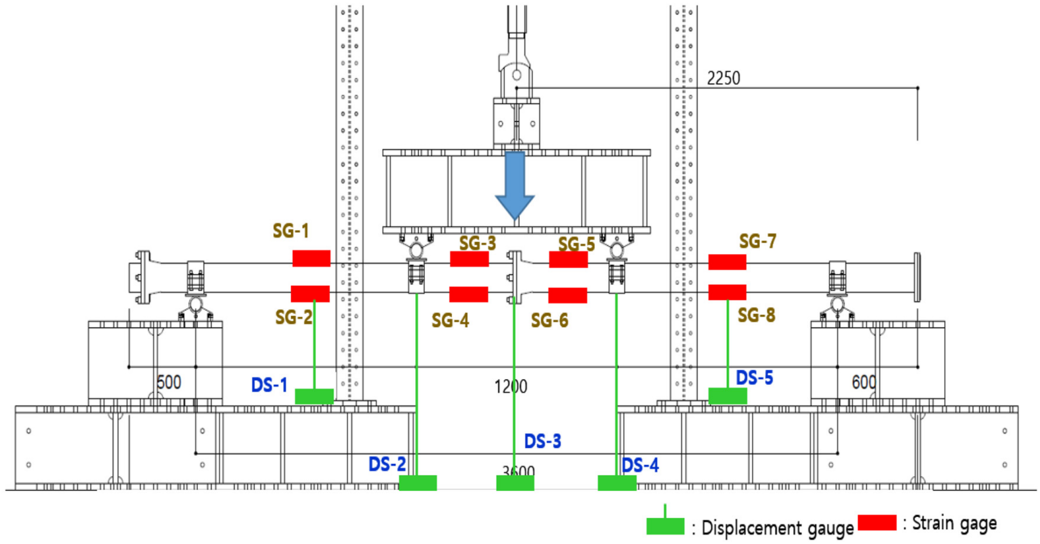

Fig. 1. Schematic of the attached gauges in the four-point bending test.

Table 2. Sensor Information of the Four-Point Bending Test

Instrument name	Location from the center joint (mm)		Sensor description
	a) Metal pipe specimen	b) Non-metallic pipe specimen	
SG-1 SG-3	−1,500 −375	−1,200 −300	Axial gauge at Crown on the Spigot end
SG-2 SG-4	−1,500 −375	−1,200 −300	Axial gauge at Invert on the Spigot end
SG-5 SG-7	+375 +1,500	+300 +1,200	Axial gauge at Crown on the Bell end
SG-6 SG-8	+375 +1,500	+300 +1,200	Axial gauge at Invert on the Bell end
DS-1 DS-2	−1,580 −750	−1,200 −600	Vertical displacement transducer under the Spigot specimen
DS-3	0 (under center)	0 (under center)	Vertical displacement transducer under the joint
DS-4 DS-5	+750 +1,580	+600 +1,200	Vertical displacement transducer under the Bell specimen

Table 3. Test Conditions for the Four-Point Bending Test

Specimen name	Maximum Load (kN)	Loading rate (mm/sec)	Displacement length target (mm)	Water pressure (bar)
FDK_1	200	0.5	220-400	5
FDC_2				
FHS_3			530	
FHS_4				
FPF_5				

were formed at the positions of both ends of the assembled pipe from the center to the left and right [24, 29].

As described above, the MTS actuator's maximum loading range was 600 mm. To consider flexible materials of HI-VP and HDPE, the non-metallic test body was shorter than the DI pipes to observe its longer deflection length. Moreover, DI and HI-VP pipes are socket kind joints and HDPE is connected using fusion bonding. As shown in Table 3, the target displacement length was determined according to the condition of each specimen in all tests. In addition, pipes were fully filled with water and pressurized to an internal water pressure of 5 bar to check its loss of function [20]. A loading rate of 0.5 mm/sec was applied to each pipe through the MTS actuator.

