Evaluation of the Mechanical Behaviors of Pipe Flange Connections with PTFE Gaskets Subjected to Bending Moment

1. Introduction

The pipe flange connection with gasket is widely used at petroleum-refining, chemical, and power-generating plants. In Japan, asbestos gaskets were widely used and intensively researched, since those were low-cost and offered excellent heat resistance, sealing performance, durability, and ease of handling.[1)－3)] However, a regulation[4)] on the use of asbestos was implemented in 2008 due to its effects on human health.

Asbestos gaskets can be categorized into two major types: the spiral-wound gasket containing asbestos filler, and the compressed asbestos fiber sheet gasket. When the asbestos regulation was introduced, replacing the asbestos of the spiral-wound gasket with flexible graphite filler did not cause any major problem. However, regarding compressed sheet gaskets, it was difficult to replace the material for several reasons, and so the compressed aramid-fiber sheet gasket was developed as an alternative to the compressed asbestos fiber sheet gasket. However, it required a higher rubber content, which caused challenges for heat resistance. While the flexible graphite sheet gasket had no problems in heat resistance, the gasket surface is vulnerable to scratches because the material is brittle. Therefore, the improved polytetrafluoroethylene (PTFE) blended gasket came to be widely used. This gasket has excellent chemical resistance as well as heat resistance, and the conventional problems of creep characteristics were overcome by devising formulation and production methods. Therefore, the improved PTFE blended gasket came to be used in many connecting parts.[5)] However, the following mechanical behaviors of pipe flange connections with PTFE gasket are not well defined: gasket contact stress distribution, sealing performance, changes in hub stress and axial bolt force, and other behaviors.

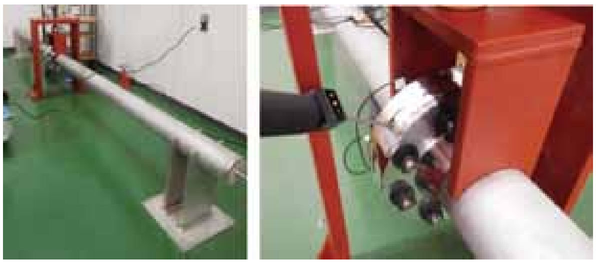
The authors previously studied the abovementioned mechanical behaviors of pipe flange connections with PTFE gasket at room temperature and high temperature and found that the connections with PTFE gasket are superior to the compressed asbestos fiber sheet gasket.[6),7)]

Japan is prone to earthquakes: recent ones include the Hyogo-ken Nanbu Earthquake in 1995, the Niigata-ken Chuetsu-oki Earthquake in 2007, the Tohoku Pacific Offshore Earthquake in 2011, and the Kumamoto Earthquake in 2016. In addition, according to some, the Nankai Megathrust Earthquake is expected to occur within the next 10 years. There are many plants and buildings located near the postulated seismic center, which would likely suffer serious damage. In the Hyogo-ken Nanbu Earthquake, liquefaction caused bending on pipe flange connections, resulting in leakage of LP gas and the issuance of an evacuation advisory to 70,000 people. Therefore, countermeasures against earthquakes are essential for plants. Sawa et al. studied the mechanical behaviors of the flange connection with spiral-wound gasket when subjected to bending moment.[8)-10)] At the Tightness Testing and Research Laboratory of Ecole Polytechnique de Montreal (Canada), the characteristics of change in axial bolt force when flange connections with expanded PTFE gasket are subjected to bending moment were studied.[11)] Meanwhile, Koves et al. described a method to evaluate the effects of bending

