NUMERICAL MODELLING AND EXPERIMENTAL VALIDATION OF THE FLANGED JOINT OF A PIPING SYSTEM IN NUCLEAR POWER PLANTS

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ABSTRACT

In a previous experimental study for the flanged joint of a RHR piping system in a nuclear power plant, leakage happened at the tested flanged joint due to its loosened bolts while the joint was subjecting pure-bending loading. To clarify the cause of this phenomenon, this study aims at investigating the effect of the deformation of the flange gasket on the decrease in the prestress of the bolts. In the first part of this study, a series of compression loading tests for components of the flange gasket is executed to realize detailed behaviour of the flange gasket with prestressed bolts. Next, according to the deformation behaviour of the gasket obtained from tests, the flanged joint is modelled using ABAQUS commercial code. Finally, shaking table tests for a part of the RHR piping system with the flanged joint are executed to verify the accuracy of the corresponding numerical model under dynamic loading. The applicability of ASME’s Boiler and Pressure Vessel Code to evaluate the leakage of this type of flanged joints is discussed as well.

INTRODUCTION

In nuclear power plants (NPPs), a Residual Heat Removal (RHR) system is one of the most important safety-related systems. When a plant encounters accidents such as earthquakes, the RHR system ensures the cooling ability for reactors and other critical units to prevent damages caused by high temperatures. The RHR system consists of pumps, injection valves, testable check valves, pump discharge check valves, isolation valves, heat exchangers, motor operated valves (MOVs), piping and supports, etc. The contented water is about 35°C and under hydrostatic pressure. The system is only started to operate when an extremely accident event happens.

According to the seismic risk assessment results presented in the Final Safety Analysis Report (FSAR) for a NPP in Taiwan, the failure of RHR piping system is identified with the highest contributions for a nuclear melt-down under the safety shutdown earthquake in the accident sequences. In the RHR systems, most piping segments are connected with welding joints, and only several flanged joints are used for the configuration of flowmeters.

In order to investigate the seismic demand and capacity of the RHR piping system in the case of NPP to ensure the function of the liquid transmission system and avoid content leakage and following accidents, a part of the RHR piping system including a flanged joint and a MOV of 1,624 kg is picked out as the research subject. It has been proved from a series of tests and analysis [1] that the selected range of the RHR piping system will bear a great inertia force caused by the heavy MOV during strong earthquakes. This paper aims to investigate seismic performances of the flanged joint to clarify that the sealability of piping is maintained at this discontinuous segment during earthquakes. Conducted tests included
component testing under pure-bending loads and material tests of the flanged gasket. Further numerical analyses are also proposed to effectively estimate the capacity with relation to the failure mode of leakage. The accuracy of the numerical models is verified by the component testing of flanged joints and shaking table tests for the selected range of the RHR piping system.

**Specification of the flanged joint**

According to the diagrammatic piping drawings and in-situ investigation in the NPP, the flanged joint belonging to the RHR-piping system is reproduced for further studies. As shown in Figure 1, the components of the flanged joint include a spiral-wound gasket, sixteen bolts (A193 Gr B7) and nuts (A194 Gr B7). The flanged joint was mainly made of A350 carbon steel, and the material of pipes was SA333Gr6 carbon steel with yield and ultimate tensile strengths of 324 and 449 MPa, respectively. The nominal diameters of the connected pipes (Schedule 40) are 300 mm.

![Figure 1](image)

**Design Requirement of Flanged Joints**

Flanged joints belonging to class 1 components of the nuclear facility, which are subjected to the combinations of moment and pressure, shall meet the requirements of the ASME Code [2] and the design specification [3]. In the ASME Code, the design for piping system is classified into four levels, Level A to D, according to its service condition. The flanged joint tested in this study belongs to the RHR piping system, hence, it should be analyzed under the loading combinations in the postulated plant events according to the design specification requirements. In order to compare the test results with the design requirements as specified for ASME Service Levels B and D, Table 1 depicts the plant events associated with earthquakes as well as the related service loading combination, the expected performance levels and the associated limitation of dynamic moments. Although the design specification requires that all ASME Code Class 1, 2 and 3 Piping systems essential for safe shutdown should be designed to meet the requirements of NUREG 1367 [4], there is little discussion on flanged joints in NUREG 1367 since the loss of functional capability of a flanged joint is deemed to be incredible.