2.3. Test Protocol and Deflection Analysis

To perform this test, a hoist was used to place metal and non-metallic pipes on white rollers installed on both sides of the supporting frame jigs set at distances of 2,500 mm (DI) and 1,800 mm (HI-VP, HDPE) from the middle of the specimen to the left and right. Two temporary supports were installed in the middle to sustain and prevent the test pipe from self-weight vertical displacement. To set the load point location, it was located to make each test specimen interval 1/3 of the total length. Strain gauges were attached at the crown and the invert part while displacement gauges were attached at the invert part of the test specimen. Moreover, water was injected into the pipes through a specially made flange stopper shown in Fig. S3. In the specially made flange stopper, two holes were added so that water enters one hole with pressure and air escapes from the other hole. Then, temporary supports were removed after the pipes were completely filled with water under a pressure of 5 bar, as shown in Fig. S4 [25]. The internal pressure was not adjusted during the test to determine if the specimen lost its function. Each test specimen was tested by an actuator-applied load until the leak was confirmed or the target displacement was reached. Fig. S5 summarizes the test method in a flow chart. The performance of each test specimen pipe during the four-point bending test was evaluated using the deflection angle, which was calculated using Eq. (1) [24-27].

$$\theta\ (Pipe\ deflection\ degree) = [tan^{-1}(\frac{B}{A}) \times \frac{180}{\pi}] + [tan^{-1}(\frac{B'}{A'}) \times \frac{180}{\pi}] \quad (1)$$

Eq. (1) is used to determine the deformation degree of the leak point for all test specimen where A and A are the distance between one side of the pressure point of test specimen to the displacement gauge in each bell and spigot side, respectively. B and B are the total specimen displacement length (displacement length recorded added with the self-weight displacement length) of each bell and spigot, respectively.

3. Results and discussion

3.1. Performance of the Vertical Displacement with the Joint Deflection Degree

Fig. 2 shows that each test specimen shows good agreement between the vertical movement measurements at equal distances from the center (joint) point of the test. The continuous progression of these displacements is further indication that the assumption of specimen motion in Eq. (1) can be used to determine its rotations. In the middle of the test, FDK_1 (Four-point bending test Ductile iron KP mechanical joint) and FDC_2 (Four-point bending test Ductile iron Collar mechanical joint) lost their function with vertical

