Chapter 24
FE-Analysis of Deformation and Failure of Structural Elements under Quasistatic Multifactor Effects

Vasilii Gorokhov, Dmitrii Zhegalov, Dmitrii Kazakov, Sergei Kapustin,
and Yuriy Churilov

Abstract Description of the numerical modeling technique within the framework of the damaged medium mechanics approaches to the processes of deformation and destruction of structures under quasi-static multifactor influences is presented. The results of finite element modeling of crack formation and development in structures under the following conditions: elastoplastic deformation, high-temperature creep, influence of aggressive corrosive medium are given.

Keywords: Plasticity · Creep · Crack · Corrosion · Finite element method · Mechanics of the damaged medium

24.1 Introduction

Operating conditions of modern structures are characterized by multiparametric effects of external fields of different nature. This leads to the degradation of the strength properties of the material and, ultimately, to the exhaustion of the design resource. Evolving damage strongly affects the mechanical characteristics of the material and, in particular, is the main reason for the loss of bearing capacity of materials with viscous types of fracture. This leads to the need to take into account the mutual influence of deformation and damage effects when formulating the equations of state of materials, which allow describing the influence of defects developing in the material on the mechanical behavior of the damaged material with the help of appropriate macroscopic parameters.

V. A. Gorokhov, D. V. Zhegalov, D. A. Kazakov, S. A. Kapustin, Yu. A. Churilov
Research Institute for Mechanics, National Research Lobachevsky State University of Nizhni Novgorod, av. Gagarin 23b6, Nizhny Novgorod, 603950, Russia
e-mail: vas-gor@rambler.ru, zhegalov@mech.unn.ru, kazakov@mech.unn.ru, sergei.kapustin@mail.ru, chyuan@rambler.ru

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The introduction of such a macroscopic parameter was first proposed in Rabotnov (1966); Kachanov (1974) in the study of the processes of destruction of materials in the conditions of creep as a measure of damage ω, which is a measure of reducing the effective areas of action of stresses in relation to their initial undamaged value. Currently, in most practical applications, the damage measure ω is assumed to be a scalar value varying from $\omega = 0$ for undamaged material to $\omega = 1$ for completely destroyed material. Some theoretical and applied aspects of the development of approaches to the mechanics of the damaged medium (MDM) are presented in Bondar et al (1979); Murakami (1983); Lemaitre (1985); Shevchenko and Mazur (1986); Chaboche (1987); Beh and Korotkikh (1989); Kapustin (1989); Ju (1989); Bondar (1990); Kazakov et al (1999); Volkov and Korotkikh (2008); Kapustin et al (2015); Placidi et al (2018b,a); Placidi and Barchiesi (2018).

Modern theoretical and experimental studies of fracture phenomena make it possible to consider it as a multistage process of occurrence and development of irreversible defects in the material, determined by the entire kinetics of the stress-strain state of structures in the process of their loading (Kazakov et al, 1999; Fedorov, 1985; Mitenkov, 2007). According to this representation, three main stages of the material destruction process are successively developed. Within the limits of the first stage of development there is a need for more scattered on volume material of every kind in the form of micropores and microdefects which does not bring to appreciable influence of these on physical and mechanical characteristics of a material. The second stage is characterized by a further development and by the fact that the emerging issues are of critical importance, corresponding to the infringement of the continuity of the material at the point in question and its increasing influence on the physical and mechanical character of the material. With approach of this stage the intensive interaction of the damages defined by various mechanisms of destruction begins. The end of the stage corresponds to the appearance in the domain of macroscopic crack. In the limits of the third stage there is a merge of the formed macrodefects in one or several cracks leading to splitting into parts (fragmentation) of the considered element of a design.

Taking into account the above mentioned stages in the models used to describe the processes of damage accumulation in structural materials allows to expand the scope of application of the damaged medium mechanics relations, to explain the interaction of different damage mechanisms and the phenomenon of nonlinear damage summation.