The moment demands for Levels B and D in Table 1 were calculated according to the equations given in the paragraph NB-3658 “Analysis of Flanged Joints” in the ASME Division 1-Subsection NB to prevent excessive leakage at the joints. In the ASME Code, the pressure shall not exceed 1.1 times the rated pressure for Level B service limits. In terms of the service condition involving dynamic loading, the acceptance criteria of Level B given by Eq. (1) shall be satisfied. In addition, the acceptance criteria of Level D given by Eq. (2) shall be also satisfied:
\[ M_{fd} \leq 43.4A_b \cdot C\left(\frac{S_y}{250}\right) \]  
\[ M_{fd} \leq [78.1A_b - (\pi/16)D_f^2P_{fd}] \cdot C\left(\frac{S_y}{250}\right) \]

where

- \( A_b \) = total cross-sectional area of bolts, \( mm^2 \)
- \( C \) = diameter of bolt circle, \( mm \)
- \( S_y \) = yield strength of flanged material at Design Temperature, \( Mpa \)
- \( M_{fd} \) = bending or torsion moment applied to the joint due to weight, thermal expansion of the piping, sustained anchor movements, relief valve steady-state thrust, other sustained mechanical loads, and dynamic loadings applied to the flanged joint, \( N-mm \)
- \( D_f \) = outside diameter of raised face, \( mm \)
- \( P_{fd} \) = pressure concurrent with \( M_{fd} \), \( Mpa \)

Table 1: Acceptance criteria suggested by ASME code [2] and design specification [3]

<table>
<thead>
<tr>
<th>ASME Code and Design Designation</th>
<th>Level B</th>
<th>Level D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Service Condition of the Plant</strong></td>
<td>Upset (moderate probability)</td>
<td>Faulted (Extremely Low Probability)</td>
</tr>
<tr>
<td><strong>Event Encounter Probability per Reactor Year (P)</strong></td>
<td>( 1.0 &gt; P \geq 10^{-2} )</td>
<td>( 10^{-4} &gt; P \geq 10^{-6} )</td>
</tr>
<tr>
<td><strong>Plant Events associated with Earthquake</strong></td>
<td>• SOT + OBE</td>
<td>• SBL or IBL + SSE</td>
</tr>
<tr>
<td></td>
<td>• NO + OBE</td>
<td>• LBL + SSE</td>
</tr>
<tr>
<td><strong>Service Loading Combination associated with Earthquake</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• N + SRV + OBE</td>
<td>• N + SBL or IBL + SSE + SRV</td>
</tr>
<tr>
<td></td>
<td>• N + OBE</td>
<td>• N + LBL + SSE</td>
</tr>
<tr>
<td><strong>Performance Level</strong></td>
<td>Without damage requiring repair</td>
<td>Gross general deformations</td>
</tr>
<tr>
<td><strong>Limitation of Moment (N-mm)</strong></td>
<td>( 201.2 \times 10^6 )</td>
<td>( 352 \times 10^6 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IDs</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOT</td>
<td>System Operational Transient</td>
</tr>
<tr>
<td>SBL</td>
<td>Loads induced by small break loss-of-coolant accident (LOCA)</td>
</tr>
<tr>
<td>SSE</td>
<td>Loads induced by safe shutdown earthquake</td>
</tr>
<tr>
<td>NO</td>
<td>Normal Operation</td>
</tr>
<tr>
<td>SRV</td>
<td>Loads induced by Safety/relief valves actions</td>
</tr>
<tr>
<td>OBE</td>
<td>Loads induced by operating basis earthquake</td>
</tr>
<tr>
<td>IBL</td>
<td>Loads induced by intermediate LOCA</td>
</tr>
<tr>
<td>LBL</td>
<td>Loads induced by large break LOCA</td>
</tr>
<tr>
<td>ML</td>
<td>Gradually increasing cyclic pure bending loads</td>
</tr>
<tr>
<td>N</td>
<td>Loads associated with the system operating conditions</td>
</tr>
</tbody>
</table>

