Improvement of contact pressure evaluation method in elastic region between ICI tube and penetration hole of reactor lower head under severe accidents

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1. Introduction

The relocated core materials with high temperature in the form of molten pools or solidified debris can attack the reactor lower head and penetration area, such as in-core instrument (ICI) tube in PWR and control rod guide tube (CRGT) in BWR. In the early 1990s, two lower head penetration failure modes, 'failure by tube heat-up' and 'tube ejection and rupture', have been proposed by NUREG/CR-5642 [1]. Because the diameter of ICI tube penetrations is relatively small comparing to that of CRGTs, the melt penetration distance will be short. This results in low possibility of failure by tube heat-up. Therefore, penetration failure by tube ejection will be the main failure mode of lower head with ICI penetrations. The essential of the existing evaluation method of tube ejection is to calculate the contact pressure between tube and lower head penetration. The contact pressure is expressed as a function of radius of tube and hole, length of interface, and material properties. The contact pressures at the elastic and plastic range are compared and the smaller one is selected. However, the main limitation of contact pressure evaluation by NUREG/CR-5642 is to ignore the effect of lower head deformation by considering only a single hollow cylinder which represents an ICI tube. In this study, the existing contact pressure evaluation method at the tube-hole interface is validated and the improved analytical evaluation method is proposed.

2. Validation of the existing method

The applied force to reactor lower head and the interface between penetration tube and hole in the reactor lower head by RCS internal pressure is shown in Fig. 1. The ejection of a penetration tube can be resisted by high friction force at the interface of tube and hole. If the weld is failed and the friction force defined by Eq. (1) is less than ejection force by internal pressure, the tube will be ejected.

$$F_f = \int dF_f = \int_0^{l_f} f \cdot P_s \cdot 2\pi r_o \cdot dl \tag{1}$$

where F_f : friction force,
f : friction coefficient at the interface,
l_f : length of contact interface,
P_s : contact pressure,
r_o : outer radius of tube.

The contact pressure between tube and penetration hole, P_s, is evaluated by Eqs. (2) and (3).

$$\delta < 0,\ P_s = lesser\ of \begin{cases} \dfrac{\delta \cdot E(r_o^2 - r_i^2)}{r_o[r_o^2(1-2\nu_t)+r_i^2(1+\nu_t)]} \\ \dfrac{2}{\sqrt{3}}\sigma_u \ln\left(\dfrac{r_o}{r_i}\right) \end{cases} \tag{2}$$

$$\delta \geq 0,\ P_s = 0 \tag{3}$$

where δ: difference of displacement between tube and hole.

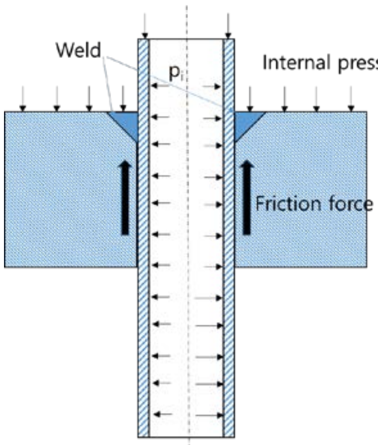

Fig. 1. Schematics of applied forces to reactor lower head penetration

However, because Eq. (2) for contact pressure has been used without appropriate validation, the actual meaning of Eq. (2) has to be investigated. At first, the following assumptions are known from the information of NUREG/CR-5642.

- Radial stress at the outer surface of the tube is same as the contact pressure.
- The contact pressure is a function of displacement at the outer surface of the tube.
- If stress approaches to the critical value, which is a function of ultimate strength, contact pressure maintains the constant value at a certain temperature.

The geometry of tube-hole interface shown in Fig. 1 can be suggested as follows;

- Single hollow cylinder : inner tube (ICI tube) vs. rigid hole structure (lower head penetration hole)

- Double hollow cylinders : inner tube (ICI tube) vs. outer tube (lower head penetration hole)

For the single hollow cylinder case shown in Fig. 2, force equilibrium equation of a volume element can be expressed as Eq. (4).

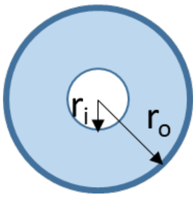

Fig. 2. Cross-section of single hollow tube

$$\frac{\sigma_r-\sigma_\theta}{r}+\frac{d\sigma_r}{dr}=0 \qquad (4)$$

where σ_r and σ_θ: radial and circumferential stress.