24.2 Technique of Numerical Modeling of Deformation and Accumulation of Damages in Structural Elements under Quasi-Static Loading

In the proposed variant of the model of hierarchical model of the damaged material it is assumed that the additivity of the elastic $\varDelta e_{ij}^{e}$ and irreversible components of $\varDelta e_{ij}^{irr}$ changes in the deformation tensor (plasticity of $\varDelta e_{ij}^{p}$ and thermal creep of

Δe^c_{ij}) and incompressibility of the material under the conditions of plasticity and creep are valid.

It is also assumed that the influence of different types of damage on the deformation process is carried out by means of the scalar function introduced by Kachanov and Rabotnov.

The direct influence of damage on the deformation process is taken into account in the equations of equilibrium by introducing the dependence of the elastic characteristics of the material on the current value of the function ω. In this regard, when formulating a compound model of the damaged material, two stress characteristics were introduced into consideration: effective σ_{ij} acting on the damaged areas and reduced σ^*_{ij} statically equivalent to the first, but referred to intact areas. The former appear in all partial models that determine the state of the material at the point of the body, while the latter are used at the level of design description in the formulation of equilibrium equations and static boundary conditions.

Taking into account the comments made, specific equations of the compound model of the damaged material, which establish a link between the changes of the reduced stresses $\Delta\sigma^*_{ij}$ and deformations Δe_{ij} at the elementary step of the change of external influences, as well as the parameters characterizing the current state of the material, can be written in the form:

$$\begin{gathered}
\Delta\sigma^*_{ij} = 2G(\Delta e_{ij} - \Delta d_{ij}) + \delta_{ij}(K - \frac{2}{3}G)(\Delta e_{ii} - \Delta d_{ii})\ , \\
\Delta d_{ij} = \Delta e^*_{ij} + \omega(\Delta e_{ij} - \Delta e^*_{ij})\ , \\
\Delta e^*_{ij} = \Delta e^p_{ij} + \Delta e^c_{ij} - \frac{\Delta G^* \bar{\sigma}'_{ij}}{2G^*\bar{G}^*} + \delta_{ij}\left(\Delta(\alpha T) - \frac{\Delta K^* \bar{\sigma}}{3K^*\bar{K}^*}\right)\ , \\
\Delta G^* = G^* - \bar{G}^*, G^* = (1-\omega)G, \bar{G}^* = (1-\bar{\omega})\bar{G}\ , \\
\Delta K^* = K^* - \bar{K}^*, K^* = (1-\omega)K, \bar{K}^* = (1-\bar{\omega})\bar{K}\ , \\
\Delta(\alpha T) = \alpha T - \bar{\alpha}\bar{T}\ .
\end{gathered} \tag{24.1}$$

where $\bar{K} = K(\bar{T}), K = K(T), \bar{G} = G(\bar{T}), G = G(T)$ - modules of bulk and shear deformation of intact material, referred to the temperature level in the initial (at the beginning of the step) and current (at the end of the step) states; $\bar{\alpha} = \alpha(\bar{T})$, $\alpha = \alpha(T)$ - values of temperature expansion coefficients; $\bar{\sigma}'_{ij}$, $\bar{\sigma}$- values of deviator and volumetric components of the stress tensor in the initial state. The values of change of plasticity Δe^p_{ij} and creep Δe^c_{ij} deformations appearing in (24.1) are described by the corresponding particular models.

Particular models of plasticity, creep, and damage accumulation, implemented as part of the considered model of damaged material, are based on variants of thermoplasticity and thermal creep models, as well as various variants of kinetic equations describing damage accumulation for various fracture mechanisms. In particular, to describe the processes of elastoplastic deformation, a variant of the thermoplasticity model with combined hardening, proposed in Kazakov et al (1999); Volkov and Korotkikh (2008) and a modified version of this model (Kazakov et al, 1999; Kapustin et al, 2015) were employed. To describe the processes of thermal creep as a part of the general model of damaged material, a number of creep models based on the hypothesis of the existence of a creep surface and the gradient to it of the creep strain vector $\dot{e}^c_{ij}$ (Kazakov et al, 1999; Kapustin et al, 2015, 2008) have been implemented.

