Mechanical behavior simulation of TMI-2 lower head using LOHEY module

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Abstract: LOHEY module allowing to simulate the deformation behavior and failure of reactor vessel lower head under heavy thermal loading has been used for investigation of structural response of pressurised vessel lower head during TMI-2 accident. The failure probability due to uncertainties of accident thermal conditions and material properties has been analysed. Investigation shows that temperature of external surface of lower head has a great influence on integrity of reactor vessel.

1. INTRODUCTION

The TMI-2 Vessel Investigation Project has shown that a localized region of the vessel, approximately 1 m by 0,8 m reached temperature 1100\(^\circ\)C during accident. Intensive creep and plastic deformation are characteristic response of lower head on high temperature gradient in the wall of pressurized vessel. LOHEY module has been developed for simulation of lower head deformation behavior in this condition. Uncertainties and insufficient knowledge of thermal conditions and material properties demand the usage probabilistic approaches for simulation of lower head deformation behavior during severe accident. LOHEY module allows to investigate the uncertainties of failure conditions cased by uncertainties of mechanical properties. This article gives the description of approaches used by LOHEY module and the short result of investigation of the probability of lower head failure during TMI-2.

2. STRUCTURAL MODEL OF LOWER HEAD DEFORMATION BEHAVIOR

Main assumptions of used structural model:
- the half spherical or half ellipsoidal lower head is considered as a set of symmetric about vessel axis hoop elements deformed independently (see Fig. 1);
- the following loads acts in hoop element: temperature loads, meridional and hoop normal forces caused by internal overpressure and weight corium and vessel wall;
- the hoop element is considered as a multilayer shell;
- the layer temperature along radial, hoop and meridian direction is constant;
- the vessel steel has elastic, plastic, creep and thermal expansion properties
- the layer stress state is assumed biaxial; radial stress is not considered.

The basic equations which allow to describe the lower head stress-strain state evolution with account of these assumptions can be written by the following way.

The hoop and meridian layer strain in each layer may be written as:
\[ \varepsilon_i(t) = \varepsilon_i^{el}(t) + \varepsilon_i^{pl}(t) + \varepsilon_i^{cr}(t) + \varepsilon_i^{th}(t), \quad (i = m, \theta) \]  

where \( \varepsilon_i(t), \varepsilon_i^{el}(t), \varepsilon_i^{pl}(t), \varepsilon_i^{cr}(t), \varepsilon_i^{th}(t) \) - meridional \((i = m)\) and hoop \((i = \theta)\) strain: 
total, elastic, creep and thermal; \( t \) - time. 
Elastic and thermal strain are written as: 
\[ \varepsilon_i^{pl}(t) = S_{ij} \sigma_j(t); \quad \varepsilon_i^{th}(t) = \alpha^{th} \Delta T(t), \]  

where \( S_{ij} \) - the components of the elastic constant tensor; \( \alpha^{th}, \Delta T \) - the thermal expansion coefficient and the temperature increment; \( \sigma_j(t) \) - stress components. 
Instant plastic strain and creep strain are written as: 
\[ \varepsilon_i^{\alpha}(t) = \int_0^t d\varepsilon_i^{\alpha}, \quad (\alpha = pl, cr; i = m, \theta), \]  

where 
\[ d\varepsilon_i^{\alpha} = \frac{3}{2} \frac{d\varepsilon_{int}^{\alpha}}{\sigma_{int}} (\sigma_i - \sigma_0), \] 

where \( d\varepsilon_{int}^{\alpha} \) - the intensity increment of \( \alpha \)-th strain component (plastic or creep strain); \( \sigma_{int} \) - the stress intensity; \( \sigma_0 = (\sigma_m + \sigma_\theta) / 3 \). 