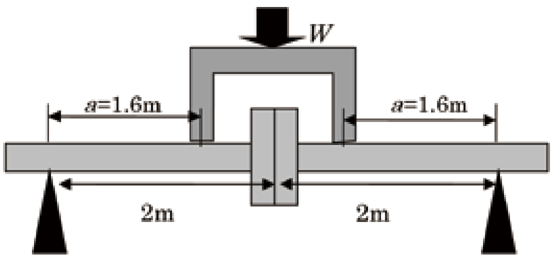
moment using equivalent internal pressure.[12) -16)]
However, there have been no studies on the pipe flange connection with PTFE gasket subjected to bending moment and internal pressure. As PTFE-blended gaskets are widely used, countermeasures for disasters including earthquakes are required, and so it is important to evaluate the mechanical behavior of pipe flange connections with PTFE gasket.
This study aimed to determine the mechanical behaviors of the pipe flange connection with PTFE gasket subjected to bending moment and internal pressure using FEM stress analyses and experiments. Firstly, the fundamental characteristics of a gasket were measured according to JIS B 2490. In finite element method (FEM) stress analyses, axial bolt force, hub stress, and the gasket contact stress distribution were calculated. In addition, leak rate was estimated based on the gasket contact stress distribution and fundamental characteristics. To verify the method of FEM stress analyses, the FEM results were compared with those from experiments on axial bolt force and hub stress. In the experiments, leak rate from connections, axial bolt force, and hub stress were measured.The connection size was ASME/ANSI class 300 4-inch. The gasket used was the No. GF300, which contains no rubber and so suffers no chemical degradation due to heat and deterioration over time. Accordingly, it is possible to conduct a precise mechanical evaluation with the No. GF300.

2. Experimental method

Figure1 (a) shows the experiment equipment used to study the effects of bending moment on the pipe flange connection; Figure1 (b) outlines the equipment. Through four-point bending, bending moment was applied to the pipe flange connection. In addition, internal pressure could be applied to the piping through a connected helium gas cylinder. The connection size was ASME/ANSI class 300 4-inch; the flange and pipe material was SUS304.[17)] Each pipe was 2 m long, and the total length of the equipment was approximately 4 m. To match the connection, the nominal diameter of the gasket was ASME/ANSI class 300 4-inch with a thickness of 1.5 mm.
Flange hub stress and axial bolt forces were measured using the strain gauges; the leak rate was measured with a helium leak detector according to the sniffer method. The initial bolt tightening was conducted according to JIS B 2251 "Bolt tightening procedure for pressure boundary flanged joint assembly."[18)] After bolt tightening, four-point bending moment and inner pressure were applied and then flange hub stress, change in axial bolt force and leak rate were measured. M, which is the bending moment acting on the connection, was calculated using the equation $M = W/2 \times a$, where a is the effective pipe length (= 1.6 m). The initial axial bolt force was 11.1 kN per bolt to give an average gasket stress 10 MPa; the internal pressure applied on the connection was 2 MPa.



(a) Equipment



(b) Outline of the equipment

Figure1 Experiment equipment used to measure the mechanical behaviors of a pipe flange connection subjected to four-point bending moment

3. Gasket characteristics

For FEM stress analyses, compression and sealing characteristics of gaskets were evaluated.

3-1) Compression characteristics

The stress-strain curve of gasket at room

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temperature was evaluated. Figure2 shows an outline of the experimental equipment used for the evaluation.[19] The size of the flange raised face is equivalent to the size stipulated in JIS 10K 50A; the raised face was compressed in a compression tester. Figure3 shows the stress–strain curve of No. GF300 gaskets obtained from the experiments. The strain value was calculated by averaging the indicated values of three displacement gauges to obtain the amount of compression, and then dividing the compression amount by the initial thickness to obtain the strain value.

3-2) Sealing performance

The sealing performance of gasket was evaluated using the equipment shown in Figure2 according to JIS B 2490. The pressure of the helium gas supplied from the cylinder was increased to 2 MPa, then the leak rate from the gasket, which was collected using a sleeve, was measured with a soap-film flowmeter. Figure4 indicates the relationship between the leak rate and gasket contact stress obtained from the experiment.

