Analysis of the effect of some calculation factors on the fracture resistance assessment for NPP equipment elements

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Abstract. A general procedure for conducting fracture resistance calculation for WWER reactor pressure vessels in the simulation of emergency core cooling conditions has been developed. A significant influence of such factors as history of elastoplastic deformation of the material in the vicinity of the crack front, use of various concepts for calculating the elastoplastic fracture parameters in discrete FEM models, different ways of accounting for fields of residual post-welding stresses and plastic strains, regularity and density of the finite-element mesh in the vicinity of the crack front on the calculated assessment of the RPV fracture resistance is shown. The results of the fracture resistance assessment for collector-to-nozzle welded joint in the steam generator in the simulation of operational loading conditions considering history of elastoplastic deformation have been obtained. It is found that neglecting residual stresses in the fillet region of the welded joint after hydraulic testing results in an exaggerated estimate of structural safety margins.

Introduction

Fracture resistance analysis for critical elements of NPP equipment with WWER, in particular reactor pressure vessels and steam generators, involves the solution of the boundary-value problems of non-isothermal thermoplasticity and fracture mechanics problems. Moreover, such features of the computational analysis as development of a general method for computational modeling and of adequate computational models, schematization of postulated defects and use of the modern fracture mechanics concepts become topical in the world practice.

The relevant publications [1-13] present a large amount of data representing current state, standard approaches, experience and different aspects of computational substantiation of strength for NPP equipment elements. The strength analysis of state-of-the-art models, methods and software products has been conducted and specific examples of their application to various types of calculations and computational models of NPP structures are provided.

The present paper is devoted to development of the computational method and features of the elastoplastic analysis of fracture resistance for WWER reactor pressure vessels and steam generators in the simulation of operational and emergency loading conditions. The analysis of the effect of some calculation factors on the assessment of fracture resistance of WWER-1000 reactor pressure vessel and welded joint between the hot collector and PGV-1000 steam generator nozzle has been performed using developed computational methods and software products.

In performing the fracture resistance analysis for the RPV it is required to consider the combined influence of various factors such as nonuniformity of heating and cooling, history of elastoplastic deformation, residual stresses and strains, inhomogeneity of physical-mechanical material properties and their temperature dependence.

The fracture resistance calculation with account for the abovementioned factors is not possible for the entire spectrum of computational loading variants for the RPV, since solution to the non-stationary and non-linear boundary-value problems of thermomechanics is a quite difficult procedure whose practical implementation leads to unacceptable computation costs.

Furthermore, well-known commercial software products, which computational analysis is based on the finite-element method (FEM), are found to be not enough accurate and efficient in solving applied problems of elastoplastic fracture mechanics, since high dimensionality of the discrete problem and significant non-linearity of material properties at the crack front can result in loss of stability and misconvergence of computational processes.

Traditional approaches to increase the accuracy by increasing the density of finite-element discretization or transition to more sophisticated finite elements are not always efficient even in case of non-linear problems. These approaches are practically not acceptable for non-stationary and non-linear three-dimensional problems of thermomechanics, since an increase in the order of the solvable system of non-linear algebraic equations and a large number of time steps and iterations lead to a significant increase in computation costs. Consequently, this involves the necessity to develop more sophisticated equipment for conducting computational investigations including new approaches and algorithms of solution to the boundary-value problem of non-isothermal thermoplasticity and fracture mechanics problems.

In the present paper the following features of the fracture resistance calculation for the RPV are considered:

- computational analysis based on the simplified and refined procedures for the fracture resistance calculation for WWER reactor pressure vessels in the simulation of emergency core cooling conditions;
- application of G-integral concept ‘crack closure’ in discrete FEM models;
- influence of the density of the finite-element mesh at the crack tip on the accuracy in determining fracture parameters;
- influence of the scenarios of accounting for fields of residual stresses and strains on the calculated assessment of fracture resistance of reactor pressure vessel.

Basic Features of the Brittle Fracture Resistance Analysis for RPV. The fracture resistance analysis is based on the provisions of the regulatory documents [8-10] and it involves two stages:

- brittle fracture resistance analysis accomplished by a simplified procedure to determine the most critical accident conditions and locations of the postulated defects;
- fracture resistance analysis accomplished by a refined procedure in the elastoplastic statement using direct simulation of the postulated defects for the computational model for the most unfavorable variants of loading.