The processes of damage accumulation within the used model are described on the basis of the assumption that the damage at a point in the material occurs when the critical $W = W^R$ value is reached at this point by some energy W. The specific form of this energy is determined by the mechanism of the failure under consideration.

The ψ damage function is a normalized analogue of energy W (Kazakov et al, 1999; Kapustin et al, 2015). For undamaged material $\psi = 0$, the ψ value increases to a limit value of $\psi = 1$ during fracture. When several types of damage develop simultaneously in the material, the ψ_k function is used to describe each species. In the developed variant of the compound model the kinetic equations of damage accumulation are realized, which are conditioned by the development of plasticity deformations (on the basis of plastic loosening energy), creep deformations (on the basis of creep dissipation energy), and also on the basis of the criterion of brittle fracture (Kapustin et al, 2015; Gorokhov et al, 2010).

The change in the damage measure of each $\Delta\omega_k$ species is in turn related to the accumulated $\bar{\omega}$ value as well as the change in the damage function of the respective $\Delta\psi_k$ species.

The stage of damage accumulation is taken into account by introducing a variable that determines the completion of the first stage. This variable is the ψ^a_k value determined for each k-th damage type by the value of the above mentioned damage function by the end of the first stage. The dependence of the change in the $\Delta\omega_k$ damage measure on the change in the $\Delta\psi_k$ damage function is taken as (Kazakov et al, 1999; Kapustin et al, 2015):

$$\begin{gathered}
\Delta\omega_k = q\bar{\omega}^{\frac{q-1}{q}}\Delta\psi^0_k\,, \\
\Delta\psi^0_k = \frac{\Delta\psi_k}{1-\psi^a_k}\ \text{ when }\ \psi_k > \psi^a_k\,, \\
\Delta\psi^0_k = 0\ \text{ when }\ \psi_k \le \psi^a_k\,.
\end{gathered} \tag{24.2}$$

where $q = q(T)$ is a function of the material.

Research of behavior of designs on the basis of the considered physical relations is carried out by means of the combined step-by-step scheme in which steps of each level bear different functional loading, thus their sizes are defined for various reasons.

At the top level steps, called load steps, the task is linearized externally. The actual loading path is represented as a piecewise linear curve in the space of loading parameters and is approximated by a set of straight-line sections, the value of which is determined only from the conditions of satisfactory approximation of the real loading paths. The solution of nonlinear problems at the stages is carried out in the form of the method of initial stresses by iterative refinement of the equilibrium state for the current deformed configuration of the structure.

To calculate the changes in irreversible deformations and damage measures within a step, the latter is broken down into a series of lower level steps. On the internal steps all calculations are made independently for individual points of the structure without correction of equilibrium equations.

At each stage of loading, a non-linear boundary value problem is solved for the corresponding change of external influences, taking into account the entire previous history of irreversible deformation and accumulated damage to the material. The linearization of the problem at the loading stage is carried out in the form of the initial stress method. Numerical solution of linearized problems is carried out on the basis of FEM with the use of isoparametric square-law FE.

For the problems concerning estimation of durability of designs the analysis of performance of corresponding criterion conditions is made. The first one, associated with a local violation of strength, is determined by the condition that one or more adjacent physical nodes achieve an acceptable value of the damage measure ω_f

$$\omega \geq \omega_f \, . \tag{24.3}$$

The second criterion determines the condition of exhaustion by the design of its bearing capacity. Moreover, a small change in external influences of a given type leads to large changes in displacements and deformations, which increase rapidly with increasing load parameter, i.e. there is a loss of stability of irreversible deformation. Verification of this state of the structure is carried out by changing the determinant of the system of algebraic equations at the loading stages, as well as by analyzing changes in the vector of nodal displacements of the nonlinear part of the solution of the problem at the current stage in the process of successive approximations.