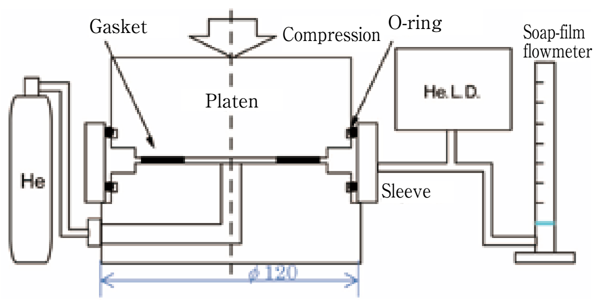

Figure2 Outline of test equipment used to evaluate gasket characteristics

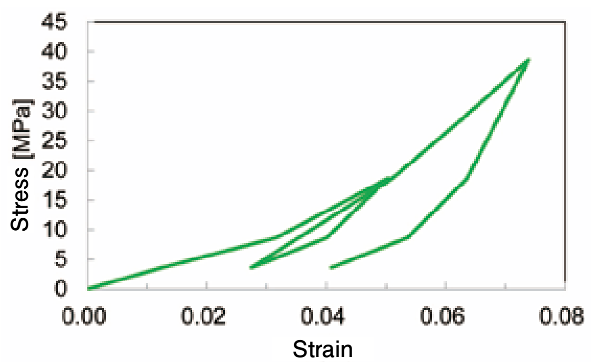

Figure3 Stress–strain curves of No. GF300 gasket

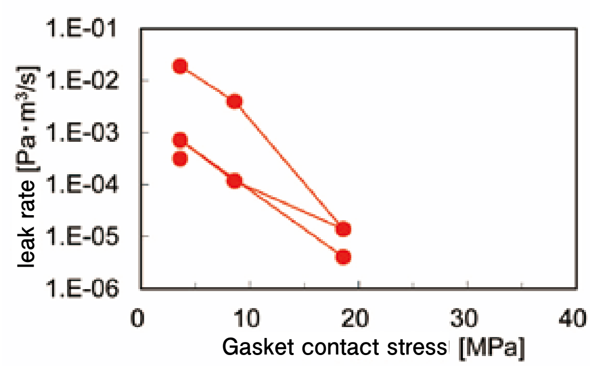

Figure4 Relationship between leakrate and gasket contact stress

Even though the gasket contact stress was increased to approximately 40 MPa, the leak rate was too small to be measured when the contact stress exceeded 20 MPa, so no data is shown in the graph.

4. FEM stress analysis

Figure5 shows the FEM model of the pipe flange connection with gasket subjected to four-point bending and internal pressure as shown in Figure1. In consideration of symmetry, the model was arranged at 1/4 scale (axial direction = 1/2, circumferential direction = 1/2) . The threads of bolts and nuts were omitted, and the nut shape was simplified from hexagonal to circular having the same cross sectional area. Figure 6 shows a boundary condition for the FEM stress analyses. In the illustration, the condition was replicated in the following manner: 1) Symmetric faces were fixed, and 2) Regarding bolt tightening, tension equivalent to the axial force was applied to each bolt model. Regarding four-point bending after tightening the piping ends, a load of $W/2$ was applied to jigs located around flanges. The effects of internal pressure were replicated by applying pressure to the internal side of the pipe flange vessel. Flanges and bolts were modeled using elastoplasticity elements; gaskets were modeled using ABAQUS gasket elements. In the FEM analyses, axial bolt force, flange hub stress, and the gasket contact stress distribution were calculated.

