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LEAK-BEFORE-BREAK ANALYSIS OF A PRESSURIZER - ESTIMATION OF THE ELASTIC-PLASTIC SEMI-ELLIPTICAL THROUGH-WALL CRACK OPENING DISPLACEMENT

PRIMENA KONCEPTA PROCURIVANJA PRE LOMA NA POSUDU POD PRITISKOM - PROCENA ELASTO-PLASTIČNOG OTVARANJA POLU-ELIPTIČNE PROLAZNE PRSLINE

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Keywords
- semi-elliptical through-wall crack
- crack opening displacement
- GE/EPRI approach
- leak-before-break analysis
- reference stress approach

Ključne reči
- polueliptična prolazna prslina
- pomeranje otvaranjem prsline
- GE/EPRI pristup
- analiza curenja-pre-loma
- pristup referentnim naponom

Abstract

The work presents methods to estimate elastic-plastic semi-elliptical through-wall Crack Opening Displacement (COD) for the Leak-Before-Break analysis of a pressurizer. Usually proposed methods are based on GE/EPRI approach or on the reference stress and J-integral as stress intensity factor (SIF) along the crack tip. J-integral calculation provides the value of SIF at each node of mesh along the crack tip, where values vary from the surface to middle section of material in respect to material properties. COD value is calculated through thickness along the centre of crack. The COD values are less sensitive to distance from crack tip and material properties. The engineering approach for the calculation of J-integral by using COD values and material full stress-strain data is given. COD values are proportional to surface length of semi-elliptical through wall crack of the pressurizer.

Izvod

U radu su predstavljene metode za procenu otvaranja polueliptične prolazne prsline (COD) za analizu curenja-pre-loma kod posude pod pritiskom. Obično se predlažu metode na bazi pristupa GE/ EPRI ili primenom referentnog napona i J integrala kao faktora intenziteta napona (SIF) oko vrha prsline. Proračun J integrala daje vrednosti SIF u svakom čvoru mreže u okolini vrha prsline, gde se vrednosti menjaju od površine sredine preseka materijala u zavisnosti od osobina materijala. Vrednosti COD su manje osetljive na rastojanje od vrha prsline i na osobinu materijala. Dat je inženjerski pristup za proračun J integrala primenom COD i podataka napon-deformacija. Vrednosti COD su proporcionalne dužini površine polueliptične prolazne prsline locirane u zidu posude pod pritiskom.

INTRODUCTION

In regular service of nuclear power plant, the pressurizer has a main role to ensure steam pressure and damping of pressure caused by water level changes in pressurized water reactor-PWR. The most loaded is the lower spherical section of the pressurizer. This part is made from two material clad and substrate. The lower spherical section and noodle for pipeline are connected by welded joint. The pressurizer is subjected during service to the constant internal pressure p = 15.51 MPa. A three-dimension finite element model is made for the pressurizer with a through wall crack. The value of the J-integral has been calculated along the crack tip from outside to inside surface. Apart from the J integral, also the maximal crack opening displacement of an elliptical crack, as shown in Fig. 1, is calculated. The finite element software ABAQUS for a non-linear three dimensional problem is used. Conditions for Leak-Before-Break (LBB) are met if value of J-integral does not overcome the J-value at stable crack initiation. Under this condition the size of the orifice is possible to estimate by using calculated COD values in respect to the postulated crack length $2a$. The mass flow of water through the orifice is possible to estimate by using the formula:

$$\dot{m} = C \cdot A_2 \sqrt{2\rho(P_1 - P_2)} \qquad (1)$$

where C is the dimensionless orifice flow coefficient, R is fluid density in (kg/m^2), P_1 is fluid upsteam pressure in Pa, and P_2 is fluid downsteam pressure in Pa, A_2 is the cross section area of the orifice hole, calculated as surface of elliptical crack:

$$A_2 = 0.5a \cdot \mathrm{COD} \cdot \pi \tag{2}$$

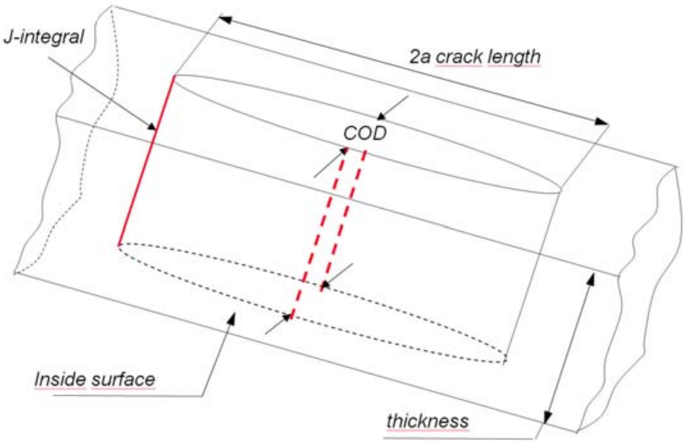

Figure 1. Schematic view of through-wall crack with calculated fracture parameters: J-integral and COD.
Slika 1. Shema prolazne prsline sa sračunatim parametrima loma: J integral i COD

MATERIAL

Three materials at the pressurizer bottom, with their mechanical properties and the fracture toughness of the nuclear pressurized vessel material are all listed in Tables 1 and 2, respectively.

The substrate material SA 508 C1.2 has a lower toughness than the clad material and the weld metal. Therefore it is assumed that postulated semi-elliptical crack can appear in the clad material.

Table 1. Mechanical properties of pressurizer materials.
Tabela 1. Mehaničke osobine materijala kompenzacione komore

Material	Westinghouse label	E (GPa)	$\sigma_y = R_{p0.2}, R_{eH}$ (MPa)	R_m (MPa)
Substrate	SA 508 C1.2	210	448	620
Clad	SS-Clading 309L	185	207	517
Weld metal	SA-182	185	172	448

Table 2. Fracture toughness parameters for pressurizer materials.
Tabela 2. Parametri žilavosti loma za materijal komore

Material	Westinghouse label	J_i (N/mm)	$J_{\max}$ (N/mm)
Substrate	SA 508 C1.2	210	448
Clad	SS-Clading 309L	185	207
Weld metal	SA-182	185	172

NUMERICAL MODELLING

Nuclear power plant pressure vessels have complex structures and the task should be appropriately simplified. The task is focused only a system of a pressurizer bottom and nozzle at the vessel-pipe system joint. From the theoretical point of view, the highest stresses could be expected on the outer side of the pressurizer bottom. The first step by finite element analysis using ABAQUS, /1/, was to prove this assumption, defining the critical location of the surface crack (position and orientation). In that sense, a 3D finite element model is created. The finite element mesh structure taken is the symmetric part that occupies half of the pressurizer bottom and half of the nozzle. As for the setting up of boundary conditions, according to the symmetrical characteristics, at the interface of the pressurizer and nozzle, the normal displacement of lengthways cross-section is given as zero. On the other symmetrical side, the normal displacement of lengthways cross section is also given zero. Considering the constraint of the axial rigid body displacement of the vessel, the normal displacement of the bottom cross section-leg is set up to be zero. Thus, the top part can still freely move along the axial direction, so the model is in accord with the practical situation. The model is loaded by increasing the temperature from +20°C to +300°C and increasing internal pressure up to p = 15.51 MPa. In order to find the maximal stress gradient through wall thickness, a couple of simulations are performed.

The through thickness crack is modelled by ABAQUS combining tetrahedral and hexagonal elements in the vicinity of the crack front. A through thickness crack with length of $2c$ = 120 mm is postulated. The position of the through thickness crack is shown in Fig. 2.

The equivalent von Mises stress filed is shown in Fig. 3. Figure 4 shows J integral values along the crack tip from the outer surface to the inner surface. The stress intensity solution in the term of the J integral is calculated at each node along the crack-tip through thickness. Segments are cut perpendicular to the crack tip curve and numerical integration is performed in order to calculate J-integral values. The decreasing of J-integral values in the region of austenitic clad material is obvious. However, the maximal J-integral value at the internal pressure p = 15.51 MPa overcomes the fracture toughness at stable crack initiation J_{mat} = 6.2 N/mm but is lower than maximal fracture resistance $J_{\max}$ = 29.7 N/mm. Therefore, the crack driving force is enough for stable crack propagation under pressure p = 15.51 MPa. Figure 3 shows the crack opening displacement at the middle of the crack. The maximal opening at pressure p = 15.51 MPa is COD = 0.015 mm. At such crack opening size the leak and break is possible. It seems that conditions for LBB are fulfilled for the smaller critical crack length.