24.3 Technique of Modeling the Processes of Nucleation and Propagation of Cracks

In the majority of works devoted to application of MDM methods for analysis of structural failure, the study of the process ends with the moment of appearance of one or several macro-defects. However, the appearance of such macro-defects in individual points of the material cannot be a sign of structural failure, which usually occurs as a result of their subsequent merger into a crack and the propagation of this crack to a certain limit size. Therefore, the approaches that allow predicting the development of defects in the material from the moment of their origin to the maximum crack opening within the framework of MDM relations are of particular interest for the evaluation of structural strength.

In accordance with the above model ideas, in the process of step-by-step solution of the problem in separate zones of the structure material, the damage zones may appear and evolve, the intensity of which is characterized by the measure of damage ω. The increase in measure ω in the physical node of the construction leads to a decrease in the elasticity of the material (G and K modulus) in this node and thus to a decrease in its resistance. At the same time in the area of such nodes there is a redistribution of stresses on the volume of material.

By the time the limit value $\omega = \omega_f$ is reached in the node (in calculations the limit value of the damage measure is taken equal to $\omega_f = 0.99$), the material in the area of such node ceases to resist further deformation, redistributing the perceived load on the nearest physical nodes. In the process of further evolution of the damage the following nodes are destroyed. At the same time, the interpolation of the damage functions between the neighboring destroyed nodes forms the line $\omega = \omega_f$, which corresponds to the trajectory of the studied crack propagation (Kapustin et al, 2015; Gorokhov et al, 2010). The implementation of this approach eliminates the need to rebuild the FE mesh of the partition of the studied area, and, therefore, change the topology and structure of information arrays for each case of local strength failure, without violating the conditions of the equilibrium state in the local damage zone and the structure as a whole. In this case, the process of successive destruction of neighboring nodes during loading can be considered as a process of crack propagation and continue calculations without changing the initial topology of the studied area.

To illustrate the possibility of using the proposed methodology in studying the nucleation and propagation of cracks, examples of numerical modeling of fracture processes of structural elements in various modes of quasistatic loading are considered below.

24.4 Numerical Modeling of Elastoplastic Fracture of a Flat Specimen with a Notch under Conditions of Plane Bending

The test sample is a rectangular prism with a length $l = 65$ mm, a width $b = 20$ mm and a height $h = 10$ mm, having in the middle section a transverse notch with a depth $\delta = 4$ mm constant over the entire width of the sample. The sample is made of AK-4 aluminum alloy and pivotally supported on two rigid supports. The loading of the sample was carried out by moving the grips of the testing machine through an indenter installed along the width of the sample in its central section.

Experimental studies related to the construction of the material functions of the material and to the study of the destruction process of such a sample were carried out by L.N. Kramarev. The material functions of the models of deformation and fracture of the AK-4 alloy, necessary for further calculations, are constructed from the results of tests of a series of standard samples under uniaxial tension. The verification of the obtained functions was carried out on the basis of numerical simulation of the process of destruction of a standard cylindrical sample of this material in an axisymmetric formulation.

In a numerical study, real loading was modeled by vertical displacements applied through a compensating spacer along a narrow strip on the upper face of the sample. Similar compensating gaskets were also installed in the area of supports to exclude the occurrence of undesirable plastic deformations during numerical studies.

Numerical modeling of the processes of deformation and fracture of the sample was carried out in a spatial setting for the symmetric 1/4 of its part, limited by the planes of symmetry in the longitudinal and transverse directions, using twenty-node isoparametric finite elements.

The load step size was selected on the basis of preliminary calculations from the condition of a satisfactory description of the $P - V$ curve (P is the force applied to the sample, V is the vertical displacement of the upper point of the central section of the sample), which characterizes the fracture of the sample.

Fig. 24.1 shows a picture of the crack propagation in the cross-section of the sample and a picture of the sample destroyed as a result of the experiment.

