3D transient seal analysis of reactor pressure vessel using coupled thermo-elasto-plastic contact method

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1. INTRODUCTION

The sealing system of a reactor pressure vessel (RPV) is composed of flanges, bolts, cylindrical shell and spherical head. The seal failure of the bolt-connected flanges is a primary failure mode of the nuclear reactor pressure vessel as it operates under severe working conditions of high temperature, high pressure and exposure to radioactive substance. Hence sealing analysis of the bolt-connected flanges is critical to the overall structural integrity, reliability and safety of the RPV system. The global stiffness and deformation of the structure, heat transfer behaviour and other factors such as material and manufacturing techniques used are the key considerations in seal analysis. The aim of this paper is to develop a finite element (FE) based method for seal analysis of the RPV and to predict the seal behaviour of the bolt-connected flanges in order to improve the design quality and reliability of the RPV.

The seal behaviour of the bolt-connected RPV flanges involves elastoplastic material deformation, transient heat transfer and complex contact conditions between the flange surfaces and the pre-stressed O-ring component for sealing. Based on the FE method of the coupled thermal elastoplastic contact problems, a 3-D transient seal analysis program for nuclear reactor pressure vessel is developed. In this program a mixed finite element method is derived to predict the contact forces and displacements at the joint interfaces. To simulate the pre-tensioning of the bolted joint, a contact correction approach for the bolt connection is proposed. The Newton-Raphson iterative procedure is used to solve the nonlinear equations of the coupled thermal elastoplastic contact problem, whilst a Galerkin method in combination with backward finite difference process is employed to carry out the transient heat transfer analysis. The numerical results derived from this method are in a good agreement with experimental test data.

2. THE GOVERNING EQUATION OF TRANSIENT SEALING ANALYSIS

The sealing analysis procedure of the RPV flanges can be expressed by the following governing equation

$$\boldsymbol{K}(\boldsymbol{\delta})\boldsymbol{\delta} = \boldsymbol{P} + \boldsymbol{F}(\boldsymbol{\delta}) + \boldsymbol{L}(\boldsymbol{T}) + \boldsymbol{R}(\boldsymbol{\delta}) \equiv \varphi(\boldsymbol{\delta}) \tag{1}$$

where $\boldsymbol{K}(\boldsymbol{\delta})$ is the global stiffness matrix including all contact bodies and it is a function of the nodal displacement vector $\boldsymbol{\delta}$; $\boldsymbol{P}$ is the external load vector; $\boldsymbol{F}(\boldsymbol{\delta})$ is the contact force vector as a function of displacement vector $\boldsymbol{\delta}$; $\boldsymbol{T}$ is the transient temperature field; $\boldsymbol{L}(\boldsymbol{T})$ is the thermal load vector also as a function of nodal temperature $\boldsymbol{T}$; $\boldsymbol{R}(\boldsymbol{\delta})$ is the vector of seal ring gasket reaction which can be determined by the load-deformation characteristics function of the seal ring and the relative displacement of the seal surface; $\varphi(\boldsymbol{\delta})$ is the vector of the sum of total right hand term.

Due to the incremental loading the non-linear equation (1) should be solved by Newton-Raphson method in the outer iterative loop while the contact force vector $\boldsymbol{F}(\boldsymbol{\delta})$ can be obtained through an inner loop of computations.

The Newton-Raphson procedure can be expressed in the following equations.

$$\Delta\boldsymbol{\delta}^{(\mathrm{n})}=-[\boldsymbol{K}_{\mathrm{T}}(\boldsymbol{\delta})]^{-1}[\int_{\mathrm{V}}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{\sigma}^{(\mathrm{n})}\mathrm{d}v-\varphi(\boldsymbol{\delta}^{(\mathrm{n})})-\Delta\boldsymbol{F}(\Delta\boldsymbol{\delta}^{(\mathrm{n})})-\Delta\boldsymbol{R}(\Delta\boldsymbol{\delta}^{(\mathrm{n})})] \tag{2}$$

$$\boldsymbol{\delta}^{(\mathrm{n+1})}=\boldsymbol{\delta}^{(\mathrm{n})}+\Delta\boldsymbol{\delta}^{(\mathrm{n})} \tag{3}$$

where Δ represents increments in computations; the superscript (n) indicates the number of iterations; $\boldsymbol{K}_{\mathrm{T}}(\boldsymbol{\delta})$ is the tangential stiffness matrix; $\boldsymbol{B}$ and $\boldsymbol{\sigma}$ are the strain matrix and stress vector respectively.