**TESTS OF THE FLANGED JOINT AND GASKET**

**Pure-bending Test of a Flanged Joint**

In order to apply pure-bending loading at the flanged joint, the test setup was arranged to be the four-point bending configuration, where the support at one end was a hinge and the other end was a roller (Figure 2). As shown in Figure 3, the cyclic loading was applied by the actuator through the adapter composed of a beam and rotary fixtures allocated to both sides of the piping joint to impose the pure bend loading on the segment between rotary fixtures. The loading protocol was designed according to the cyclic displacement schedules proposed by ISO-16670[5]. In this study, the ultimate displacement (\( v_u \)) was decided to be 50 mm that according to the numerical analysis results. Table 2 depicts the amplitude of each cycle in the percentage of \( v_u \). The specimen consisted of two equal-length segments of straight pipes (Schedule 40) which were connected with a bolted flanged joint. In order to observe the leakage condition, the internal pressure of 8 kgf/cm\(^2\) was applied by feeding water into the specimen.
In the pure-bending test for the flanged joint, the leakage condition occurred due to loosening of bolts without breakage. The force-displacement hysteretic loops of the Flange specimen were established using the commanded displacement and associated force of actuator (Figure 4). The initial stiffness of vertical displacement in the elastic stage (depicted with red line) is about 30.0 kN/m. While the applied forces of the actuator was about 600 kN, the stress concentration effect at the area of loading points caused the local plastic deformation of piping segment and also resulted in gaps between fixtures and the specimen. From the signals measured by load cells and tiltmeters, the moment-rotation hysteretic loops were presented in Figure 5. The rotation stiffness in the elastic stage (depicted with red line) is about 1000 kN-m/degree and decreases to 250 kN-m/degree in the plastic stage (depicted with black line) due to several loosened bolts at the top and bottom of the flange. The leakage was occurred with loosened but undamaged flanged bolts when the displacement applied by actuator was 20 mm and the associated moment was 100 kN-m.

It can be seen that leakage occurred when the bending moment was 100 kN-m, and it is due to the loosened flange bolts without any permanent deformation or damages of other components of the flanged joint. Comparing the test result and the allowable bending moments listed in Table 1, the capacity of flanged joints against leakage is much smaller than the allowable bending moment of 201.19 kN-m defined for Service Level B under the consideration of loads induced by operating basis earthquake and normal operation or system operational transient. The capacity obtained from the test is also smaller than the allowable bending moment defined by 352 kN-m for Service Level D under the consideration of loads.

Table 2: Loading protocol

<table>
<thead>
<tr>
<th>Step</th>
<th>cycles</th>
<th>Amplitude (mm)</th>
<th>Step</th>
<th>cycles</th>
<th>Amplitude (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.25% of $v_u$ 0.625</td>
<td>7</td>
<td>3</td>
<td>40% of $v_u$ 20</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2.5% of $v_u$ 1.25</td>
<td>8</td>
<td>3</td>
<td>60% of $v_u$ 30</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>5% of $v_u$ 2.5</td>
<td>9</td>
<td>3</td>
<td>80% of $v_u$ 40</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>7.5% of $v_u$ 3.75</td>
<td>10</td>
<td>3</td>
<td>100% of $v_u$ 50</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>10% of $v_u$ 5</td>
<td>11</td>
<td>3</td>
<td>Increments of 20% of $v_u$ 60</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>20% of $v_u$ 10</td>
<td>12</td>
<td>3</td>
<td>Increments of 40% of $v_u$ 70</td>
</tr>
</tbody>
</table>

In the pure-bending test for the flanged joint, the leakage condition occurred due to loosening of bolts without breakage. The force-displacement hysteretic loops of the Flange specimen were established using the commanded displacement and associated force of actuator (Figure 4). The initial stiffness of vertical displacement in the elastic stage (depicted with red line) is about 30.0 kN/m. While the applied forces of the actuator was about 600 kN, the stress concentration effect at the area of loading points caused the local plastic deformation of piping segment and also resulted in gaps between fixtures and the specimen. From the signals measured by load cells and tiltmeters, the moment-rotation hysteretic loops were presented in Figure 5. The rotation stiffness in the elastic stage (depicted with red line) is about 1000 kN-m/degree and decreases to 250 kN-m/degree in the plastic stage (depicted with black line) due to several loosened bolts at the top and bottom of the flange. The leakage was occurred with loosened but undamaged flanged bolts when the displacement applied by actuator was 20 mm and the associated moment was 100 kN-m.

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induced by normal operation, safe shutdown earthquake, the break loss-of-coolant accident and/or Safety/relief valves actions. It implies that the code-defined capacity for Service Level B and D may be less conservative for the purpose to prevent excessive leakage at the flanged joint due to its loosened bolts.