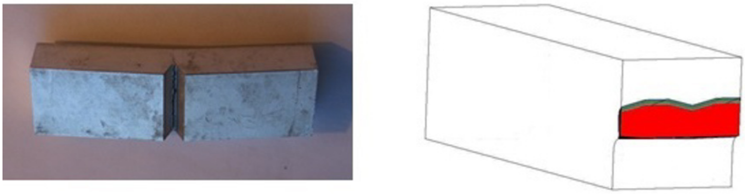

Fig. 24.1 Photograph of the sample destroyed in the experiment and a picture of the crack propagation based on the results of numerical modeling.

Fig. 24.2 shows a graph of the force P dependence on the displacement of the controlled point V, based on the results of numerical modeling, in the form of a dotted line and the results of the experiment indicated by a solid line.

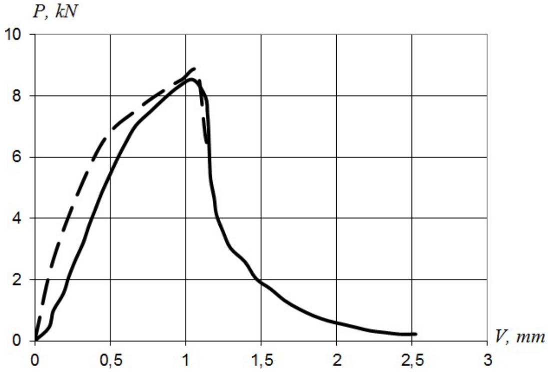

Fig. 24.2 Dependence of force P on the displacement of the controlled point V (solid line - experiment, dotted line - numerical modeling).

The given results allow us to judge that the results of numerical modeling of the fracture process on the basis of the above algorithm are in good agreement with the experimental data. The maximum force P, which differs from the experimental value by 3%, is achieved in the calculation and experiment with displacements that differ by no more than 3.6%.

24.5 Numerical Modeling of the Crack Propagation Process in a Cylindrical Specimen with a Notch in the High-Temperature Creep

For the purpose of illustration of application of the technique considered above for modeling of processes of destruction of elements of designs in the conditions of creep below results of numerical research of laws of formation and propagation of cracks in the continuous cylindrical sample of circular cross-section, with the concentrator, at an axial tension, in the conditions of high-temperature creep are presented.

The shape of the concentrator in the sample is chosen in the form of a sharp incision without any rounding. According to the theory, the stress concentration coefficient (SCC) in such a cut should strive for infinity. However, according to Neiber (1947), the SCC in the acute incision is finite and corresponds to the value of such a coefficient in the rounded incision, the radius of which is determined by the structure of the material.

A numerical study was carried out in an axisymmetric formulation for the symmetric half of the fragment of the working part of the sample. The calculated region and the loading scheme of the symmetric fragment of the working part of the sample with the concentrator under consideration are shown in the form of an angular section shown in Fig. 24.3. The figure shows: x axis - axis of symmetry, y axis - plane of symmetry, sample length $ED = 7$ mm, sample radius $CD = 5$ mm, notch depth $BF = 1$ mm, notch width $AF = 0.5$ mm.

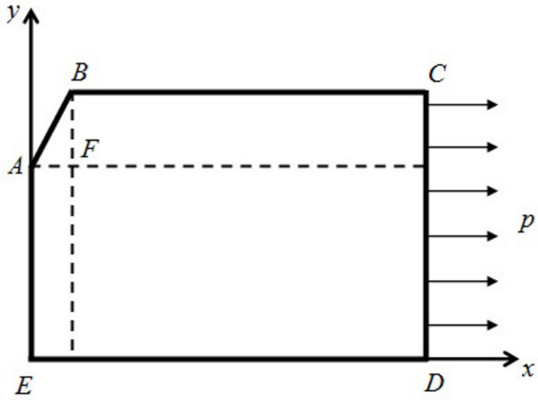

Fig. 24.3 The design scheme of the sample fragment.