The simplified procedure for analyzing brittle fracture resistance consists of the following steps:

- calculation of the non-stationary thermal fields for the analyzed accident conditions;
- elastic analysis of the kinetics of the stress-strain state (SSS) of the RPV without accounting for a crack and residual stress fields for the analyzed loading conditions;
- allowance for residual welding stresses in the metal of welded joints and residual stresses in the base metal due to cladding performed by summing the values of residual stresses with those obtained from the elastic analysis;
- brittle fracture resistance analysis using analytical dependences in determining the stress intensity factors (SIF) for the postulated cracks and calculation data on stress distribution over the thickness of the reactor pressure wall without a crack;
- determination of the most critical accident conditions and locations of the postulated cracks in respect to brittle fracture resistance based on the results from the brittle fracture resistance calculation for the RPV.

When conducting brittle fracture resistance analysis by the simplified procedure, the maximum depth of the calculated postulated cracks is specified in the regulatory documents [8-10]. Considering that the worst situation for non-stationary loading conditions of the RPV in respect to brittle fracture is not always realized for the maximum depth of the crack, the brittle fracture resistance analysis using the simplified procedure is also conducted for the calculated cracks of smaller depth.

The fracture resistance analysis is accomplished using the refined procedure for the most dangerous accident conditions and locations of the postulated cracks determined from the performed simplified brittle fracture resistance analysis.

The brittle fracture resistance analysis using the refined procedure is carried out in the following sequence:

- calculation of residual stress fields and plastic strains in welded joint, base metal and cladding;
- calculation of non-stationary thermal fields for the most dangerous accident conditions;

- elastoplastic analysis of the kinetics of the stress-strain state of the RPV for the most critical conditions with the postulated crack included into the computational model and with account for residual stresses and strains;
- calculation of the design SIF values for the postulated cracks using the results from the elastoplastic analysis performed and the G– integral concept "crack closure"[2];
- fracture resistance analysis according to the regulatory documents [8-10] with determination of the maximum allowable critical brittleness temperature of the RPV metal.

Analysis of the Kinetics of the Stress-Strain State (SSS). The calculation of the stress-strain state (SSS) is based on a sequential solution to the problems of non-stationary heat conductivity and boundary-value problem of non-isothermal thermoplasticity. The calculation of the kinetics of the SSS in the elastoplastic statement is conducted based on FEM using the two-dimensional and three-dimensional calculation models of RPV with a postulated crack built into the discrete model. The finite element analysis in the present paper is based on the mixed FEM scheme [14] ensuring continuous approximation for both displacements and stresses, which makes it possible to determine the parameters of SSS and fracture mechanics with high accuracy.

Calculated Assessment of the Fields of Residual Stresses and Plastic Strains. A procedure for the assessment of the fields of residual stresses and strains involves simulation of the following processing cycles: welding; high-temperature tempering; anticorrosion cladding; high-temperature tempering; hydrotesting at the factory. In the calculation of the kinetics of stresses and strains due to processing operations of welding, cladding followed by heat treatment and hydraulic tests, the hypothesis of axial symmetry was used, which makes it possible to consider the problem on determining the fields of residual stresses and strains in axisymmetrical formulation. The results obtained for the distribution and levels of residual stresses and plastic strains in the simulation of the processing cycle welding-cladding-heat treatment agree completely with the known calculated data given in [5, 8].

Computational Method for Determining SIF. The basic tenets of the developed computational method for determining SIF in RPV are based on the use of *G*–integral concept "crack closure". The computational justification and use of the *G*–integral concept for solving the problems of crack theory based on FEM are presented in [16].

Under plane strain conditions and considering certain assumptions made for determining the *G*-integral, an invariant contour J-integral introduced by Cherepanov and Rice [17], which is independent of the integration path, can be used. Moreover, it should be considered that invariance of the J-integral values is found to occur only when the body is either elastic, or is governed by the equation based on deformation plasticity theory. If it is assumed that the material undergoes deformation in the plastic region according to the flow theory equations, then the *J*-integral is not an invariant. The mentioned plasticity theories coincide in case when the body with a crack is subjected to monotonically increasing load in proportion to a single parameter, then the equality $G = J$ is correct. However, under arbitrary history of loading, for instance, under RPV emergency cooling conditions with unloading of the material at the crack tip and, also, under repeated loading the equality of two integrals *G* and *J* becomes invalid. In this case, an elastic-plastic fracture resistance analysis using the J-integral concept becomes unreasonable.