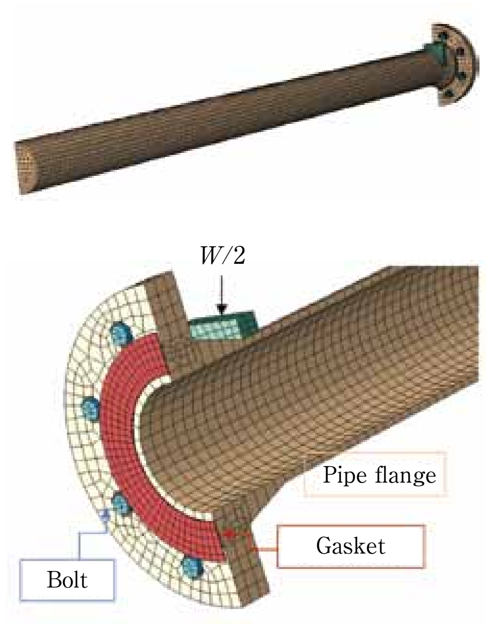

Figure5　FEM model of a pipe flange connection

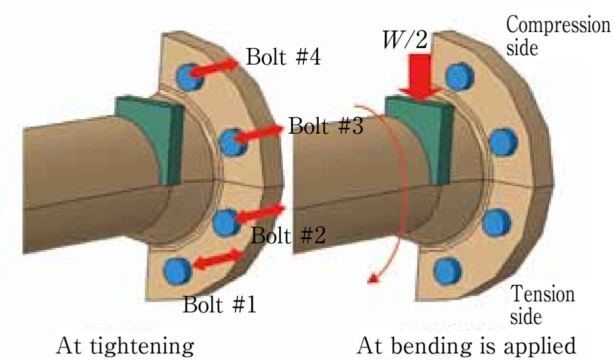

Figure6　Boundary conditions in FEM stress analyses

5. Results of FEM stress analyses and experiments

5-1) Change in Axial bolt force

Figure7 shows changes in axial force for the four bolts shown in Figure6. The values were obtained by FEM stress analyses and experiments. The abscissa represents the bending moment M; the ordinate represents axial bolt force; the solid line represents the results of experiments; the dashed line represents the results of FEM stress analyses. The axial force values of bolt #1 and #2 increase with increasing bending moment, whereas those of bolt #3 and #4 decrease. The contact surface of the flange opens due to bending moment on the piping. The opening applies tension to the bolts, resulting in increased axial force. The increased tension on the side of bolt #1 and #2 is due to this increased axial force. On the other hand, the contact surface of the flange closes. The closing compresses bolts, reducing axial force on the side of bolt #3 and #4. The results of the FEM analyses and experiments matched well, verifying the robustness of the FEM stress analyses.

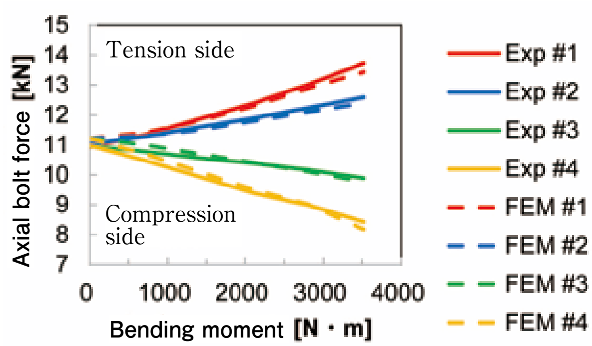

Figure7　Changes in axial bolt force when bending moment is applied to the pipe flange connection (The bending moment was calculated from FEM stress analyses and experiments.)

5-2) Gasket Contact stress distribution

Figure8 shows contour figures of the gasket contact stress distribution at the following timings: when the flange was initially tightened; when a bending moment of 3500 N/m was applied to the pipe flange connection; and when a bending moment of 3500 N/m and internal pressure were applied to the pipe flange connection. The contact gasket stress is found to be zero at the non-contacted gasket area, that is, at the most outer radius part of the gasket. The gasket contact stress distribution at initial tightening indicates increasing contact stress in the radius direction of the outside diameter due to flange rotation. In the circumferential direction, the contact-stress gradient is negligible.

When a bending moment of 3500 N/m was applied, part of the gasket's contact stress significantly decreased (left figure); when internal pressure was applied, the gasket's contact stress decreased further.

Figure9 shows the gasket contact stress distribution in the outermost diameter contact area (r = 46.05 mm) in the circumferential direction at each step. The graph indicates marked changes in contact stress distribution due to opening of the flange's contact surface; the opening was caused by the bending moment applied to the flange.