The sample is made of a heat-resistant alloy, for which the material functions used to implement the above-mentioned models of ductility, creep, and damage accumulation were obtained and verified in Kapustin et al (2008). The process of loading the sample was carried out in three stages: stage 1 - warming up to temperature $T = 850°C$; stage 2 - stretching by axial forces with intensity p, distributed over the ends of the sample; stage 3 - holding the loaded sample for 40 hours.

The destruction of the sample is considered as viscous due to the development of creep deformations, without taking into account the possible effects of brittle damage.

Numerical studies were carried out on a number of calculation options, differing in the value of tensile forces p, sampling FE parameters with constant sample sizes and shape, and the values of stress concentration factors in the region of the notch due to the sampling scheme used.

For the level of tensile stresses $p = 100$ MPa, several variants of problems have been calculated with various finite-element discretization schemes of the computational domain.

Fig. 24.4 shows the calculated curves of the dependence of the crack length l on the time of its steady propagation t for some of the considered options, indicated by numbers, characterizing the number of partitions n and the stress concentration coefficient value K_σ: 1) $n = 12, K_\sigma = 4.15$; 2) $n = 15, K_\sigma = 5.21$; 3) $n = 20, K_\sigma = 5.22$; 4) $n = 32, K_\sigma = 6.075$.

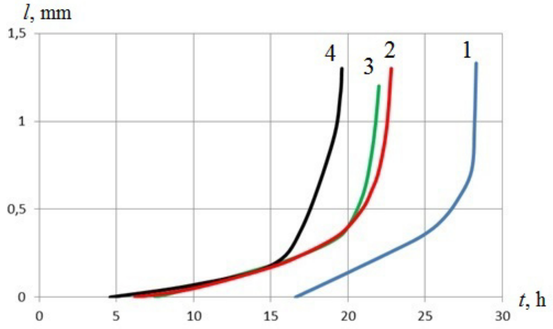

Fig. 24.4 The dependence of the crack length on the time of its propagation for different values of the stress concentration coefficient.

In all the considered variants, a uniform grid step was taken along the axis y. In addition, for all elements located along the AE line, the same aspect ratio of the mesh cells was assumed to be $h_x = h_y$.

The influence of the level of applied load p on the patterns of crack propagation in the specimen was also considered. Five variants of loads are considered: 1) $p = 140$ MPa; 2) $p = 120$ MPa; 3) $p = 100$ MPa; 4) $p = 90$ MPa; 5) $p = 80$ MPa. In all the considered variants, the $n = 20$ finite-element discretization scheme was used.

Fig. 24.5 presents the dependence of the crack length l on the exposure time. In the figure, the figure corresponds to the considered variant of the load level p.

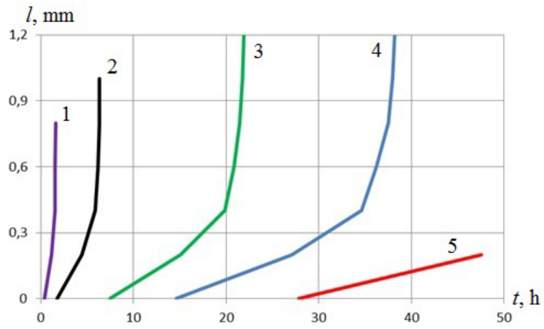

Fig. 24.5 The dependence of the crack length on time for different stress values.

The results show that an increase in tensile load leads to a decrease in time to the moment of crack formation, an increase in speed and a reduction in the time of its steady growth. For option load 1 ($p = 140$ MPa), the sample was destroyed almost immediately after the formation of a crack; for option 5 ($p = 80$ MPa), a crack was formed, but during the 40-hour holding period, the sample did not practically propagate into the sample.