By the Hook's law, directional strains (ϵ_r, ϵ_θ, and ϵ_z) can be expressed as Eqs. (5) – (7).

$$\epsilon_r=\frac{1}{E}[\sigma_r-\nu(\sigma_\theta+\sigma_z)] \qquad (5)$$
$$\epsilon_\theta=\frac{1}{E}[\sigma_\theta-\nu(\sigma_z+\sigma_r)] \qquad (6)$$
$$\epsilon_z=\frac{1}{E}[\sigma_z-\nu(\sigma_r+\sigma_\theta)] \qquad (7)$$

where σ_z : longitudinal stress,
E : elastic modulus,
ν : Poisson's ratio.

In general, the axial stress or strain can be simplified according to the assumptions of Eq. (8) – (10);

$$\epsilon_z=0 \text{ (plane strain, clamped ends)} \qquad (8)$$
$$\sigma_z=0 \text{ (plane stress, free open ends)} \qquad (9)$$
$$\sigma_z=\frac{1}{2}(\sigma_r+\sigma_\theta) \text{ (free closed ends)} \qquad (10)$$

In order to express the radial stress as a function of displacement of outer wall, u_o, the boundary conditions at the inner and outer surface should be as Eqs. (11) and (12).

$$r=r_i,\ \sigma_r=P_i \qquad (11)$$
$$r=r_o,\ u=u_o \qquad (12)$$

where P_i : pressure at the inner surface,
u : radial displacement,

By solving Eq. (4) with the conditions shown in Eqs. (8) – (10) by applying the Eqs. (11) and (12) and $P_i=0$, the pressures at the outer surface, P_s, which is same as the radial stress at the outer surface, become Eqs. (13) – (15), respectively.

$$\epsilon_z=0,\ P_s=\frac{Eu_o(r_o^2-r_i^2)}{r_o(1+\nu)[(1-2\nu)r_o^2+r_i^2]}, \qquad (13)$$

$$\sigma_z=0,\ P_s=\frac{Eu_o(r_o^2-r_i^2)}{r_o[(1+\nu)r_i^2+(1-\nu)r_o^2]} \qquad (14)$$
$$\sigma_z=\frac{1}{2}(\sigma_r+\sigma_\theta),\ \ P_s=\frac{Eu_o(r_o^2-r_i^2)}{r_o[(1-2\nu)r_o^2+(1+\nu)r_i^2]} \qquad (15)$$

By comparing the upper part of the right hand side of Eq. (2) with Eqs. (13) – (15), Eq. (15) is exactly same with Eq. (2). This is the contact pressure at the interface in elastic region. Therefore, it can be concluded that the contact pressure in NUREG/CR-5642 is derived by following conditions.

- The contact pressure is a radial stress at the outer surface of a 'single hollow cylinder.'
- The displacement at the outer surface of a cylinder is given as a boundary condition.
- Both ends are freely closed.
- Internal pressure is zero.
- Deformation of the lower head penetration hole is ignored.

3. Derivation of the improved model

If a lower head with the penetration hole can be considered as the other hollow cylinder with large outer radius, the geometrical configuration of this tube and hole can be assumed as double hollow cylinders whose interface is in contact as shown in Fig. 3.

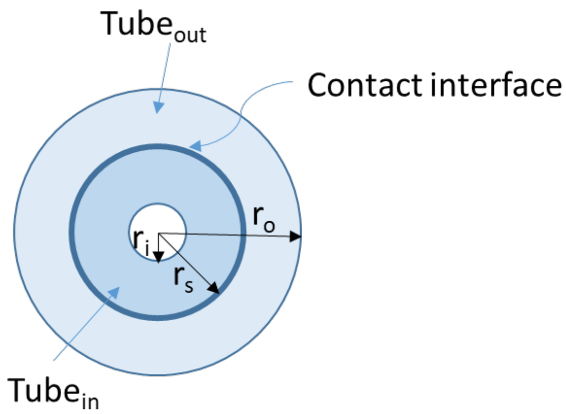

Fig. 3. Cross-section of double hollow tube

The general boundary conditions with pressures at the inner and outer surface (P_i and P_o) with contact pressure P_s are shown in Eqs. (16) – (18).

$$r=r_i,\ P=P_i \qquad (16)$$
$$r=r_s,\ P=P_s \qquad (17)$$
$$r=r_o,\ P=P_o \qquad (18)$$

If difference of the displacement at the contact interface, δ, which is defined by Eq. (19) is known, the contact pressure should be a function of δ.

