3 D Finite Element Analysis of Steel Vessels for a LOCA Condition

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Abstract
This paper attempts to present analysis of Steel Pressure Vessels for Pressurised Water Reactors (PWR). A three dimensional finite element analysis has been developed. Service loads and LOCA conditions are also included. The analysis and the specially developed computer program SWEL have been applied to the proposed steel vessel for SIZEWELL 'B'. Results obtained from the analysis have been fully corroborated with those available from published data.

1. Introduction
A three-dimensional elasto-plastic fracture analysis has been carried out to assess fracture under LOCA conditions.

An isotropic material properties and thermal conductances have been included in the analysis for studs and ligaments. Throughout the analysis for LOCA conditions the stud preload, the limit case of separation of the nut from the closure head, mechanical loads associated with the core barred dead weight and clamping load have been taken into consideration. A sophisticated finite element modelling for the control rod mechanism tube penetration's forms a part of the overall analysis such that the contribution offered by the geometrically tortuous regions of the Vessel is included. A step-by-step analysis is carried out by the first author is included in the form of a flow chart. The safety factors prior to the LOCA conditions are plotted on the vessel. These factors are reduced in some regions by almost 45% under extreme load conditions at the time of LOCA. Accelerated Newton-Raphson Procedure is adopted as a solution technique (1). Cracks are predicted in three-dimension (1,2,3,4). Stresses and strains are evaluated at the initiation, closure and reopening of cracks.

2. Program SWEL
2.1 Definition of Symbols

$P_{ex}$ - total external load.

$\Delta e_{th}$ - thermal strain increment.

$\varepsilon_i$ - strain at iteration i

$\Delta e$ - $(\Delta e_1 - \Delta e_{th})$ - strain increment

$e_{i-1}$ - strain at iteration i-1

$\sigma_{i-1}$ - stress at iteration i-1
\( \{ \sigma_i \} \) - stress at iteration \( i \)  
\( \{ \Delta \sigma_i \} \) - stress increment  

IFLA - stress point indicator  
\( =0 \) - elastic point  
\( =1 \) - plastic point  
\( =2 \) - unloading from plastic state  

\( \sigma_Y \) - uniaxial yield stress  
\( \bar{\sigma} \) - equivalent stress  

\( \bar{\sigma}_Y = f(\sigma) \) - Von Mises yield function  
\( [D_E] \) - elastic material matrix  
\( [D_{EP}] \) - elasto-plastic material matrix  

2.2 Step-by-Step Analysis

```
START

CALCULATE:
\( \{ \Delta \sigma \}' = [D_E] \{ \Delta \varepsilon \} \)
\( \sigma = \sigma_1 \)
\( \sigma_1 = \sigma_{i-1} + \{ \Delta \sigma_1 \}' \)
\( \sigma_1 = f[\sigma_1] \)
\( \bar{\sigma} = \sigma_Y \)

IFLA = 1

ELASTIC POINT, NO

\( \bar{\sigma}_1 \geq \sigma_Y \)

NO

ELASTIC LOADING OR UNLOADING

\( \sigma_1 = \sigma_1' \)

YES

YES, PLASTIC POINT

\( \bar{\sigma}_1 \geq \sigma_Y \)

NO

TRANSITIONAL LOADING

\( \sigma_1 = \sigma_{i-1} + \{ \Delta \sigma_1 \} \)

CALCULATE:

\( \{ \Delta \sigma \}' = [D_E] \{ \Delta \varepsilon \} \)
\( \sigma = f[\sigma_1] \)

UNLOADING MAY NOT BE REAL

\( \sigma_1 = \sigma_{i-1} + \{ \Delta \sigma_1 \} \)

PLASTIC LOADING

TOTAL STRESS

\( \sigma_1 = \sigma_1' \)

①

②

③

④

STOP
```
At the end of each load increment, yield stress is updated for plastic points only, i.e. if IFLAG = 1.