Next, The leak rate from the connection is estimated using the contact gasket stress distribution obtained from the FEM and the fundamental leakage performance shown in Figure4[20)－21)]. Figure10 shows the estimated leak rate and the experimental results. As the bending moment increases, the leak rate gradually increases; when the bending moment exceeds approximately 3000N/m, the leak rate substantially increases. As Figure8 shows, part of the gasket's contact stress became zero due to bending moment; this zero stress appears to have caused the substantial increase. The estimated leak rate and the experimental results matched well, indicating the validity of the FEM analyses and the method of estimating leak rate.

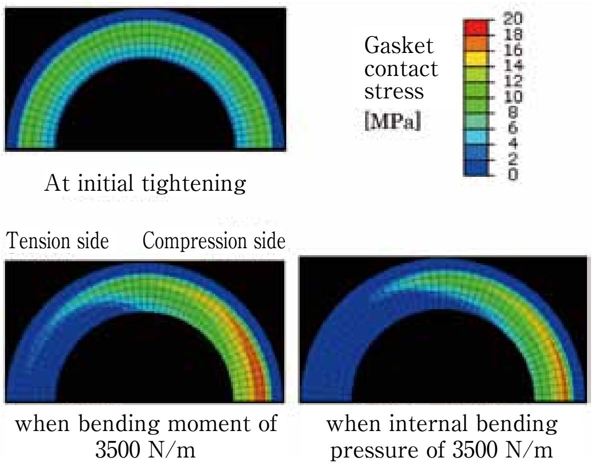

Figure8 Gasket Contact stress distribution obtained from FEM stress analyses

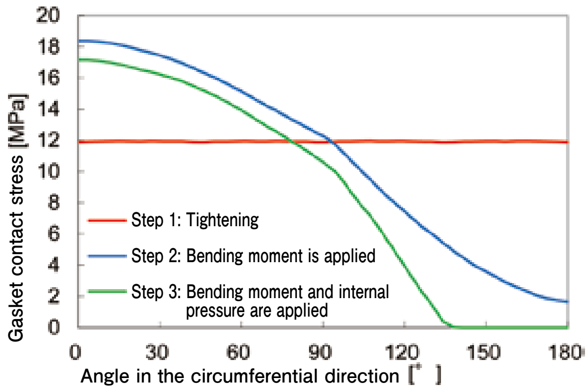

Figure9 Gasket Contact stress distribution at each step

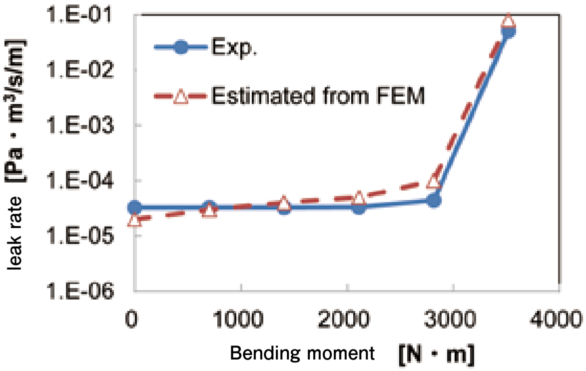

Figure10 Comparison of leak rate from connection when bending moment is applied

5-3) Flange Hub stress

Figure11 shows the relationship between the maximum principal stress in the axial direction, which occurs at the flange hub, and bending moment. The graph also shows values calculated using an ASME Boiler & Pressure Vessel Code Section Ⅷ Division 1 "Rules for construction of Pressure Vessels" App.2, (2004). (in this case, ASME values were calculated under the condition of zero bending moment).[22)] This graph indicates that as the bending moment increases, hub stress, which was evaluated from the experiments and FEM stress analyses, increases. The results of the experiments and FEM stress analyses matched well, indicating the validity of the analyses.