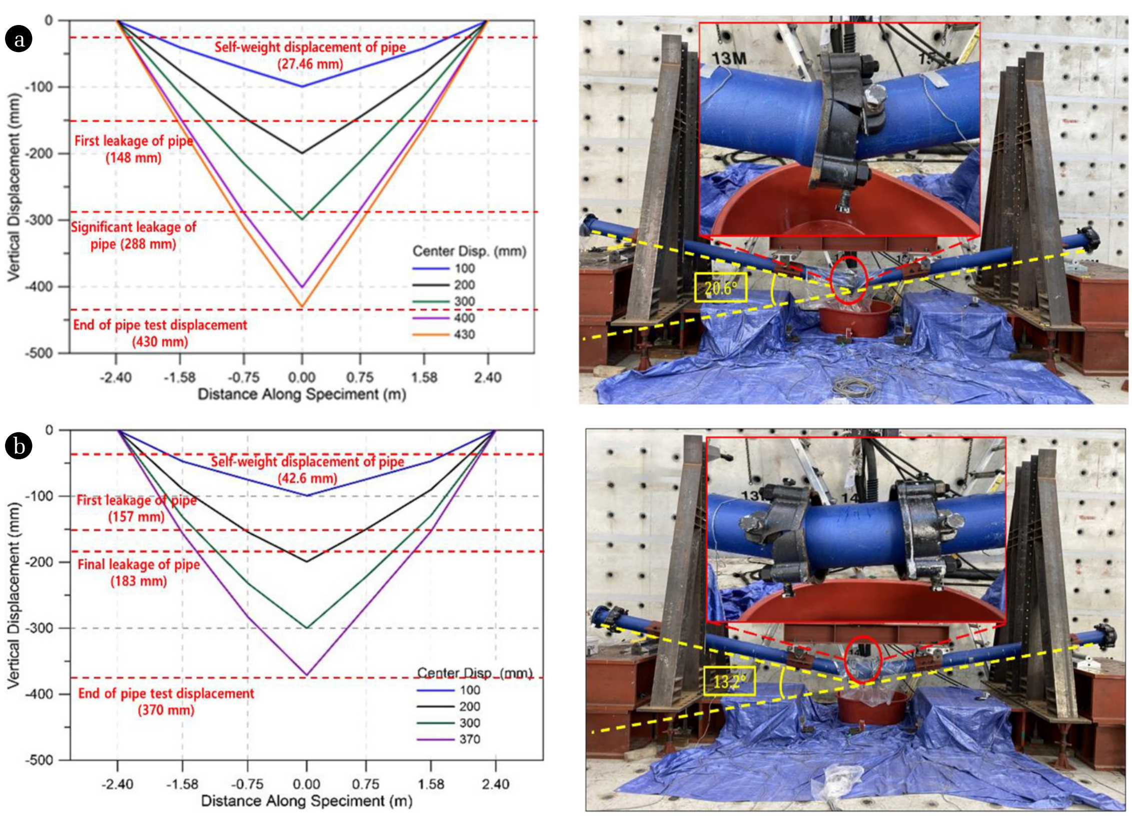

Fig. 2. Axial displacement of each test specimen. a: FDK_1 (Four-point bending test_DI_KP mechanical joint); b: FDC_2 (DI_Collar connection joint); c: FHS_3 (HI-VP_Socket joint with one rubber-ring); d: FHS_4 (HI-VP_Socket joint with two rubber-ring); e: FPF_5 (HDPE_Fusion bonding).