Thus, under arbitrary history of loading and plastic flow of the material the J-integral is not an invariant and can not be taken as fracture parameter, whereas the value for G-integral retains its justified physical meaning as specific heat value required for stationary crack growth onset in an elastoplastic body. The use of the G-integral concept in discrete FEM models demonstrates that the results of elastoplastic calculation are in complete agreement with the problem of small-scale plastic flow at the crack tip, in particular, with the Irwin plasticity correction, and it remains unchanged with mesh refinement [16].

To obtain reliable and stable numerical results for determining G-integral and SIF, the calculations are performed on a sequence of refined FEM meshes. The value of the mesh spacing in the vicinity of the crack front point calculated is chosen from the condition for which the calculated values of the fracture parameters obtained for the two successively refined FEM meshes are found to be sufficiently close between themselves.

At the stages of active loading, the use of the G-concept in discrete FEM models results in obtaining constant results of the SIF calculation using sufficiently moderate discretization in the vicinity of the crack front. In unloading of the material in the vicinity of the calculated point of the crack front, convergence of the results obtained from determination of the calculated values for SIF is attained using much finer discretization.

Software Used In Calculations. The calculation of non-stationary thermal fields, kinetics of SSS and SIF was conducted using the software SPACE-RELAX [18]. The computer complex software SPACE-RELAX was developed at the G.S.Pisarenko Institute for Problems of Strength under the National Academy of Sciences of Ukraine for solving a wide range of applied problems being involved in mathematical modeling of the processes of formation and redistribution of stresses and strains in critical elements of WWER –type reactor pressure vessels of NPP.

Calculated Postulated Defects. In the fracture resistance analysis of the RPV using the simplified and refined procedure, a postulated defect was defined as a flat undercladding semi-elliptical crack with the ratio of half-axes equal to 0.3 and the depth a= 0.007-0.125s where s is the thickness of the reactor pressure vessel wall with the allowance for the cladding thickness [8-10]. A calculated postulated crack with axial and circumferential orientation in the metal of circumferential welded joints that located on the axis of cold water plumes under the inlet nozzle was considered. It should be emphasized that the calculated defect was postulated as an undercladding crack in the base metal of RPV in contrast to the conventional approach used in calculations, according to which in the simplified calculation a surface crack is postulated, whereas in the elastoplastic analysis an undercladding crack is modeled [8,9].

Effect of the Density of FE-Meshes. The assessment of the effect of the density of finite element meshes at the crack tip was performed in the simulation of the specific cooling conditions for WWER-1000 RPV. The calculations were carried out in the axisymmetric statement accounting for fields of residual stresses and strains. In the solution of problems, a uniform triangular mesh was used at the undercladding circumferential 20 mm deep crack tip located on the axis of cold water plumes at the level of welded joint No 4.

The convergence and accuracy of the calculation results was verified on a sequence of refined FEM meshes. The mesh spacing at the crack tip was considered as 1000, 100, 10, 1, 0.1 and 0.01 μm. Fig.1 presents the results of elastoplastic calculations, whence it follows that the mesh spacing at the crack tip has a significant influence on the determination of the calculated SIF values. The particular feature of the elastoplastic solution is the presence of a descending branch at the end of temperature dependence of SIF, which is due to the material unloading and formation of a compressive stress zone at the crack tip. The use of sufficiently fine meshes in the elastoplastic calculations does not make it possible to discover the unloading zone at the crack tip, which distorts the temperature-dependence of SIF obtained using sufficiently dense meshes that provide convergence of numerical results. The analysis of the results of the elastoplastic calculations in three-dimensional statement shows an analogous situation. The described circumstance is regarded as rather significant calculated factor, since neglecting the unloading at the crack tip results in more conservative assessment for the allowable critical brittleness temperature for RPV.