The intensity increment of instant plastic strain is calculated with help the of \( \varepsilon_{int}^{pl} - \sigma_{int} \) diagram by the following way: 
\[ d\varepsilon_{int}^{pl} = \frac{K_{load}}{E_n^{pl}} d\sigma_{int}, \] 

where \( K_{load} \) - the loading condition coefficient: neutral loading and unloading conditions correspond to \( K_{load} = 0 \), loading conditions corresponds to \( K_{load} = 1 \); \( E_n^{pl} \) - the tangent plastic modules according to \( \varepsilon_{int}^{pl} - \sigma_{int} \) diagram. 
The correlation for the creep strain intensity increment may be written as: 
\[ d\varepsilon_{int}^{cr} = A \sigma_{int}^{m}(t) e^{-\frac{T(t)}{\tau(t)}} dt \]  

where \( A, m, Q \) - the creep constants.; \( dt \) - the time increment. 
Using the plain section assumption it is possible to write 2N-2 correlations: 
\[ \varepsilon_{i,n} R_{i}^{n} = \varepsilon_{i,n+1} R_{i}^{n+1}, \quad (i = m, \theta; \ n=1,\ldots,N-1) \]  

where \( R_{i}^{n} \) - meridional \((i = m)\) and hoop \((i = \theta)\) radii of \( n \)-th layer. 
After substitution (1) - (3) into (4) we have the system of the 2N-2 equations in 2N unknown stress components \( \sigma_{i,n} \) \((i=m,\theta)\). The two additional equation are obtained from the consideration of the force balance: 
\[ \sum_{r=1}^{N} \sigma_{i,n}(t) \delta_n(t) = T_i \quad (i = m, \theta) \]  

where \( T_i \) - meridional \((i = m)\) and hoop \((i = \theta)\) normal forces; \( \delta_n(t) \) - the thickness of \( n \)-th layer. It is assumed that thickness \( \delta_n(t) \) changes due to unelastic deformation.
Meridional and hoop normal forces equilibrate the external loads - vessel overpressure and weight of corium and vessel wall.

**Pressure loads.** The normal forces in half ellipsoidal lower head caused by vessel overpressure are equal:

\[
T^\text{press}_m = \frac{PR_\theta}{2}; \quad T^\text{press}_\theta = \frac{PR_\theta}{2} \left(2 - \frac{R_\theta}{R_m}\right),
\]

(6)

where \( P \) - vessel pressure.

**Weight loads.** Let's consider the lower head in section with polar angle \( \varphi \). It is assumed that corium is liquid and top level of corium is characterized by polar angle \( \varphi_{cor} \). If considered section is placed under the corium top level, normal forces are caused by (1) hydrostatic pressure \( P_{hydr} \) of liquid corium, placed above the considered section, and (2) by weight \( W(\varphi) \) of vessel wall and corium, placed under the considered section. The normal forces in a lower head wall caused by hydrostatic pressure of liquid corium is estimated with help of (7), where

\[
P = P_{hydr} = \rho_{cor} gh,
\]

(7)

where \( \rho_{cor} \) - the corium density; \( g \) - the acceleration of free fall; \( h \) - the height of corium placed above the considered section.

If to suggest that hoop force caused by the weight of corium and vessel wall is negligible then we receive the correlations for normal meridional force:

\[
2\pi R(\varphi)T^\text{weight}_m = W(\varphi) \sin \theta;
\]

(8)

Because described approach considers only normal forces and it does not consider the bending component of loads (and the shear force), caused by meridional gradient of physical parameters, we take into account only meridional force \( T^\text{weight}_m \) as source of stresses into vessel wall.
So, the normal forces in the force balance equation (6) are equal:

\[ T_m = T_m^{\text{press}} + T_m^{\text{hydro}} + T_m^{\text{weight}} \]  

\[ T_\theta = T_\theta^{\text{press}} + T_\theta^{\text{hydro}}. \]  

Failure criteria. Due to melting and failure the current number of layers (wall thickness) can change.

Two failure criterion are included in the considered model. According to the first criteria the layer fails if the plastic strain intensity exceeds the ultimate failure strain. The second criterion is based on the analysis of material damage induced by creep strains. Using the correlation for time to rupture at the given stress and temperature the current damage of each layer is determined. A life fraction rule was used to calculate the damage under transient conditions. The life fraction rule assumed that material damage was cumulative.