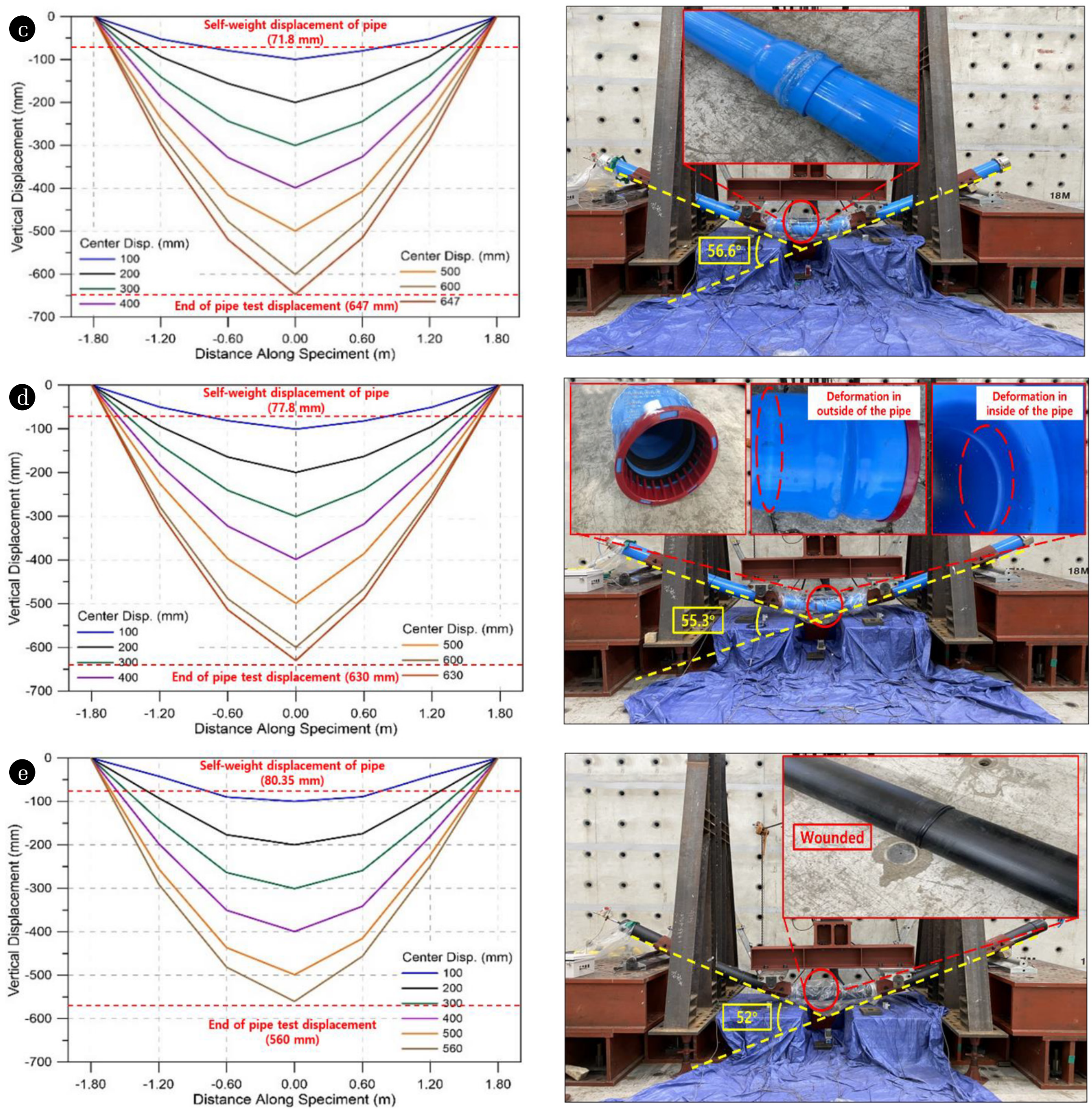

Fig. 2. Continue

displacements of the leakage marked in Fig. 2(a) and (b). The results also describe the joint in the form of deformation and fracture at the maximum vertical displacement of FDK_1 and FDC_2 [24]. In the DI test specimen pipe results, the deformation of the pipe was insignificant. However, the deformation and deflection angle which occurred at the joint caused the loss of function. However, the rest of the non-metallic pipes did not lose their function, rather they reached the maximum vertical displacement of the MTS actuator. Due to the non-metallic pipe results, the deflection degree was assumed to be their maximum vertical displacement [29].

The joint deflection degree of each test specimen was confirmed using Eq. (1) with adding the self-weight displacement length shown in Fig. 2. Table 4 summarizes the joint deflection degree of each specimen. According to Eq. (1), the joint deflection degrees of FDK_1 at the forced first leakage and leakage at the time of pipe failure (significant leakage) were 10.7 and 20.6°, respectively. For the joint displacement, the forced first leakage and leakage when the pipe loses its function were 148 and 288 mm, respectively. Moreover, the joint deflection degrees of FDC_2 for the forced first leakage and leakage when the pipe lost its function were 11.3 and 13.2°, respectively. The joint displacements were 157 and 183 mm, respectively, and were the same values as test specimen No. 1.

However, in the case of the four-point bending test results of the HI-VP and HDPE specimens, the loss of pipe function could not be confirmed due to limitations of the test equipment. The deformation of each non-metallic test specimen increased significantly not only in the joint but also in the pipe body. As shown in Fig. 2(c)-(e), the deformation of the non-metallic test specimen body was confirmed visually. The maximum displacement lengths of non-metallic test specimens (FHS_3 (Four-point bending test

Table 4. Performance and Standard Class of the Test Specimen Joint Deflection Degree

Metallic Test specimen	Inner diameter (mm)	Joint deflection degree (θ) Forced first leakage	Joint deflection degree (θ) Significant leakage	Standard class (ISO 16134)	Ref
FDK_1	150	10.7	20.6	M-1	-
FDC_2		11.3	13.2	M-1	-
DI; FR-FRE (American)		7.8	9.9	M-1	[24]
DI; EJS (Earthquake Joint System); (American)		12.7	16.6		[24]
DI; TR-Flex (McWane)		11.9	21.3	M-1	[25]
DI; SFC (Seismic Flex Coupling); (McWane)		1.8	32.5		[25]
DI; ERDIP T1 (Kubota)		12.2	14.3	M-1	[26]
DI; TR-Xtreme (US pipe)		-	9.1	M-1	[27]
Non-metallic Test specimen	**Inner diameter (mm)**	**Maximum joint deflection degree (θ)**		**Standard class (ISO 16134)**	**Ref**
FHS_3	150	56.6		M-1	-
FHS_4		55.3		M-1	-
FPF_5		50		M-1	-
PVC; i-PVC (PPI)		52		M-1	[29]