Crack indicators - NCK(1), NCK(2), NCK(3)

- NCK(1) - crack normal to the principal stress '1'
- NCK(2) - crack normal to the principal stress '2'
- NCK(3) - crack normal to the principal stress '3'

\[
\begin{align*}
NCK(1) = 0 & \quad \text{no cracks} \\
NCK(2) = 0 & \quad \text{cracks closed} \\
NCK(3) = 0 & \quad \text{cracks open} \\
NCK(1) = 1 & \quad \text{cracks open} \\
NCK(2) = 1 & \quad \text{cracks open} \\
NCK(3) = 1 & \quad \text{cracks open}
\end{align*}
\]

- \( \sigma \) - stress/strain state at integration point
- \( \sigma_i \) - principal stresses; \( i = 1, 2, 3 \)
- \( \alpha_t \) - limiting tensile strength
- \( \sigma \) - transformation matrix
3. Application to Sizewell 'B' Vessel

3.1 Vessel Parameters

The parameters of a 4 loop PWR pressure vessel proposed to be adopted for Sizewell B are given below (Fig.1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel overall height</td>
<td>13660 mm</td>
</tr>
<tr>
<td>Inside diameter</td>
<td>4394 mm</td>
</tr>
<tr>
<td>Wall thickness opposite core</td>
<td>215 mm</td>
</tr>
<tr>
<td>Wall thickness at the flange</td>
<td>500 mm</td>
</tr>
<tr>
<td>Nominal clad thickness</td>
<td>6 mm</td>
</tr>
<tr>
<td>Thickness of the dome top</td>
<td>178 mm</td>
</tr>
<tr>
<td>Thickness of the dome bottom</td>
<td>127 mm</td>
</tr>
<tr>
<td>Inside diameter of inlet nozzle</td>
<td>700 mm</td>
</tr>
<tr>
<td>Diameter of closure studs</td>
<td>173 mm</td>
</tr>
<tr>
<td>Number of closure studs</td>
<td>54 (Each 1466 high)</td>
</tr>
<tr>
<td>(Nut 268x203)</td>
<td></td>
</tr>
<tr>
<td>(Washer 268x38)</td>
<td></td>
</tr>
<tr>
<td>Dry weight of the pressure vessel</td>
<td>434.8 x 10² kg</td>
</tr>
<tr>
<td>Normal operating pressure</td>
<td>15.98 M pa</td>
</tr>
<tr>
<td>Design pressure</td>
<td>17.13 M pa</td>
</tr>
<tr>
<td>Initial Hydraulic Pressure</td>
<td>21.42 M pa</td>
</tr>
<tr>
<td>Normal Operating Outlet Temperature</td>
<td>327°C</td>
</tr>
<tr>
<td>Thermal Temperature</td>
<td>288°C</td>
</tr>
<tr>
<td>Normal Operating Inlet Temperature</td>
<td>343°C</td>
</tr>
<tr>
<td>No Load Temperature</td>
<td>292°C</td>
</tr>
<tr>
<td>Design Life</td>
<td>40 years at 80% load</td>
</tr>
</tbody>
</table>

\[ E_s = C \times E \times 10^6 \text{ Mpa} \quad \text{C varies with temperature.} \]

3.2 Structural Analysis of a Vessel

In order to determine the stresses in a reactor pressure vessel caused by static and thermal loads, a three dimensional finite element model using 20 node isoparametric elements has been adopted. The adoption of three dimensional model is based on the fact that the vessel has non-axisymmetric components such as holes in the dome section and closure headbolts, control rod penetrations and other irregular boundaries. Figures 1a and 1b show the finite element meshes of the vessel, closure head wall flange region, wall nozzle region and wall-closure head. In order to determine stresses, deformations, plastic zones and safety margins of various areas, a three dimensional finite element analysis has successfully been carried out. In addition for the transient start up of the nuclear power plant, transient temperature analysis has also been carried out taking into consideration the temperature dependence of the material properties. Temperature distribution of the closure head flange, bolt closure head flange, nozzle ring points, wall together with corresponding stresses have been obtained. Figure 2 shows safety factors under operational conditions prior to to LOCA. These factors are on average reduced by about 45% at the time LOCA.

At this stage typical results for axial and hoop stresses along nozzle course and beltline region for large LOCA at 2000 secs are presented. They are shown in Fig.3.
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References.


