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.	$\{\Delta\epsilon\}$	$(\underset{\sim}{\Delta\epsilon}_i - \underset{\sim}{\Delta\epsilon}_{th})$ - strain increment
$\{\Delta\epsilon_{th}\}$	thermal strain increment.	$\{\epsilon_{i-1}\}$	strain at interation i-1
$\{\epsilon_i\}$	strain at iteration i	$\{\sigma_{i-1}\}$	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

σ_Y - uniaxial yield stress

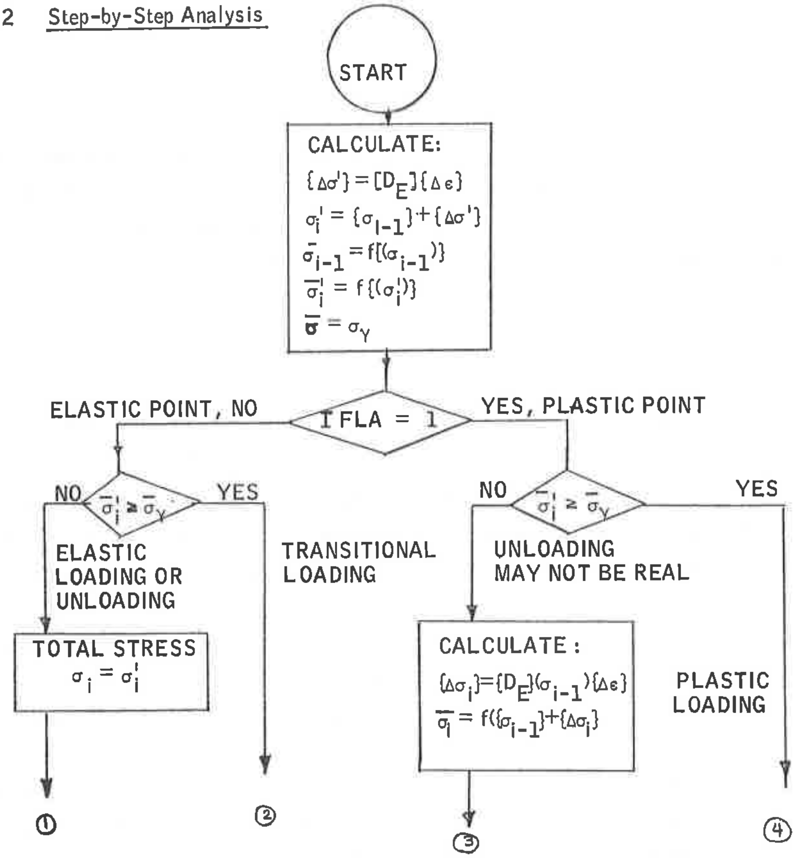
$\bar{\sigma}_Y$ - equivalent stress

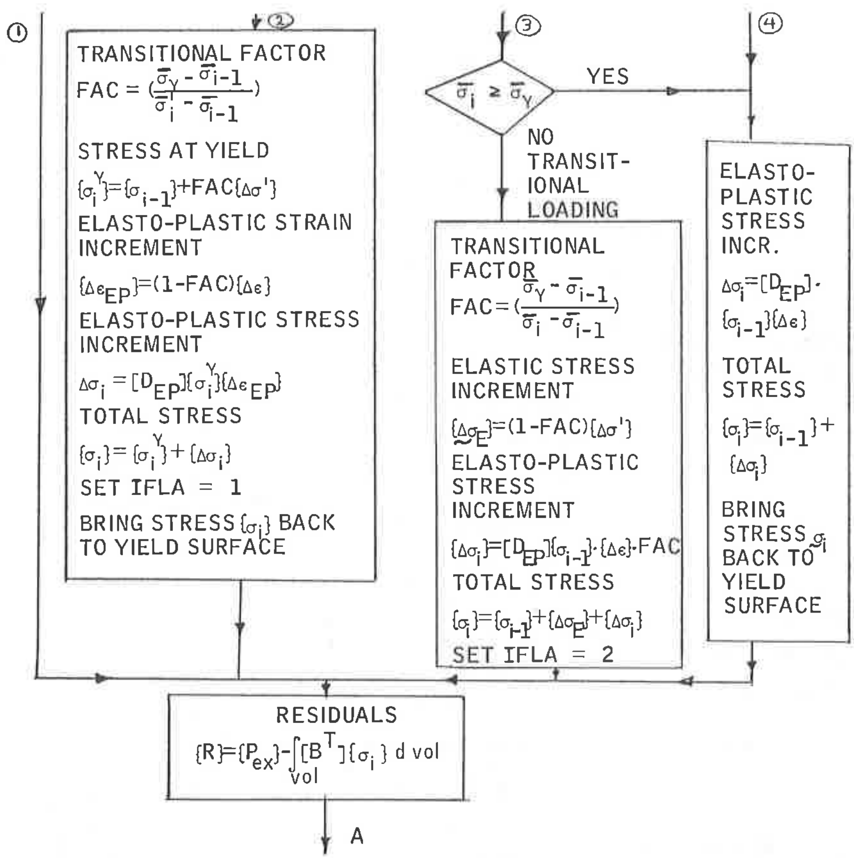
$\bar{\sigma}$ = $f(\underset{\sim}{\sigma})$ - Von Mises yield function