HI-VP Socket joint), FHS_4 and FPF_5 (Four-point bending test PE bonding joint) were 647 mm, 630 mm, and 560 mm, respectively. The maximum joint deflection degrees of FHS_3, FHS_4, and FPF_5 were 56.6, 55.3, and 50°, respectively, as shown in Table 4. In Eq. (1), the maximum displacement length of each specimen was applied to B and B'. Moreover, distance A was applied as the distance from the DS-1 point of the spigot pipe to the joint (center) and in the case of A, it is the distance from the DS-5 point of the bell pipe to the joint (center), where the applied value is the same as A. Table 4 describes the performance standard of the pipe joint deflection degree (ISO 16134), which represents the settling resistance performance of buried water supply pipes compared to the test specimen and previous test experiments. For each joint deflection result, the grade of each test specimen is also listed. First leakage refers to the leakage that occurs first during the test. In the case of significant leakage, it was assumed that 100 ml/min or greater leakage occurred, and it was confirmed that the function of the specimen was lost when the leakage occurred in the corresponding range. Table 4 compares the results of the first and significant leakage for the four-point bending test for Tyton joints in a previous study with the results of this study. In the case of first leakage, mechanical joints widely used in Korea and Tyton in the US show similar results. The initial leakage deflection degree for the common Tyton pipes in US (FR-FRE, TR-Flex, DRDIP T1, and TR-Xtreme) was between 7.8 to 12.7°. For the significant leakage deflection degree, it was between 9.1 to 21.3°, which is similar to the maximum values of the FDK_1 and FDC_2 results. For seismic products (EJS and SFC), the deflection angle was improved compared to the general joints of the same manufacturer.

3.2. Performance and Response of the Four-Point Bending Test

3.2.1. Metallic test specimen (DI)

In Fig. 3, the left side of the graphs indicates the relationship between the moment and rotation, while the right side of the graphs describes the relationship of strain deformation and axial displacement. In Fig. 3(a), when the joint rotations of test specimen FDK_1 were 10.8 and 12.6°, the moment value rapidly decreased. As shown in Fig. 2(a), the upper part of separation restraint wheel surrounding the KP mechanical joint showed a steady break and the joint's load-resisting capacity was continuously lost. Moreover, the strain deformation value rapidly decreased at the point where the joint separation restraint of FDK_1 started to break. As the separation restraint wheel was broken, the deformation of the test specimen itself does not increase anymore and is concentrated on the rotational deformation of the joint. In Fig. 3(b), when the joint rotation of test specimen FDC_2 is 18.3°, the moment value rapidly decreased. The load-resisting capacity of the joint was lost as the upper left part of the separation restraint wheel installed on both sides of the collar connection joint was damaged, as shown in Fig. 3(b).

Also, the strain deformation value rapidly decreased at the point where the joint separation restraint was broken, which confirms that it is concentrated on rotational deformation rather than the increase of deformation, as shown in Fig. 3(b). In the case of a collar coupling joint (FDC_2), the moment value is approximately 2.3 times higher than that of a KP mechanical joint (FDK_1) because there is one more joint separation constraint, which means that the load resistance capacity is stronger. However, if a break occurs, the collar connection joint loses its functionality. For the KP mechanical joint (FDK_1), the axial displacement is slightly more flexible than FDC_2. In the case of metal pipes, the deformation is a straight line because there is almost no deformation of the body part of both pipes connecting at the joint. Through FDK_1 and FDC_2, SG-3, 4, 5, and 6 were located close to the joint and the results were larger than those of SG-1, 2, 7, and 8, which was near the supporting frame side of the specimen. Moreover, in the case of FDK_1 and FDC_2, as the vertical displacement increases, the value of strain decreases suddenly. FDC_2 maintained a straight shape due to its loading capacity and showed a 190% larger strain value when it reached the maximum result. The strain of FDK_1 increased non-linearly due to the joint and the pipe became gradually unscrewed as the test proceeded. In the case of the strain value of