Thus, as a result of the studies, the possibility of numerical modeling based on the FEM of the processes of the appearance and propagation of cracks in structural elements under high-temperature creep has been demonstrated. The regularities of crack initiation and development in a cylindrical sample with a concentrator subjected to axial tension under high-temperature creep conditions are established based on the assumption of viscosity of sample failure. The dependence of the calculation results on the FE parameters of the sample discretization in the region of the crack development path is shown. The dependences of the times of formation, steady growth, and the rate of crack propagation on the value of the stress concentration coefficient in the notch and the tensile stress intensity are established.

24.6 Numerical Modeling of Corrosion Failure of a Tubular Specimen under axial Tension

One of the important factors that significantly affect the physicomechanical characteristics of metals is the environment in which the structures under study or their individual elements are located.

The liquid or gas medium surrounding the metal can act on the surface layer of metals and, when it comes into physical or chemical interaction with it, harden or soften it. As a result of this interaction, the deformation and strength properties of metals change significantly. The long stay of loaded structures in an aggressive environment often leads to corrosion of the metal.

In Kapustin et al (2013), a modeling technique was developed on the basis of the ratios of the mechanics of the damaged medium of stress corrosion cracking (SCC) processes.

In order to check the efficiency of the proposed technique the numerical modeling of the process of corrosion destruction of a thin-walled tubular sample is performed. The results of experimental study of the destruction of such samples and the influence of various operational factors (stress level, temperature, composition of the environment) on the resistance against SCC steel X18H10T are given in Sandler and Kozin (1984).

Numerical modeling was carried out for a sample fragment (its working part) - a thin-walled cylindrical shell with a length of $L = 26$ mm, having an internal diameter of $D = 10$ mm, and a wall thickness of $h = 1.5$ mm.

The left part of the sample (along the length of the working part $L = 13$ mm) was immersed in a liquid chlorine-containing medium 0.5% NaCl solution), heated to a temperature of $T = 150°C$. The temperature distribution was assumed constant over the thickness of the sample.

The temperature distribution graph along the generatrix of the sample fragment and the variant of its FE discretization are shown in Fig. 24.6.

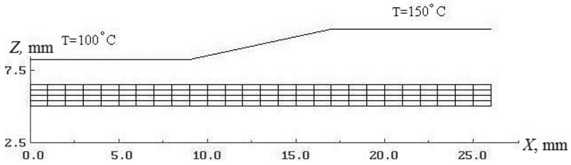

Fig. 24.6 Temperature distribution along the sample fragment.

The specimen was tensioned by the axial force q, evenly distributed over its right end-face with subsequent holding under load until it is destroyed. In the simulation, the process of loading the sample was carried out in two stages. At the first stage, an instantaneous application of axial force was performed; at the second, exposure under load was performed. The calculations of the SCC of the sample were performed for a number of different axial force intensities: $q = 75, 100, 125, 150, 200$ MPa.

The numerical solution of the problems was carried out on the basis of the FEM in axisymmetric and spatial formulations using isoparametric finite elements with a quadratic law of variation of the displacement functions for two variants of sample fragmentation. The first discretization option in axisymmetric and spatial settings is shown in Fig. 24.6 and Fig. 24.7, respectively.

In the second variant, the number of FEs doubled both in thickness and in length of the fragment. Due to the good agreement between the results of numerical studies obtained for these options, more detailed discretization of the sample fragment was not required.

The material functions of the SCC models, the values of which were used to obtain the results presented below, were obtained on the basis of experimental data on the dependence of the fracture time on the stress level and a number of assumptions

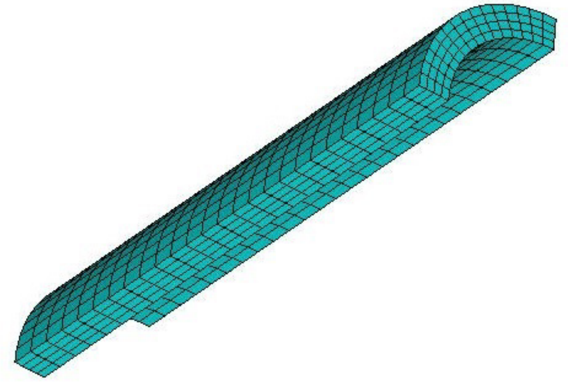

Fig. 24.7 Variant of FE discretization of a sample fragment in a spatial formulation.

about the duration of the various stages of the SCC process, which were further refined in the process of numerical simulation.