$$\delta=u(r_s)_{Tube_{out}}-u(r_s)_{Tube_{in}} \qquad (19)$$

By applying Eqs. (16) - (18) into Eq. (4) for free closed ends, the displacement of each cylinder at the contact interface can be expressed as Eq. (20) and (21) :

$$u(r_s)_{Tube_{in}} = \frac{r_s}{E_i(r_i^2-r_s^2)}[(1-2\nu_i)(r_i^2P_i - r_s^2P_s) + (1+\nu_i)r_i^2(P_i - P_s)] \tag{20}$$

$$u(r_s)_{Tube_{out}} = \frac{r_s}{E_o(r_s^2-r_o^2)}[(1-2\nu_o)(r_s^2P_s - r_o^2P_o) + (1+\nu_o)r_o^2(P_s - P_o)] \tag{21}$$

where E_i and E_o : Elastic modulus of $\mathrm{Tube_{in}}$ and $\mathrm{Tube_{out}}$,
ν_i and ν_o: Poisson's ratio of $\mathrm{Tube_{in}}$ and $\mathrm{Tube_{out}}$.

Then, Eq. (19) can be expressed as Eq. (22) by substituting Eqs. (20) and (21) :

$$P_s = \frac{\frac{\delta}{r_s} + \frac{(2-\nu_i)r_i^2P_i}{E_i(r_i^2-r_s^2)} + \frac{(2-\nu_o)r_o^2P_o}{E_o(r_s^2-r_o^2)}}{\frac{(1+\nu_i)r_i^2+(1-2\nu_i)r_s^2}{E_i(r_i^2-r_s^2)} + \frac{(1-\nu_o)r_s^2+(1+2\nu_o)r_o^2}{E_o(r_s^2-r_o^2)}} \tag{22}$$

If $P_i = P_o = 0$ and $r_o \gg 1$, Eq. (22) is simplified as Eq. (23).

$$P_s = \frac{\delta E_i E_o(r_i^2-r_s^2)}{r_s\{[E_o(1+\nu_i)-E_i(1+\nu_o)]r_i^2+[E_i(1+\nu_o)+E_o(1-2\nu_i)]r_s^2\}} \tag{23}$$

Eq. (23) also has variables of geometry and material properties of the outer cylinder, which is the lower head in the reactor case. This is the main difference with Eq. the upper part of Eq. (2), which has variables of geometry and material properties of the inner cylinder only.

4. Calculation example

For an ICI tube and a lower head vessel with penetration with same difference of displacement, δ, the contact pressures by Eqs. (2) and (23) are compared. The materials of the tube and the lower head are assumed to be INCONEL 690 and SA533B1, respectively. The material properties are shown in Figs. 4 and 5. At high temperature region, the elastic modulus and strength of SA533B1 is much lower than those of INCONEL 690, and such remarkable difference implies structural behavior of lower head can affect the contact pressure.

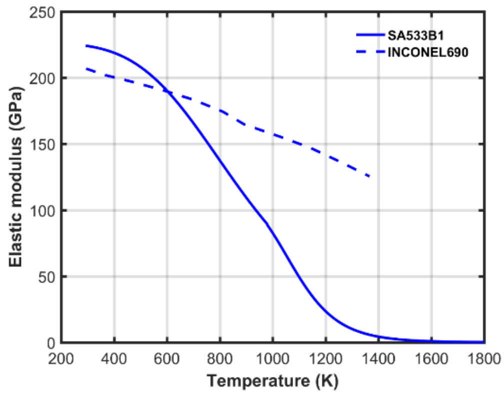

Fig. 4. Elastic modulus of INCONEL690 and SA533B1

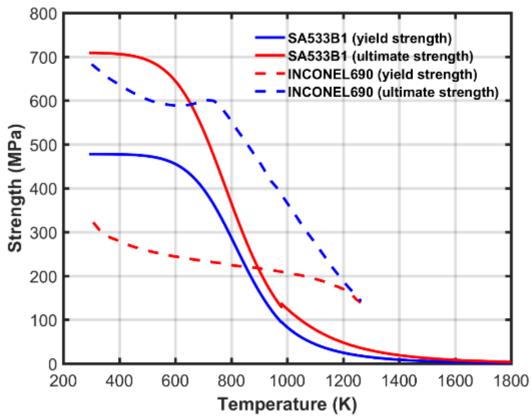

Fig. 5. Yield and ultimate strength of INCONEL690 and SA533B1

For $r_i = 9.525$ mm, $r_s = 38.1$ mm, $r_o = 2.3$ m and temperature T = 1273 K, the contact pressure with respect to δ can be evaluated as shown in Fig. 6. The contact pressure by Eq. (23) is much less than that by the upper part of Eq. (2). And because the plastic contact pressure by the lower part of Eq. (2) is representing the critical value, it is shown that the applicability of the elastic contact pressure by the upper part of Eq. (2) is limited to very small δ.