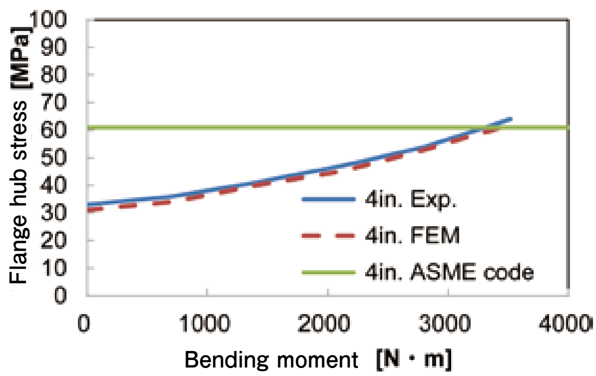

Figure11 Effects of bending moment on hub stress

6. Discussion

6-1) Effects of nominal diameter of connection on axial bolt force behavior

The effects of nominal diameter on the axial force behavior of the bolts in the connection were studied by FEM stress analysis. Figure12 shows the greatest changes in the increase and decrease of axial bolt force when bending moment was applied to a pipe flange connection with a No. GF300 gasket. The nominal diameters were chosen as 4, 8, 12, 16, 20, 24 inches and internal pressure was not applied. The ordinate represents the axial bolt force ratio (=(Ff+Ft) / Ff) ,where Ff is bolt preload and Ft is an increment in axial bolt force; the abscissa represents the bending moment per bolt. the initial mean gasket contact stress was 10 MPa; the maximum bending moment *M*, which was applied to the flange, was 3500 N/m, indicating the following: the bolt number *N* increases when nominal diameter is greater, reducing the maximum *M/N*. The solid line represents data for bolts subjected to tension by bending moment; the dashed line represents the data for bolts subjected to compression (contraction) by bending moment The figure indicates the trend that the smaller the nominal diameter, the greater the effects of bending moment on axial bolt force. Thus, for the equivalent bending moment applied to the flange, the sealing properties are safer when the nominal diameter is greater.

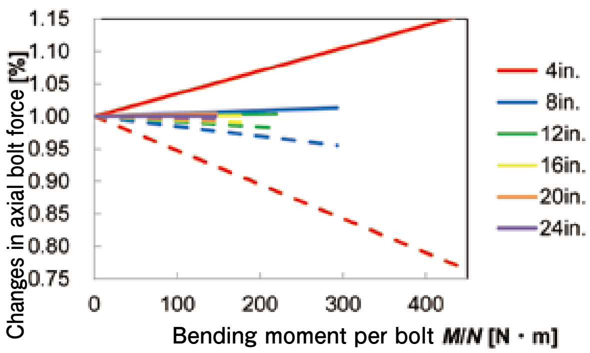

Figure12 Effects of nominal diameter on behaviors of change in axial bolt force in pipe flange connections subjected to bending moment

6-2) Effects of the order in which bending moment and inner pressure are applied

Figure13 shows the effects on the leak rate of the order in which bending moment and inner pressure are applied. The graph shows the results of leakage tests which were conducted in the following two orders: Step 1: tightening, Step 2: bending-moment application, Step 3: internal pressure application (solid red line) ; and Step 1: tightening, Step 2: internal pressure application, Step 3: bending moment application (solid blue line) . The ordinate represents the leak rate and the abscissa represents the bending moment. When the bending moment exceeds 3000 N/m, the order of "Step 2: internal pressure application, Step 3: bending moment application" is associated with slightly larger leak rate; however, the difference in leak rate was small and almost at the level of error. In the experiments, the order in which bending moment and internal pressure were applied showed no substantial effects on leak rate.