Influence of the Scenarios with Accounting for Residual Stress Fields. The analysis was conducted for five scenarios with accounting for residual stress fields, which are usually employed in calculations: 1) stress-free temperature procedure; 2) heating to a temperature of high tempering and cooling down to normal temperature; 3) stress-free procedure and additional loading, under which tensile stresses 100 MPa occur in the welded joints: 4) heating to a temperature of high tempering, cooling down to normal temperature and additional tensile stresses 100 MPa; 5) elastoplastic calculation considering the complete cycle of the formation and redistribution of the fields of residual stresses and strains.

Fig. 2 provides the results of the elastoplastic calculations for the circumferential undercladding crack in depth of 15 mm located at the level of welded joint No 4 of the WWER-1000 RPV in simulation of the specific cooling conditions. It follows from the diagrams that allowance for residual stresses using stress-free temperature procedure and scenario involving heating to a temperature of high tempering with subsequent cooling, results in difference between results less than 1%. For these two scenarios of accounting for residual stresses, the calculated values of critical brittleness temperature cause exaggerated estimate of safety margins and lifetime of RPV. It should be noted that the given two scenarios, in particular, consider only residual stresses occurring after the deposition of anticorrosion cladding on the inner surface of RPV, and do not consider residual stresses in the welded joints.

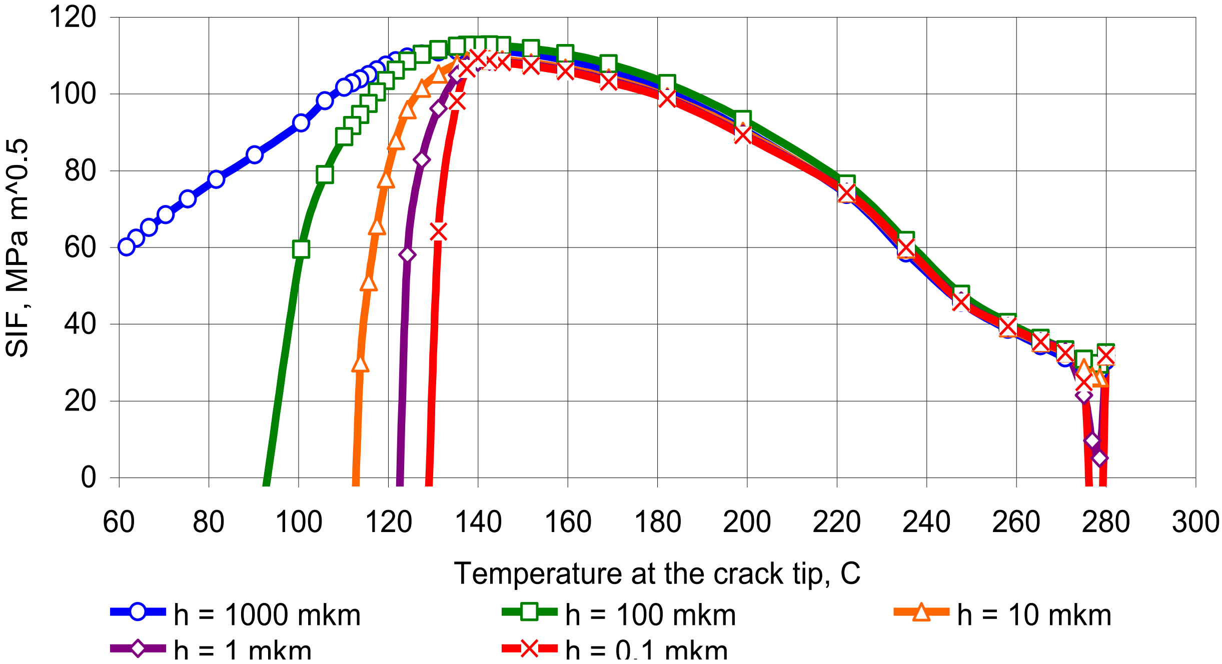

Fig. 1 Temperature-dependence of SIF for the deepest point of the circumferential undercladding crack using different mesh spacing *h*