Critical crack length is possible to determine by plotted J-integral vs. crack length diagram for points along the crack tip, as shown in Fig. 5. Graphically obtained critical COD = 0.01 mm value at the crack center, as schematically shown in Fig. 1, is used in order to determine the critical crack length for leak before break (LBB), as shown in Fig. 6.

Incompressible flow of mass through an orifice with negligible friction losses and simplification of coefficients makes estimations possible by using Eq. (1). Calculation shows that the steam mass flow at the critical crack length $2a$ = 80 mm is 0.109 kg/s. This value is significant enough in order to recognize the LBB effect before the occurrence of final rupture. Similar analysis has been performed in /2-4/.

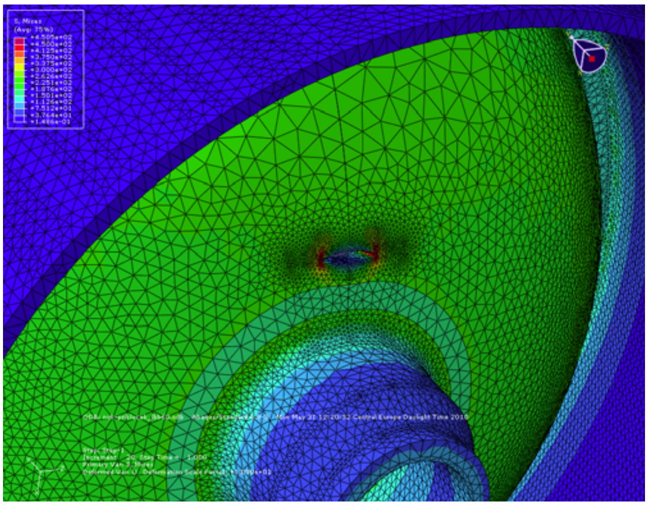

Figure 2. Pressurizer bottom with through thickness crack at pressure p = 30.02 MPa.
Slika 2. Dance komore sa prolaznom prslinom pri pritisku p = 30.02 MPa

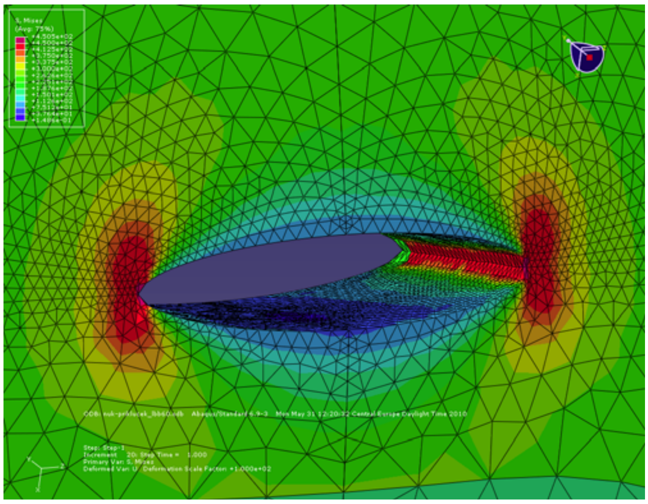

Figure 3. Equivalent von Mises stress field at the centre of crack tip in the region of welded joint at pressure p = 30.02 MPa.
Slika 3. Naponsko polje ekvivalentnog fon Mizes napona u centru vrha prsline u oblasti zavarenog spoja pri pritisku p = 30.02 MPa