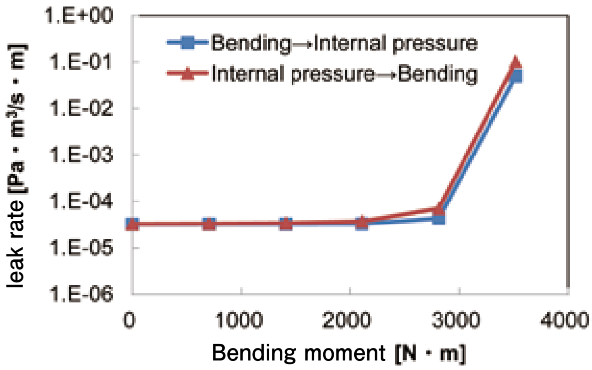

Figure13 Effects on sealing performance of the order in which bending moment and inner pressure are applied

6-3) Effects of action point of bending moment on leakage volume

As sown in Figure14, the effects of applying bending moment at different points of bolt configuration were studied. In Figure14 (a) the bolts were arranged in a vertically symmetrical manner; this configuration is widely used (pattern A) . In Figure14 (b) , two bolts are placed on the vertical line (pattern B) . Figure15 shows the relationship between leak rate and bending moment for each pattern.

The results show that pattern A was associated with smaller leak rate than pattern B. Placing bolts at the position where the opening is largest was thought to alleviate the reduction in contact pressure and sealing performance; however, the commonly-used pattern A was associated with greater sealing performance. In pattern A, four bolts resist the opening force, whereas in pattern B, only three bolts resist the opening force. Therefore, in total, the opening appeared to be greater in pattern B.

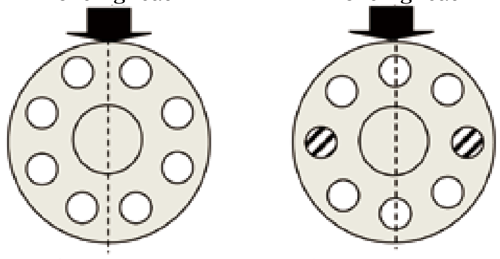

Figure14　where bending moment is applied

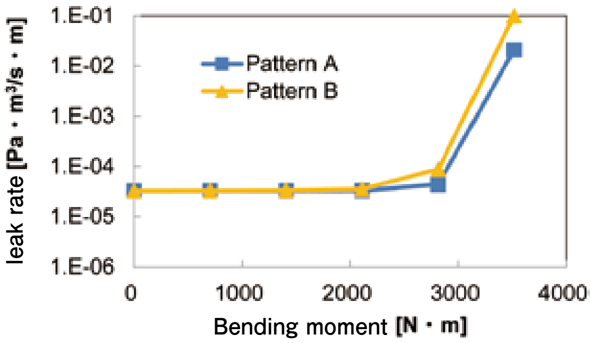

Figure15　Effects of where bending moment on sealing performance

7. Conclusions

In this study, experiments and FEM stress analyses were used to study the mechanical behaviors of axial bolt force, hub stress, and sealing performance of the pipe flange connection with PTFE gasket subjected to bending moment. The following conclusions were obtained.

(1) FEM stress analyses were used to calculate the gasket contact stress of a 4-inch pipe flange connection subjected to bending moment and internal pressure. When bending moment was applied, the contact stress decreased on part of the gasket contact surface. When the bending moment reached approximately 3500 N/m, the contact stress became zero, causing a rapid increase in leak rate.

(2) The results of the experiments and FEM stress analyses were used to evaluate the axial bolt force when bending moment was applied to the flange. The evaluation results indicated that the results of the FEM stress analyses and experiments matched well. In addition, when bending moment per bolt as M/N, the evaluation revealed the trend that the greater the nominal diameter, the stronger the resistance to bending moment.

(3) The gasket contact stress distributions were obtained from the FEM stress analyses; the relationship between the leak rate and contact stress was obtained from the experiments. Using the two results, leak rate was estimated. The estimated and experimental values matched relatively well, indicating the validity of both the methods of analyzing FEM stress and estimating leak rate.

(4) The effects on sealing performance of the order in which bending moment and internal pressure are applied were studied. The results indicated that the order does not significantly affect leak rate.

(5) The effects of the action point of bending moment on sealing performance were studied. The results indicated that the common bolt arrangement (pattern A) is associated with greater resistance to bending moment on the piping than is the arrangement in which two bolts are arranged on the vertical line (pattern B).

8. References

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