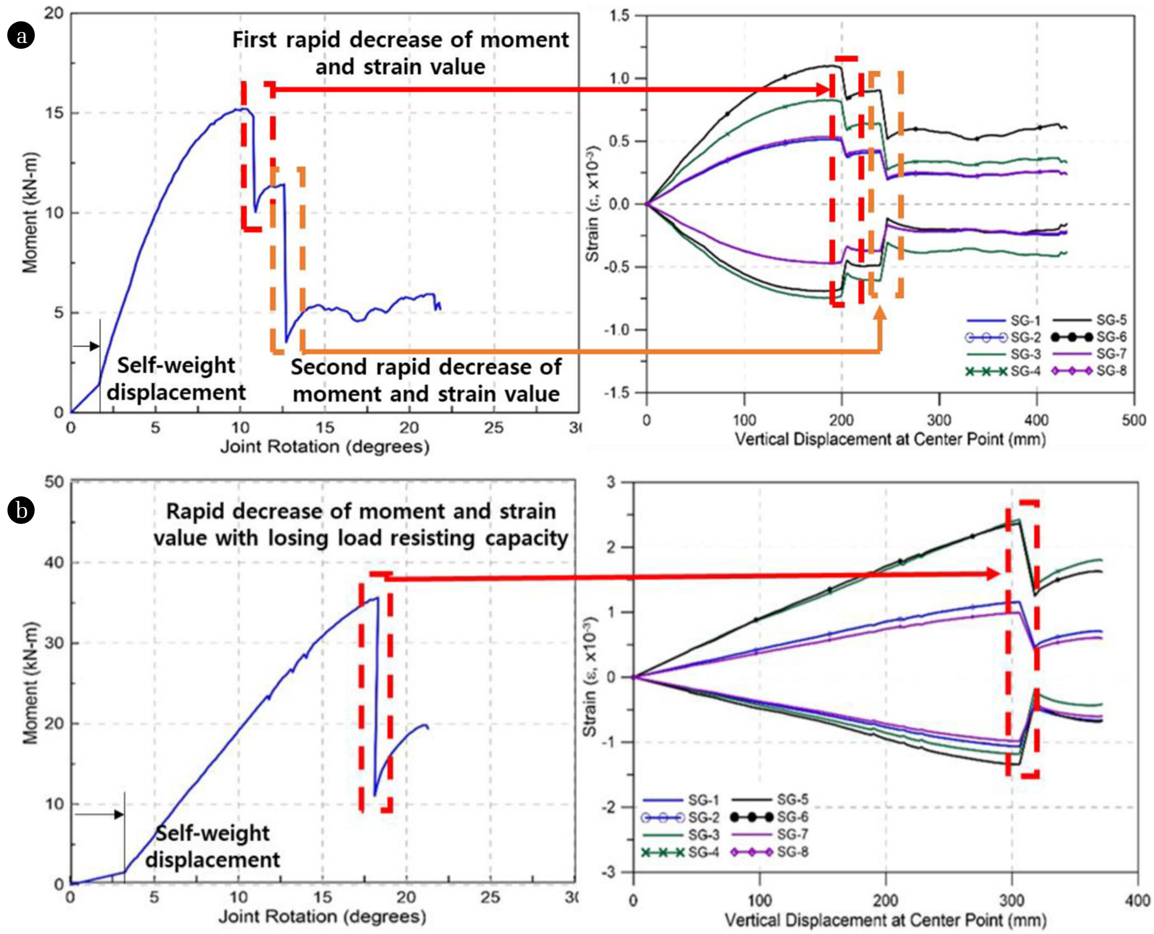

Fig. 3. Moment-rotation and strain response of the metallic test specimen. a: FDK_1 (DI_KP mechanical joint); b: FDC_2 (DI_Collar connection joint).