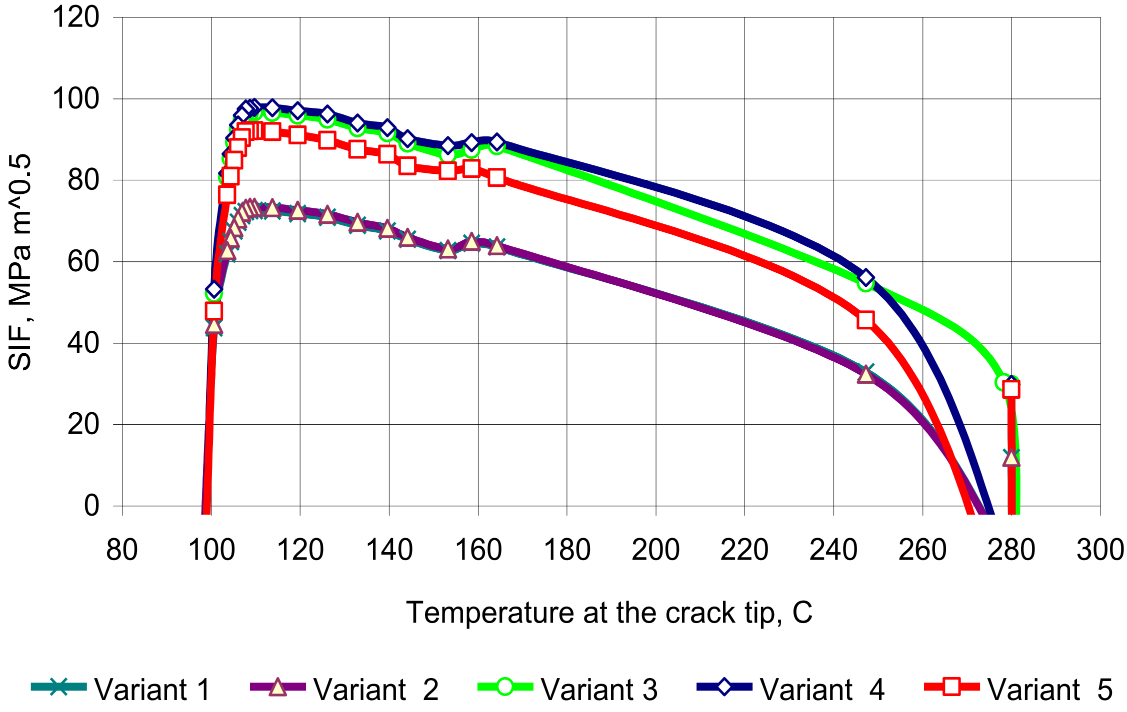

Fig. 2 Temperature-dependence of SIF for the deepest point of the circumferential undercladding crack under different scenarios of accounting for residual stress fields

One of the possible ways of accounting for post-welding stresses is the method of additional loading, under which additional axial tensile stresses 100 MPa occur in cylindrical shells of RPV. The calculations using the method of additional loading show the results, which significantly differ from the results of the first two scenarios with considering residual stresses and result in more conservative assessment for calculated SIF values and the critical brittleness temperature. The results of the SIF calculations for third and fourth scenarios significantly differ between themselves at the initial stage of cooling and virtually coincide in the region with maximum SIF values. The difference in determination of the critical brittleness temperature does not exceed 1%.

The elastoplastic calculation considering the complete cycle of the formation and redistribution of the fields of residual stresses in modeling processing cycles of welding and anticorrosion cladding results in less conservative assessment of the critical brittleness temperature compared with the scenarios with accounting for additional loading 100 MPa. At the same time, these assessments are more conservative as compared with the first scenarios, where residual stresses are not considered in the zone of welded joint.

Influence of Loading History. The assessment of the influence of thermomechanical loading history was performed in the simulation of operational loading conditions of the welded joint between the hot collector and PGV-1000 steam generator nozzle with “small-series” reactor. The calculation of the stress-strain state of the welded joint was carried out in the elastoplastic statement with account for loading history and without it.

The calculated three-dimensional finite-element model comprises a steam generator-main circulation piping –reactor pressure vessel. The calculations considering loading history were conducted for the following sequence of loading: hydraulic testing (HT) for primary and secondary circuits → unloading → normal operating conditions (NOC) →unloading. The calculation without accounting for loading history was performed for normal operating conditions through single loading. A surface semi-elliptical crack of 18 mm in depth and with the ratio of half-axes equal to 2/3 located in the region of maximum stresses in the fillet of the welded joint was postulated. The solution to the problem was obtained using the fragmentation procedure. The results of the SIF calculations along the postulated crack front are presented in Fig.3.