In order to obtain $\boldsymbol{F}(\boldsymbol{\delta})$ in Equation (1), it is convenient to establish a condensed flexibility equation of the contact force vector by a mixed formulation for the considered contact region. If the additional constraint in a presumed area of contact and the overall load equilibrium condition are taken into account, the condensed flexibility equation can be derived as follows

$$\begin{bmatrix}\boldsymbol{f}_{\mathrm{c}} & \boldsymbol{f}_{\mathrm{d}}\\ \boldsymbol{f}_{\mathrm{F}} & \boldsymbol{0}\end{bmatrix}\begin{Bmatrix}\Delta\boldsymbol{F}(\boldsymbol{\delta})\\ \Delta\boldsymbol{\delta}_{\mathrm{e}}\end{Bmatrix}=\begin{Bmatrix}-\Delta\boldsymbol{S}_{\mathrm{P}}-\boldsymbol{\varepsilon}_0\\ \Delta\boldsymbol{P}_{\mathrm{e}}\end{Bmatrix} \tag{4}$$

where $\boldsymbol{f}_{\mathrm{c}}$ is the flexibility matrix relative to contact force vector $\Delta\boldsymbol{F}(\boldsymbol{\delta})$; $\boldsymbol{f}_{\mathrm{d}}$ is a transformation matrix relative to displacement; $\boldsymbol{f}_{\mathrm{F}}$ is a transformation matrix relative to contact force; $\Delta\boldsymbol{\delta}_{\mathrm{e}}$ is the rigid body displacement vector in a presumed area of contact; $\Delta\boldsymbol{S}_{\mathrm{P}}$ is the vector of interval increment between contact nodal pair; $\boldsymbol{\varepsilon}_0$ is the initial interval vector; $\Delta\boldsymbol{P}_{\mathrm{e}}$ is the resultant force vector.

3. TRANSIENT THERMAL CONTACT ANALYSIS

In transient heat transfer analysis, finite element discretization in space domain and finite difference discretization in time domain are developed simultaneously. The element types and shape functions in heat transfer analysis are the same as that in stress-strain analysis. While in time domain the direct integration is used and the non linearity of contact heat conduction is considered by means of the mixed formulation of the contact analysis method.

The governing equation of transient thermal contact analysis can be expressed as follows

$$\boldsymbol{kT}+\boldsymbol{c}\dot{\boldsymbol{T}}=\boldsymbol{q}+\boldsymbol{Q}\equiv\boldsymbol{\psi} \tag{5}$$

where $\boldsymbol{k}$ and $\boldsymbol{c}$ are the global thermal conductivity matrix and thermal capacity matrix, respectively; $\boldsymbol{T}$ and $\dot{\boldsymbol{T}}$ are the nodal temperature vector and its first derivative with respect to time t; $\boldsymbol{q}$ is the generalized nodal heat flux vector; $\boldsymbol{Q}$ is the contact nodal heat flux vector.

The iterative procedure for the transient heat transfer analysis is solved by backward difference process as given by

$$\bar{\boldsymbol{k}}\boldsymbol{T}_{n+1}=\bar{\boldsymbol{\psi}}_{n+1} \tag{6}$$

where $\bar{\boldsymbol{k}}=\boldsymbol{k}+\dfrac{1}{\Delta t}\boldsymbol{c}$ $\qquad$ $\bar{\boldsymbol{\psi}}_{n+1}=\dfrac{1}{\Delta t}\boldsymbol{cT}_n+\boldsymbol{\psi}_{n+1}$

the subscripts n, $n+1$ indicate the number of time step, while Δt represents time interval. Because of the non-linearity in thermal conductivity on the contact surface, the contact state between contact surfaces has an effect upon the temperature field. Therefore it is necessary to carry out an iterative procedure for the thermo-contact analysis. When the gap between contact surfaces is small enough, each contact nodal pair can be prescribed by 3 possible states: (1) direct thermal conduct between flanges; (2) laminate conduct; (3) heat insulation.