FDC_2, the coupling between the joint and the pipe was not loosened until the point of significant leakage.

3.2.2. Non-metallic test specimen (HI-VP, HDPE)

In Fig. 2(c)-(e), the shape of the pipe itself became deformed in the case of non-metallic pipes. As shown in Fig. 2(c) and (d), the pipe insertion hole rotated inside the socket and a large flaw occurred at the lower end. Fig. 4 shows the moment value and strain of the specimen. The tendency of SG-3, 4, and 5 in non-metallic test specimen was larger than that of SG-1, 2, 3, and 4. Unlike metallic pipes, non-metallic pipes showed similar results in the upper and lower sides of the strain gauge. For FHS_3 and FHS_4, although the structural shape of the socket part was different than HI-VP material, similar results (strain result value, each displacement step) were obtained. Since the material of FPF_5 is more flexible, the maximum moment result value was at the quarter level compared to FDK_1 and FDC_2. The moment value of each specimen shows a gentle trend and when the maximum amount of displacement is reached, the strain at the center of the specimen (SG-3, 4, 5, 6) and at both ends (SG-1, 2, 7, 8) showed a difference of about 3 times or more. As the shear force of the socket located in the center increased, the stress and bending angle increased. As such, when the seismic accessory device is excluded from the joint part, it is judged that the shearing action is made, and it is vulnerable to earthquake resistance. In addition, it is judged that the seismic performance varies according to the material of the pipe rather than the structural shape of the socket being affected by the moment value. In comparing metallic and non-metallic pipes, non-metallic pipes have low moments and high strain values due to the flexibility of the materials.

4. Conclusions

1) Based on the results of the 4-point bending test deflection angle based on the grade suggested by ISO 16134, in the case of DI, the initial leakages of Tyton material in existing research and the materials in this study were similar and the basic performances for seismic resistance were similar. Although similar, it can be seen that the maximum bending angle can be different. In particular, in the case of significant leakage, there is a lot of significant difference from seismic joints, but since all general joints are graded M1, which is the highest grade, a standard