Lower head global rupture occurs when all layers of the hoop element melt or fail.

Some benchmark calculations results performed with help of LOHEY module are presented in [1].

3. SIMULATION OF LH DEFORMATION BEHAVIOR DURING TMI-2 ACCIDENT

Since the LH has not been ruptured during TMI-2 accident, the simulation results of TMI-2 accident can not be estimated in terms of the rupture time. Vessel strain history, performed by deterministic approach and giving some imagination about damage stage of LH, does not allow to estimate the trust to simulation result. Therefore we used the probabilistic approach for LH deformation behavior simulation during TMI-2 accident. This approach allows to estimate the sensitivity of simulation results to uncertainties of mechanical properties and the probability of LH failure during LH accident.

Beside the influence of cooling condition on failure probability is important task for investigation of LH integrity. Margin-to-Failure Calculation as part of the TMI-2 Vessel Investigation Project by OECD [3] shown that the cooling condition influence strongly on deformation behavior and failure condition of lower head. If believe that during TMI-2 accident the temperature of internal surface of LH in zone of contact with debris was increased up to 1100°C, the temperature of external surface behind debris, defined by cooling condition, can be considered as variable parameter.

![Temperature history](image1.png)

Fig. 5. Time histories of temperature of internal and external surfaces in zone of debris during and external surfaces in zone of debris during TMI-2 accident.

![Vessel pressure history](image2.png)

Fig. 6. Time histories of vessel pressure during TMI-2 accident.
Fig. 7. Temperature dependencies of yield strength and ultimate strength of TMI-2 vessel steel.

Fig. 8. Creep test experimental results and approximating dependencies of TMI-2 vessel steel.

Time histories of temperature of internal and external surfaces in zone of debris during TMI-2 accident are shown in Fig. 5. Maximal temperature $T_{\text{max}}$ of external surface is considered as variable parameter in present investigation. The vessel pressure time history during TMI-2 accident is shown in Fig. 6.

Properties of TMI-2 vessel steel. The Properties of TMI-2 vessel steel have been estimated in frame of OECD project [4]. The temperature dependencies of yield strength and ultimate strength are shown in Fig. 7. The following approximating function has been used for description of time to the creep rupture:

$$t^{\text{ru}} = B\sigma_{\text{int}}^{-k}e^{\frac{G}{T}},$$

where $B$, $k$, $G$ - the constant of a creep rupture time.

Comparison of experimental results and simulation results of $t^{\text{ru}}(T,\sigma)$ with the help of proposed function (10) is shown in Fig. 8.

Due to inaccessible of creep rate test result we used the following approach for description of creep rate. We assumed that creep rupture strains equal to 20%. For this assumption the creep rate for each test can be estimate with help of the following correlation:

$$\frac{d\varepsilon_{\text{int}}^{\text{cr}}}{dt} = \frac{0.2}{t^{\text{ru}}(T,\sigma)}.$$

Lower head failure probabilities versus time during TMI-2 accident for different $T_{\text{max}}$ are shown in Fig. 9. This curves are result of the 1000 calculations for each temperature, for considered conditions the probability of lower head failure becomes higher then 0.0 when temperature of the external surface becomes higher then 859K and does not increase practically when temperature of internal surface and pressure decrease in 1.2 hour after melt relocation. One can see from Fig. 9 the cooling condition influence strongly on carried capacity of lower head. Failure probability increase form 0.0 to 1.0 under changing of external temperature from 760K to 890K.
Fig. 9. LH failure probability versus time during TMI-2 accident for different $T_{\text{max}}$.

5. SUMMARY

Data available from the OECD Vessel Investigation Project allows to simulate the deformation behavior and failure probability of lower head during TMI-2 accident. Presented investigation shown that the cooling condition influence strongly on carried capacity of lower head. In the frame of used approaches it is possible to suppose that cooling condition during TMI-2 accident did not allow to reach the external surface temperature in hot spot the value 900K.

REFERENCES