$[D_E]$ - elastic material matrix

$[D_{EP}]$ - elasto-plastic material matrix

2.2 Step-by-Step Analysis





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'

NCK(1)=0, NCK(2)=0, NCK(3)=0 } - no cracks

NCK(1)=1, NCK(2)=1, NCK(3)=1 } - cracks open

NCK(1)=2, NCK(2)=2, NCK(3)=2 } - cracks closed

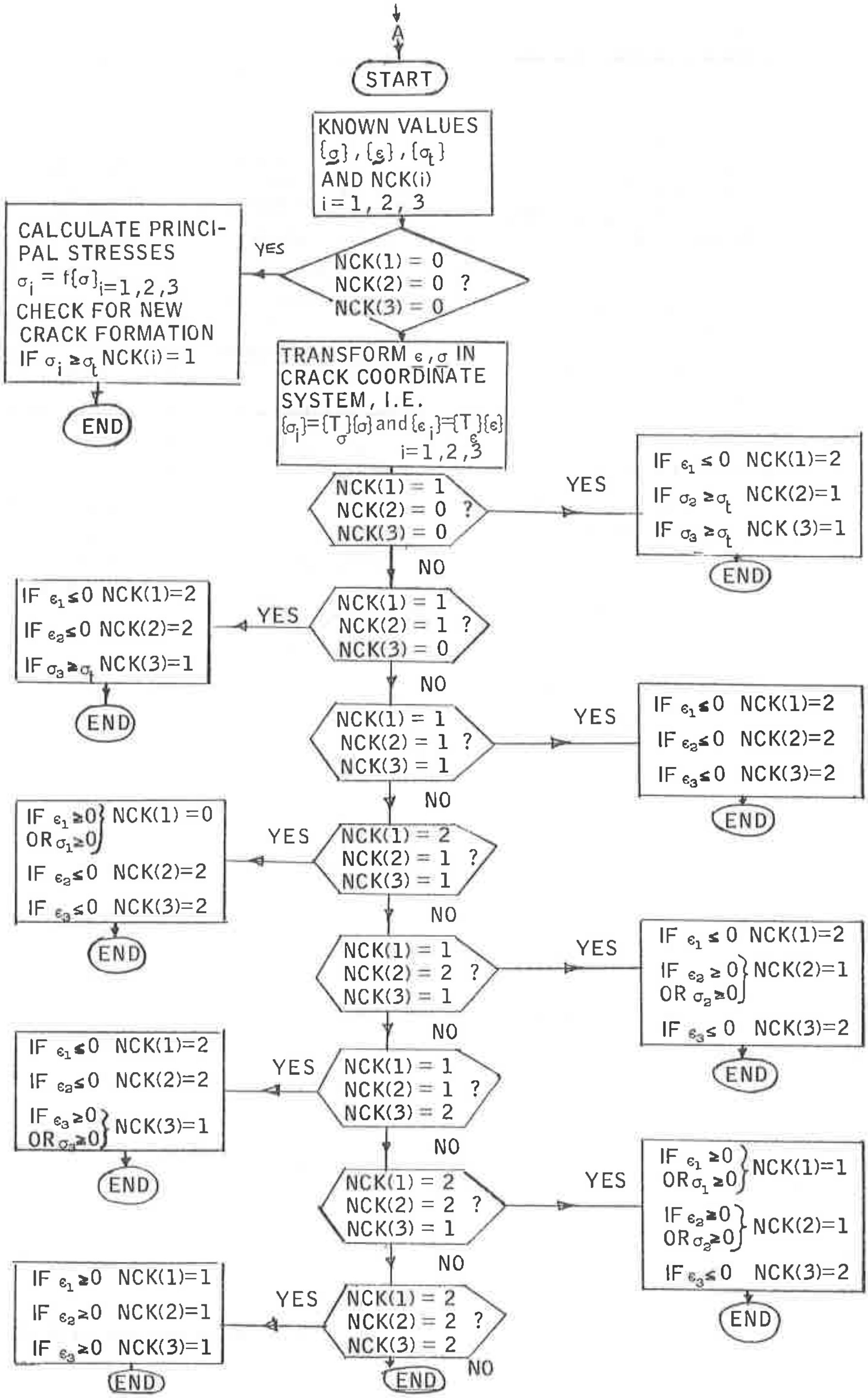
$\{\sigma\},\{\epsilon\}$ - stress/strain state at integration point