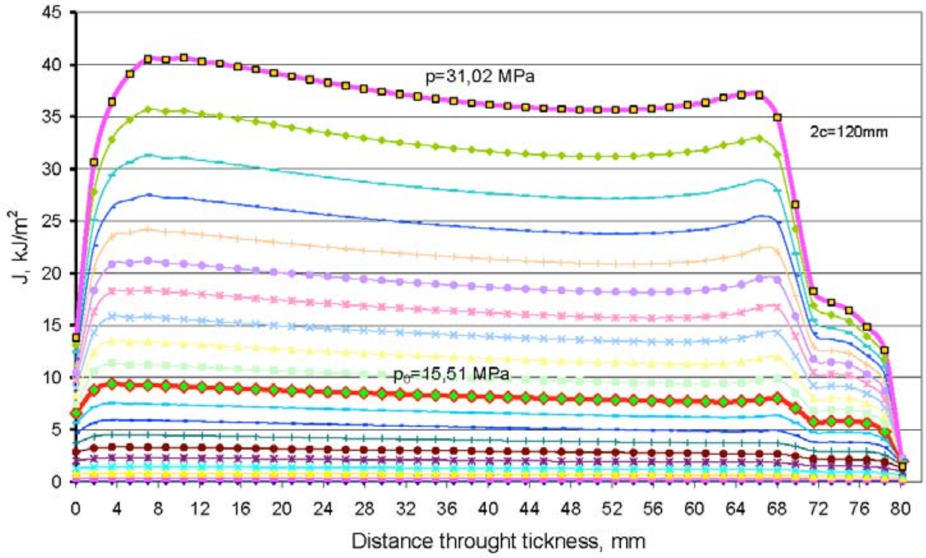

Figure 4. J-integral values along half of semi-elliptical crack-tip contour for increased pressure and temperature gradient Δp = 0.775 MPa.
Slika 4. Vrednosti J integrala duž polovine konture vrha polueliptične prsline za porast gradijenta pritiska i temperature Δp = 0.775 MPa

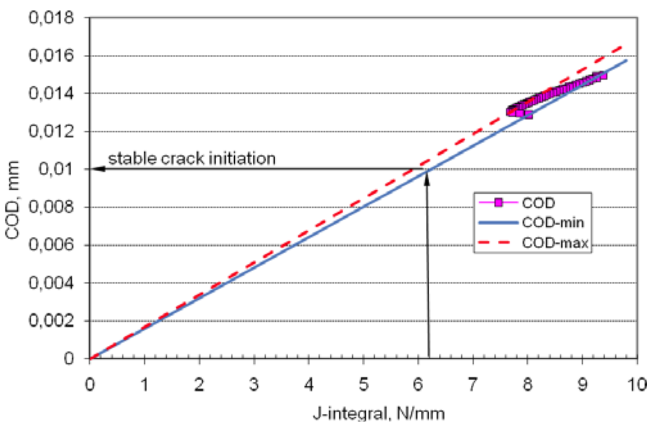

Figure 5. J-integral vs. crack length for points along the crack tip, at the pressure p = 15.51 MPa.
Slika 5. J integral u funkciji dužine prsline za tačke duž vrha prsline, pri pritisku p = 15.51 MPa

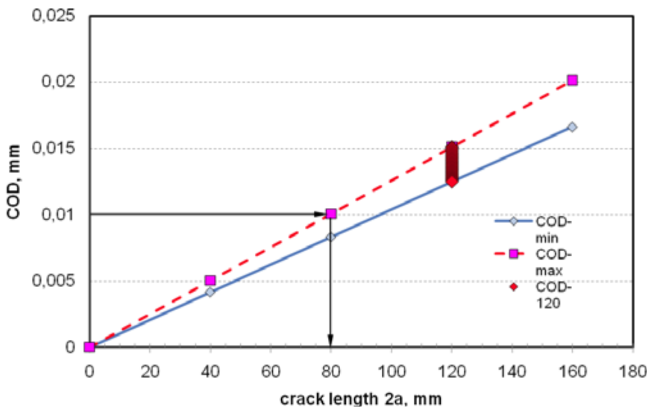

Figure 6. Determination of critical crack length $2a$ by using the COD approach.
Slika 6. Određivanje kritične dužine prsline $2a$ primenom pristupa COD

CONCLUSION

The paper presents an engineering procedure for determining critical crack length by combining J-integral values at the crack tip and the crack opening displacement-COD value, in respect to the fracture toughness of the material. The COD value is calculated through thickness along the crack centre. COD values are less sensitive to distance from the crack tip and material properties. COD values are proportional to the surface length of the semi-elliptical through wall crack of the pressurizer. Conditions for leak before break-LBB are met if any value of the J-integral overcomes the J-value at stable crack initiation. Under this condition, the orifice size is possible to estimate by using calculated COD values in respect to the postulated crack length $2a$. The calculation shows that steam mass flow at the critical crack length $2a$ = 80 mm is 0.109 kg/s. This value is significant enough in order to recognise LBB effects before final rupture occurs.

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