In order to obtain the contact heat flux vector $\boldsymbol{Q}$ in Equation (5), the following temperature flexibility equation is established

$$\boldsymbol{f}_{\mathrm{T}}\boldsymbol{Q}=-\Delta\boldsymbol{T}_{\mathrm{Q}} \tag{7}$$

where $\boldsymbol{f}_{\mathrm{T}}$ is the temperature flexibility matrix; $\Delta\boldsymbol{T}_{\mathrm{Q}}$ is the temperature difference vector caused by generalized nodal heat flux vector.

4. COMPUTATION MODEL OF THE RPV

Based on the symmetry of the structure and the boundary conditions, a 1/4 of the RPV structure is taken into account in this research. An automatic pre- and post-processing program is developed for modelling of the RPV. Using this program, the finite element mesh of the RPV model as shown in Figure 1 can be generated using 8-node hexahedron brick elements and 6-node triangular prism elements. There are a total of 29,070 elements with a total of 35,422 nodes including 611 contact node-pairs.

The loading and boundary conditions of the transient sealing analysis for the RPV are defined corresponding to the operating conditions so that the validity of the sealing analysis program may be examined. The specified pre-tension force is applied to all of the bolts firstly and the subsequent operating conditions are detailed as follows

(1) Heating for 0.9 hour to increase the water temperature to 100˚C with the inner pressure applied simultaneously;

(2) Further heating for 2.2 hours until the water temperature reaches 300˚C;

(3) Constant temperature for 3.6 hours;

(4) Cooling stage for 2 hours to allow the water temperature to decrease to 100˚C.

In the finite element model, all of the bolts are simplified to cylinders which are fixed on the lower flange whilst the nuts are adhered with the bolts. The distributed bolt pre-tension pressures are applied respectively on the contact surfaces of the nuts and the upper flange to simulate the compression of the upper flange and the elongation of the bolts under the pre-tension condition. In order to determine the load and stress of the bolt-connected flanges accurately at the end of pre-tension stage, a contact correction approach for the bolt connection is presented in which the nodal coordinates of the bolts and nuts are modified to match the deformed coordinates of the upper flange and the nodal forces on the contact surface of the nuts and upper flange are determined by the pre-tension pressure.

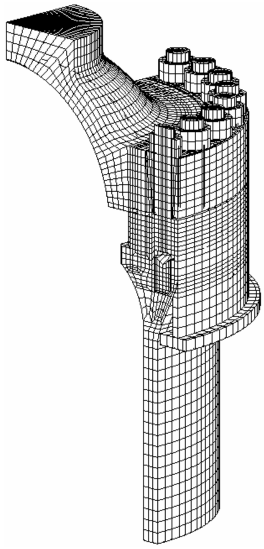

FIGURE 1. Finite element mesh

5. TRANSIENT SEALING ANALYSIS OF THE RPV FLANGES

5.1 Bolt Pre-tension Condition

The separation of inner groove increases 0.026mm but the separation of outer groove decreases 0.019mm at the end of pre-tension. It suggests that the inner seal ring is at a state of rebound and the outer seal ring is still under compression.

The maximum compressive stress (558MPa) occurs at the contact surface of flanges and the maximum tensile stress (231MPa) appears in the section of bolts. The Mises stress contour of the reactor pressure vessel is shown in Figure 2 and localised plastic deformation can be found in the contact region of the upper and lower flanges.

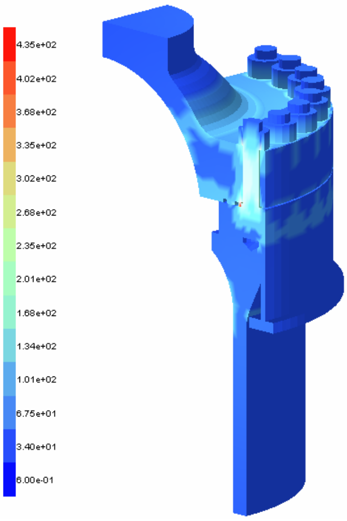

FIGURE 2. Mises stress contour at the end of the pre-tension

5.2 Operating Conditions

With the increase of pressure, the more contact nodes at the sealing surface become separated and the pre-tension forces of the bolts drop slightly. When the temperature rises, the pressure vessel is kept on expanding and the pre-tension forces of bolts are increased. In the cooling stage the pre-tension forces of the bolts decrease because the contraction of the bolts is less than that of the flanges. The tilted angle-time curves of upper and lower flanges under the operating conditions are shown in Figure 3.