Cyclic-Loading Tests for Components of the Flanged Joint

The interface layer of the flanged joint includes a flowmeter and a spiral-wound gasket, which is consist of one inter and one outer metal ring, and a composite layer made of metal hoops and sealing material (graphite) between the metal rings. During the pure-bending test, leakage of the flanged joint is observed. In order to clarify the relation between the leakage and the characteristics of the interface layer, a series of quasi-static cyclic-loading tests of the interface layer and bolt, the interface layer, and the flowmeter only was executed in this study.

In the cyclic-loading tests of the interface layer and bolt, the complete interface layer was divided into 16 sets to be used as the test specimens of the cyclic-loading test to simulate each bearing part of one bolt (Figure 6b). The fixtures between the bolt and the interface layer are 50 mm in thickness and made of medium carbon steel to simulate the metal flanges (Figure 6c). The cyclic-loading tests were designed to be force-controlled to simulate the external force to the bolt at the top position during the pure-bending test for the flanged joint. As shown in Figure 6a, the external forces to 16 bolts during the pure-bending test were evaluated based on the assumption that the section of the flanged joint is kept in a flat surface. Each bolt of the flanged joint was assumed to transmit axial force uniformly to the flange through each set of the interface layer under bending force.
The blue line in Figure 7a shows the simulating external force for the bolt and interface layer in the pure-bending test. From the test results (Figure 7), it can be seen that the initially prestressed force of the bolt (about 55 kN) gradually decayed to 12kN under the increasing cyclic axial loading. It means that the bolt has been loosen during the cyclic-loading test, which was also happened in the pure-bending test of the flanged joint. The decaying prestressed force of the bolt might be caused by the permanent deformation of the interface layer due to the broken graphite material. On the other hand, the prestressed tension force was decreased to zero while the compression loading reached to 75.8 kN, which explains the phenomenon that during the pure-bending test of the flanged joint leakage happened at the top or bottom bolts in the compression side by turns.

![Figure 7a](image1.png)  ![Figure 7b](image2.png)

Figure 7. Test results for the internal layer and bolt: (a) force-time histories; (b) displacement-force curves.

During the cyclic-loading tests for the bolt and the interface layer including the spiral-wound gasket and the flowmeter in series connection, the total resistance force was offered mainly by the bolt during tension loading, and offered together by the interface layer and the bolt during compression loading. As shown in Figure 8, cyclic-loading tests for the interface layer and for the flowmeter only were executed to clarify the resistance behavior of the spiral-wound gasket and the flowmeter respectively during the cyclic-loading tests for the bolt and the interface layer. Comparing the force-displacement curves of the interface layer and the flowmeter (Figure 9a and Figure 9b), it can be seen that the initial lower stiffness of the interface layer was mainly governed by the protruding composite layer of the spiral-wound gasket with the extremely high stiffness of the flowmeter. After the graphic material of the spiral-wound gasket crashed, the higher stiffness in the second stage of the force-displacement curve of the spiral-wound gasket was governed by the inner and outer rings. The damage of the composite layer of the gasket is confirmed to be the main reason that cause the leakage of the flanged joint and the loosened bolts.

![Figure 8a](image3.png)  ![Figure 8b](image4.png)

Figure 8. Test configuration of cyclic-loading tests: (a) interface layer; (b) flowmeter.
NUMERICAL ANALYSIS OF THE FLANGED JOINT

Spiral-Wound Gasket

According to the test results for the interface layer and for the flowmeter under cyclic-loading, as shown in Figure 10, the simplified resistance behaviour of the spiral-wound gasket was derived to establish numerical model with ABAQUS software. A single-layer grid element (GK3D18) offered by ABAQUS/Standard was adopted to establish the model of the gasket to reproduce the variable resistance stiffness and residual deformation in the thickness direction. As shown in Figure 11, the inner and outer rings were ignored and only the shape of the composite layer was simulated to represent the gasket model.