The distribution pattern of the ω damage measure over the sample volume for a moment of time close to the moment of failure for the load case $q = 100$ MPa is shown in Fig. 24.8

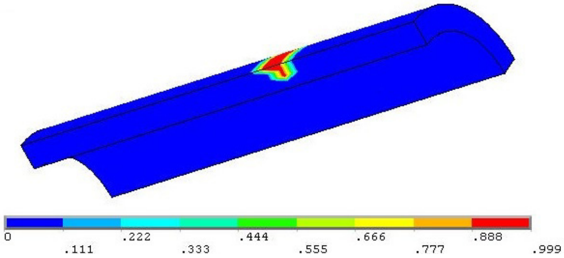

Fig. 24.8 Distribution of damage measure ω over the sample volume for load $q = 100MPa$.

A similar picture of the evolution of SCC processes was observed for other load cases. Based on the analysis of the results of numerical studies, it was found that the destruction of the sample for all the considered load cases occurs in the region of the interface between the corrosive medium and the air. The nature of the zones destroyed as a result of the SCC and the sequence of their development in time for all considered load cases qualitatively coincide. Moreover, the calculation results obtained on various types of grids within each load case are in good agreement with each other both qualitatively and quantitatively.

Fig. 24.9 shows the dependence of the fracture time of the sample on the level of the applied load obtained on the basis of experimental data (solid line) and the results of numerical simulation (points).

The given materials show that the results of numerical modeling are good quality (coincidence of the fracture zone along the length of the sample) and quantitatively

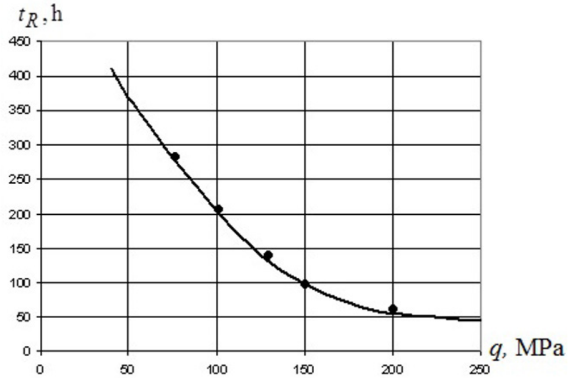

Fig. 24.9 Dependence of the failure time of the t_R sample on the applied load level q.

(the difference in the estimation of the time of complete fracture of the sample does not exceed 13%) are consistent with the experimental data.

24.7 Conclusion

The possibility of numerical modeling on the basis of FEM within the framework of the relations of mechanics of the damaged medium of the processes of occurrence and propagation of cracks in the elements of structures under the conditions of elasto-plastic deformation, high-temperature creep and influence of aggressive corrosive medium is demonstrated.

It is shown that the results of numerical modeling of the process of destruction of a sample with a concentrator, obtained on the basis of simultaneous consideration of plastic and brittle damages in the process of destruction, are in good agreement with the experimental data.

The regularities of occurrence and development of cracks in a cylindrical specimen with a concentrator under axial tension under conditions of high-temperature creep in the assumption of viscous fracture of the specimen are established. The dependence of the results of calculations on the parameters of FE-discretization of the sample in the area of the crack propagation trajectory is shown. The dependences of formation times, stable growth and crack propagation rate on the value of stress concentration coefficient in the notch and tensile stress intensity are determined.

It is shown that the results of numerical modeling of the SCC process of the sample under study are in good agreement with the experimental data. The predicted failure zone of the sample coincides with the actual one. The predicted failure times of the sample for all load variations are well consistent with the experimental values.

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