Figure 4 presents the separation-time curves of the inner and outer grooves under the operating conditions (there are no experiment results). The figure shows that the separations of the two grooves become greater at the pressure-up stage and then increase slowly during the subsequent stages of temperature variation. The separations of the inner and outer grooves finally reach the maximum value of 0.285mm and 0.086mm, respectively, toward the end of the cooling stage well within the permissible tolerance.

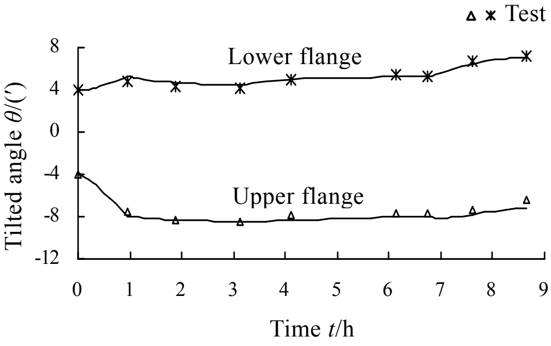

FIGURE 3. The tilted angle-time curves of the upper and lower flanges

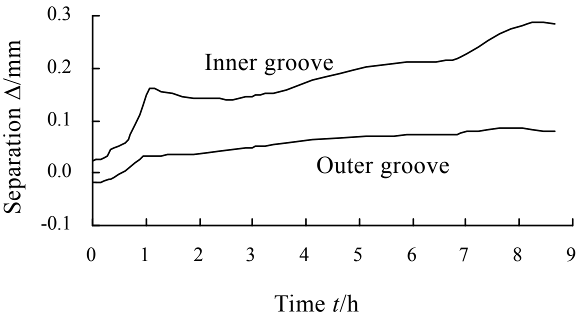

FIGURE 4. The separation-time curve at the grooves of the sealing rings

The maximum temperature differences of the pressure vessel during heating and cooling stages are 110˚C and 105˚C, respectively. At the temperature cycle, the contact stresses on the sealing surface reduces significantly and the maximum pressure stress is only 324MPa. Figures 5 and 6 show the temperature-time curves and the circumferential stress-time curves at the arc center of the exterior cover.

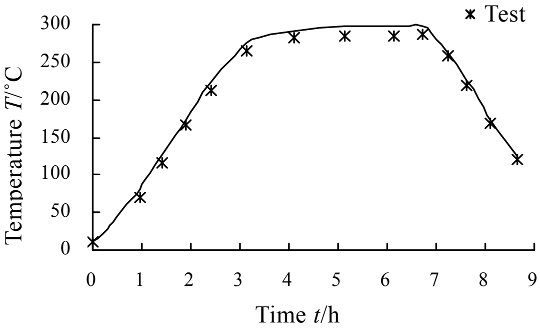

FIGURE 5. The temperature-time curves at the arc center of the exterior cover

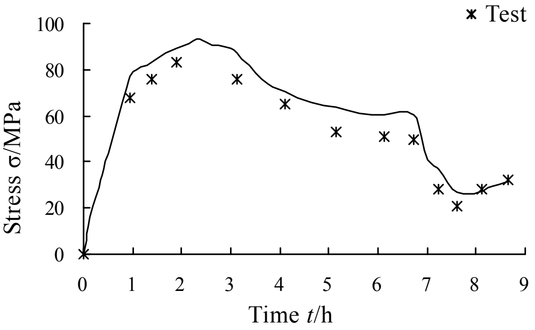

FIGURE 6. The circumferential stress-time curves at the arc center of the exterior cover

6. REMARKS

The approach presented in this paper is based on a mixed formulation for the elastoplastic contact problem and the transient heat transfer analysis with the consideration of several coupled effects. The developed program for sealing analysis can be used to predict the displacement, stress and temperature fields of the reactor pressure vessel. Further evaluation demonstrates a good agreement between the transient seal analysis and the experimental measurement. The algorithm and program has also been successfully used in analyzing sealing behaviour of other types of reactor pressure vessels.

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