Verification of the Gasket Model

In order to use the results of cyclic-loading tests to verify the accuracy of the gasket model, simulation of the cyclic-loading tests for the bolt and the internal layer was established with ABAQUS software. As shown in Figure 12a, the green parts are the spiral-wound gaskets and the red part is the flowmeter. The contact condition between the upper fixture and the upper gasket is set to be hard contact and separable during tension loading. On the other hand, the contact conditions between the nut and the fixture were set to be hard contact and friction contact in the normal and tangent directions respectively. The nut and the
screw rod were connected by the “Tie” condition. Identical to the test configuration, the initial condition of the bolt is prestressed and the achieved force of the actuator is directly applied to the upper fixture. Figure 12b depicts the comparison of the results of the cyclic-loading test and the numerical analysis. It shows that the numerical model have simulated the phenomenon that the gradually increased residual deformation of the composite layer of the gasket caused the decrease of the axial tension force of the bolt.

![Figure 12b](image)

Figure 12. Verification of the gasket model: (a) simulation of the cyclic-loading test for the bolt and the internal layer; (b) comparison of the experimental and numerical results

**Simulation of the Flanged Joint**

According to the numerical model of the internal layer and the bolt of the flanged joint, the simulation of the test specimen in the pure-bending test was established to observe the variation of the decrease of the bolt force during the increasing cyclic moment loading. As shown in Figure 13a, the achieved displacement time history of the actuator was applied at the two adapters on the both sides of the flanged joint simultaneously. The initial axial force of each bolt was set to be 76,641N. Figure 13b shows the analysis results of the axial forces of the top and bottom bolts. The axial force of the top and bottom bolts decreased to zero while the bending moment reached 152 kN-m. Comparing to the bending moment of 100 kN-m that cause the leakage happened, it means that before the bolts were loosened, leakage might happen due to the damage of the spiral-wound gasket.

![Figure 13a](image)

![Figure 13b](image)

Figure 13. Simulation of the flanged joint: (a) Flanged joint in the pure-bending test; (b) Analysis results of the axial forces of the top and bottom bolts under cyclic loading
SHAKING TABLE TESTS OF THE RHR PIPING SYSTEM

In addition to a series of tests for the flanged joint and its components, shaking table tests of the RHR piping system were carried out to clarify the seismic demand for the flanged joint under safe-shutdown earthquakes (SSEs). As introduced in Lai [1], the test specimen simulated a part of the RHR piping system including a flanged joint and a MOV of 1,624 kg, and a rigid reaction frame and the connection to the shaking table simulated the RCCV and the floor penetration boundaries respectively (Figure 14a). The initial torque value of bolts of the flanged joint were adjusted to 45 kgf-m according to the design specification, and the corresponding average axial force of the bolts derived from the measured bolt strain was 63,740N. As shown in Figure 15a, the input motions were obtained from the floor responses of the lumped-mass model of the NPP under ground motions at the strength level of SSE (PGA=0.4g). During shaking table tests at the SSE level, the maximum variation of the axial force is about 600 kgf and by far lower than the initial axial force (Figure 15b).

According to the numerical model of the flanged joint in the pure-bending tests discussed above, the corresponding numerical model for the shaking table test was established with ABAQUS software (Figure 14b). The fundamental frequency of the test specimen and the numerical model were 7.4 Hz and 7.73 Hz respectively. Figure 16 depicts the comparison of the time histories of the experimental and numerical results of the piping system at the flanged position. It can be seen that the simulation of the test specimen including piping and the flanged joint was quite accurate in terms of the global response.

Figure 14: Shaking table test and simulation of the RHR piping system: (a) test configuration; (b) numerical model

Figure 15: (a) Time histories of the input motion corresponding to 100% SSE (TAP-070); (b) axial force of the bolt of the flanged joint
CONCLUSION

Considering that the failure of RHR piping system occurs in both of the two accident sequences with the highest contributions for core damage, detailed numerical models and a series of tests were executed for the flanged joint in the RHR piping system. In the pure-bending test, the leakage condition occurred at the internal moment about 100 kN-m, which is much smaller than the allowable bending moment 352 kN-m for Service Level D in the ASME code. Top and bottom bolts of the flanged joint were also loosened during the pure-bending test. From the experimental results for the bolt and the interface layer of the flanged joint, damage of the composite layer of the gasket is confirmed to be the main reason that cause the leakage of the flanged joint and the loosened bolts. According to the simulation of the test specimen in the pure-bending test, leakage might happen due to the damage of the spiral-wound gasket before the bolts were loosened. However, the shaking table tests for the RHR piping system in the NPP shows that the seismic demands for the flanged joint under the SSE level were much smaller than the capacity for leakage or loosened bolts of the flanged joint.

REFERENCES