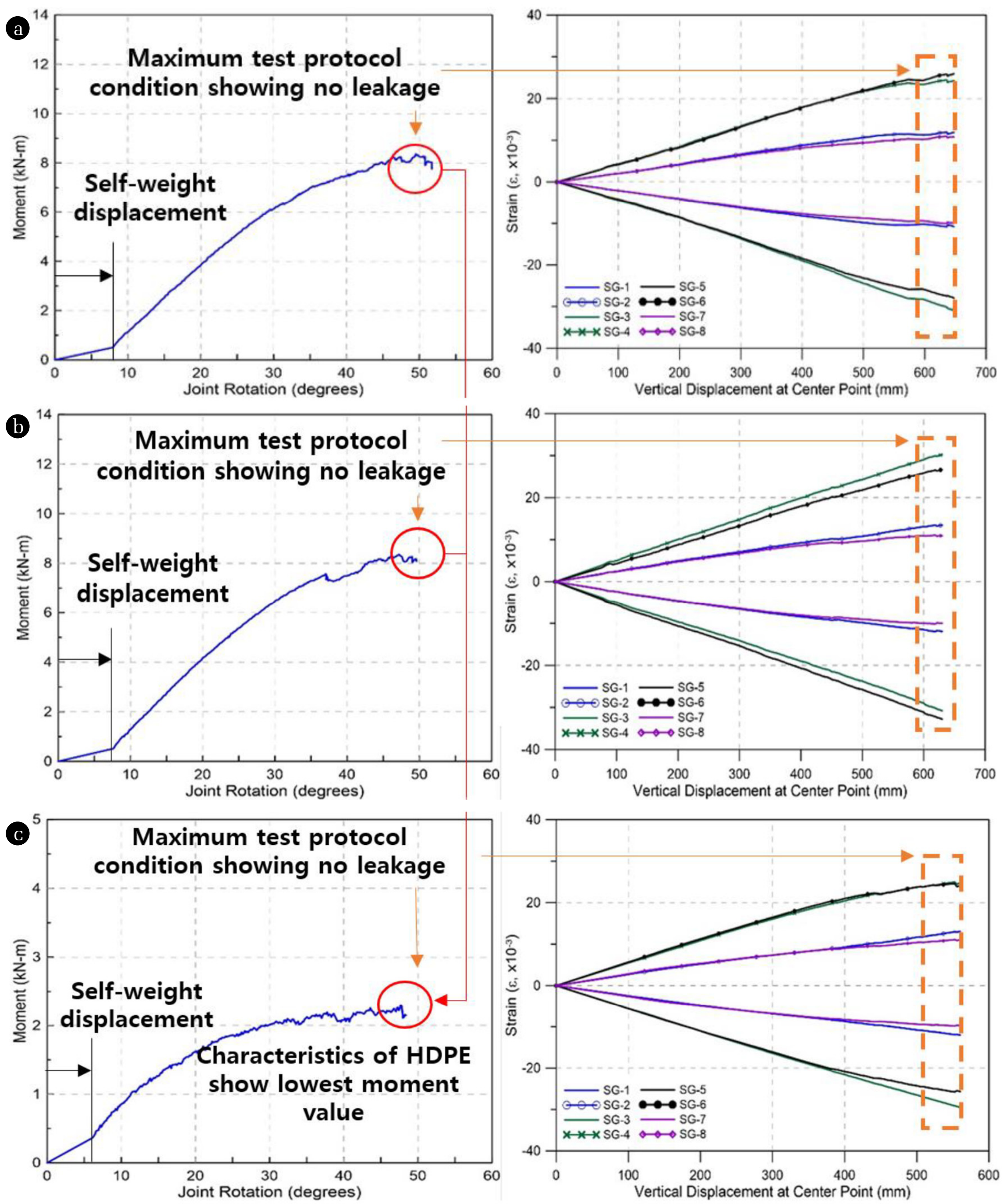

Fig. 4. Moment-rotation and strain response of each test specimen. a: FHS_3 (HI-VP_Socket joint with one rubber-ring); b: FHS_4 (HI-VP_Socket joint with two rubber-ring); c: FPF_5 (HDPE_Fusion bonding).

that can be an index for seismic joints is necessary. In addition, it is judged that the direction in which the moment is resolved is different depending on the number of joints, considering that the resistance to bending is greater when the mechanical joint is a collar joint than when there is one mechanical joint. In addition, the deformation rate of the joint is maintained linearly and then, water leakage occurs.

2) In the case of non-metallic pipes, the rotational characteristics of the joint rotation during ground subsidence increase linearly as the applied force and displacement increase. Also, since leakage does not occur, the effect of ductility in the material itself is less than the rotation of the joint itself, which is significant. Therefore, in the case of a non-metallic pipe, it is difficult to judge the ground subsidence performance only with the bending

angle of the joint and it should be determined by focusing on the tensile compressive force and the pipe material itself.

3) Based on the results of this study, it is possible to check the function maintenance evaluation regarding leakage, especially regarding the seismic performance considering the PGD by directly comparing the bending angle. It was found that the evaluation criteria should be different depending on the material, not just the type of joints. These data are expected to be utilized not only as a basis for performance evaluation in the future, but also as a major performance factor in piping design.

Acknowledgments

The work described in this paper was supported by the Korea Ministry of Environment (MOE) as "Development of vulnerability analysis technique for securing function of sewer lines and waterworks under natural disasters" (201900000001849).

Author Contributions

HY.K. (Ph.D. student) conceptualized, conducted all the experiments, and wrote the manuscript. JY.Kim. (Ph.D. student) conducted all the experiments and wrote the manuscript. YN.Kim. (Research professor) conducted part of the experiments and reviewed the manuscript. SJ.Park. (Research professor) conducted part of the experiments and reviewed the manuscript. J-O.Kim[†]. (Professor, Advisor) conceptualized, conducted all the experiments, reviewed, and edited the manuscript.

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