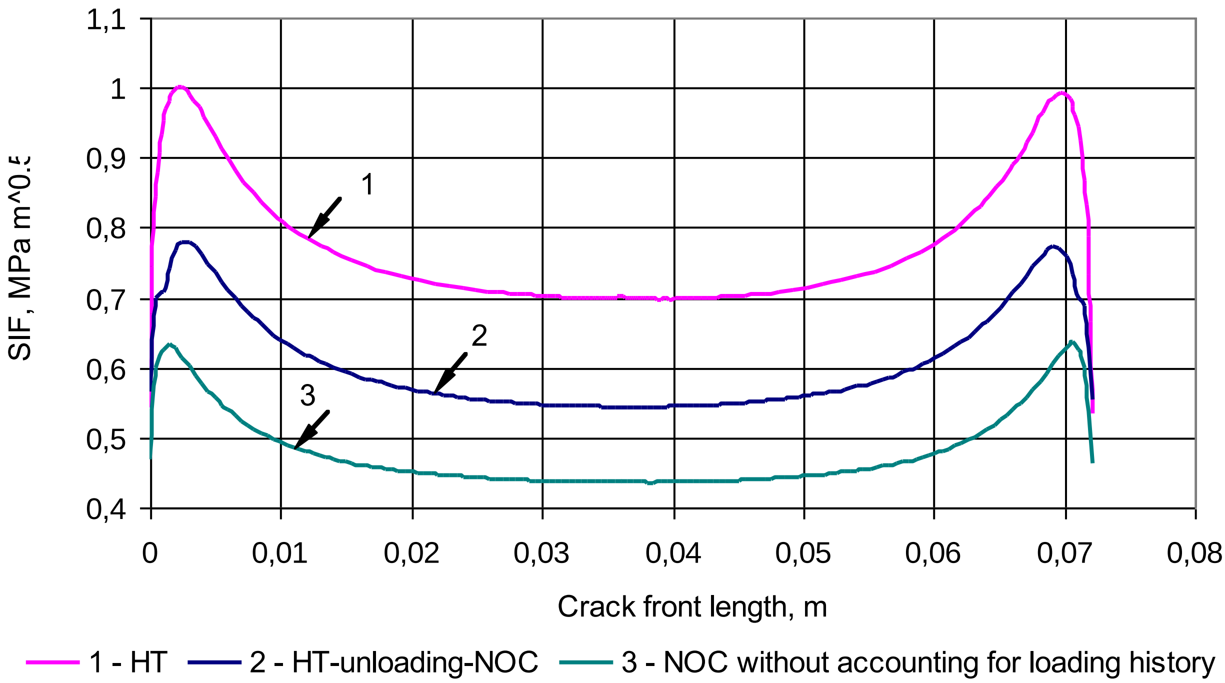

Fig. 3 Distribution of relative SIF values along the crack front

It follows from the analysis of the obtained calculation results that neglecting the residual stresses in the fillet region of the welded joint between the hot collector and steam generator nozzle in the simulation of the operational loading conditions results in conservative (up to 18%) calculated SIF values and, consequently, in non-conservative assessment of the fracture resistance for the welded joint.

Conclusion. A general procedure for conducting fracture resistance calculation for WWER reactor pressure vessels in the simulation of emergency core cooling conditions was developed. The basic tenets of the elastoplastic calculation of the kinetics of SSS for reactor pressure vessels with allowance for fields of residual stresses and strains as well as the computational method for determining SIF in the points of the postulated crack front were stated. A significant influence of such factors as history of thermomechanical loading, plastic deformation of the material in the vicinity of the crack front, different ways of accounting for fields of residual post-welding stresses and plastic strains, regularity and density of the finite-element mesh in the vicinity of the crack front, use of various concepts for calculating the elastoplastic fracture parameters in discrete FEM models on the calculated assessment of the RPV fracture resistance was found. The results of the fracture resistance assessment for collector-to-nozzle welded joint in the steam generator in the simulation of operational loading conditions considering history of elastoplastic deformation were obtained. It was found that neglecting residual stresses in the fillet region of the welded joint after hydraulic testing results in unjustified assessment of structural safety margins.

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