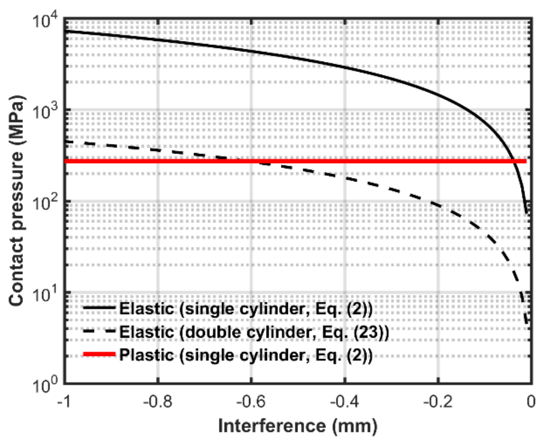

Fig. 6. Contact pressure by different geometric configuration

The contact pressures at wide temperature range by Eq. (2) and Eq. (23) for different geometry configuration are evaluated as shown in Figs. 7 and 8. In Fig. 7, the elastic contact pressure with single cylinder configuration is applied for very small δ range (less than 0.05 mm). However, in Fig. 8, the range of δ for the elastic contact pressure with double cylinder configuration becomes larger than that with single cylinder configuration, especially at high temperature region.

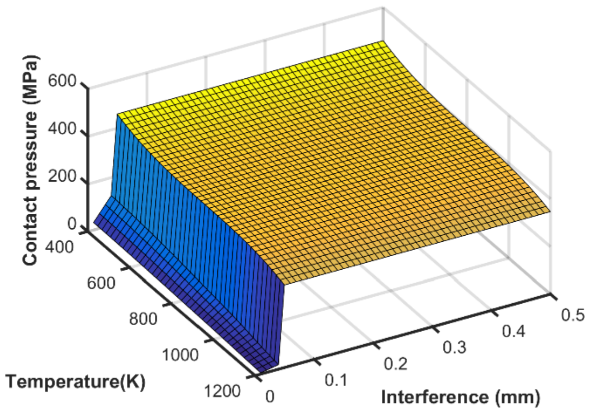

Fig. 7. Contact pressure by single cylinder configuration

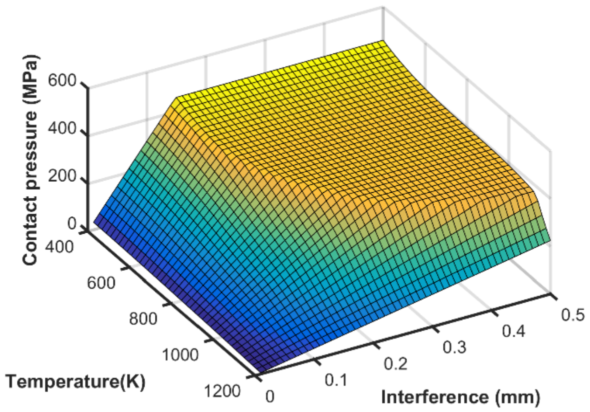

Fig. 8. Contact pressure by double cylinder configuration

5. Conclusions

The elastic contact pressure evaluation method from NUREG/CR-5642 has been reviewed in this study. The main findings regarding to the assumptions of the previous model are that the contact pressure is a radial stress at the outer surface of a 'single hollow cylinder' and the both ends of the cylinder is freely closed. However, because this model cannot take account of the structural behavior of the lower head simultaneously, the new geometrical configuration which considers double cylinders is proposed. Much less elastic contact pressure by double cylinder configuration is evaluated than that by single cylinder configuration. Because the small contact pressure results in small friction force and high possibility of tube ejection, the new evaluation method which calculate the less elastic contact pressure should be applied in order to predict tube ejection failure, especially small displace difference δ. In addition, the plastic contact pressure with double cylinder configuration will be investigated in the next study.

ACKNOWLEDGEMENT

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[1] J. L. Rempe et al., Light Water Reactor Lower Head Failure Analysis, NUREG/CR-5642, 1993.