$\{\epsilon_i\}$ - principal strains

$\{\sigma_i\}$ - principal stresses; i-1,2,3

σ_t - limiting tensile strength

$[T_\epsilon],[T_\sigma]$ - transformation matrix


A
START
KNOWN VALUES
{σ}, {ε}, {σt}
AND NCK(i)
i=1, 2, 3
NCK(1) = 0
NCK(2) = 0 ?
NCK(3) = 0
YES
CALCULATE PRINCIPAL STRESSES
σi = f{σ} i=1,2,3
CHECK FOR NEW CRACK FORMATION
IF σi ≥ σt NCK(i)=1
END
TRANSFORM ε, σ IN CRACK COORDINATE SYSTEM, I.E.
{σi}={Tσ}{σ} and {εi}={Tε}{ε}
i=1,2,3
NCK(1) = 1
NCK(2) = 0 ?
NCK(3) = 0
YES
IF ε1 ≤ 0 NCK(1)=2
IF σ2 ≥ σt NCK(2)=1
IF σ3 ≥ σt NCK(3)=1
END
NO
NCK(1) = 1
NCK(2) = 1 ?
NCK(3) = 0
YES
IF ε1 ≤ 0 NCK(1)=2
IF ε2 ≤ 0 NCK(2)=2
IF σ3 ≥ σt NCK(3)=1
END
NO
NCK(1) = 1
NCK(2) = 1 ?
NCK(3) = 1
YES
IF ε1 ≤ 0 NCK(1)=2
IF ε2 ≤ 0 NCK(2)=2
IF ε3 ≤ 0 NCK(3)=2
END
NO
NCK(1) = 2
NCK(2) = 1 ?
NCK(3) = 1
YES
IF ε1 ≥ 0 OR σ1 ≥ 0 NCK(1) = 0
IF ε2 ≤ 0 NCK(2)=2
IF ε3 ≤ 0 NCK(3)=2
END
NO
NCK(1) = 1
NCK(2) = 2 ?
NCK(3) = 1
YES
IF ε1 ≤ 0 NCK(1)=2
IF ε2 ≥ 0 OR σ2 ≥ 0 NCK(2)=1
IF ε3 ≤ 0 NCK(3)=2
END
NO
NCK(1) = 1
NCK(2) = 1 ?
NCK(3) = 2
YES
IF ε1 ≤ 0 NCK(1)=2
IF ε2 ≤ 0 NCK(2)=2
IF ε3 ≥ 0 OR σ3 ≥ 0 NCK(3)=1
END
NO
NCK(1) = 2
NCK(2) = 2 ?
NCK(3) = 1
YES
IF ε1 ≥ 0 OR σ1 ≥ 0 NCK(1)=1
IF ε2 ≥ 0 OR σ2 ≥ 0 NCK(2)=1
IF ε3 ≤ 0 NCK(3)=2
END
NO
NCK(1) = 2
NCK(2) = 2 ?
NCK(3) = 2
YES
IF ε1 ≥ 0 NCK(1)=1
IF ε2 ≥ 0 NCK(2)=1
IF ε3 ≥ 0 NCK(3)=1
END
NO
END

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).

Vessel overall height	13660 mm	Inside diameter	4394 mm
Wall thickness opposite core	215 mm	Wall thickness at the flange	500 mm
Nominal clad thickness	6 mm	Thickness of the dome top	178 mm
Thickness of the dome bottom	127 mm	Inside diameter of inlet nozzle	700 mm
Inside diameter of outlet nozzle	737 mm	Number of closure studs	54 (Each 1466 high) (Nut 268x 203) (Washer 268x38)
Diameter of closure studs	173 mm		
Dry weight of the pressure vessel	434.8 x10^3 kg		
Normal operating pressure	15.98 M pa		
Design pressure	17.13 M pa		
Initial Hydraulic Pressure	21.42 M pa	Normal Operating Inlet Temperature	288^0 C
Normal Operating Outlet Temperature	327^0 C	Design Temperature	343^0 C
No Load Temperature	292^0 C	Design Life	40 years at 80% load

E_s C x E x 10^5 Mpa 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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