EVALUATING LONG-TERM STRENGTH OF STRUCTURES

by

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The issue of evaluating strength and service life is discussed as applied to structures, the exploitation properties of which are characterized by multi-parametric nonstationary thermal mechanical effects. The main requirements to mathematical models of the related processes are formulated. In the framework of mechanics of damaged media, a mathematical model describing processes of inelastic deformation and damage accumulation due to creep is developed. The mechanics of damaged media model consists of three interconnected parts: relations defining inelastic behavior of the material accounting for its dependence on the failure process, equations describing kinetics of damage accumulation, and a strength criterion of the damaged material.

The results of numerically simulating the carrying capacity of a nuclear power plant reactor vessel in the event of a hypothetical emergency are presented. Emergency conditions were modeled by applying pressure modeling the effect of meltdown, the constant internal pressure and temperature varying within the part of the vessel in question.

The analysis of the obtained numerical results made it possible to note a number of characteristic features accompanying the process of deformation and failure of such facilities, connected with the time and place of the forming macrocracks, the stressed-strained state history and the damage degree in the failure zone, etc.

The results of comparing the numerical and experimental data make it possible to conclude that the proposed defining relations of mechanics of damaged media adequately describe degradation of the initial strength properties of the material for the long-term strength mechanism and can be effectively used in evaluating strength and service life of structures under thermal mechanical loading.

Key words: *creep, long-term strength, modeling, defining relations, temperature, durability, service life*

Introduction

In the process of long service life, materials of structural elements of equipment and systems of critical engineering facilities (CEF), the service life of which can amount to several tens of years (atomic power plants, petrochemical facilities, tanks for gaseous and liquefied chemical products, aviation gas-turbine engines and plants of new generation, *etc*.), working in the conditions of non-stationary thermal mechanical loading, accumulate damage resulting in the degradation of initial strength characteristics, nucleation and growth of cracks. During a considerable period of time these changes have an implicit character.

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Besides, the most hazardous zones determining service life of a structural element are, as a rule, inaccessible for non-destructive inspection means. To guarantee safe exploitation of CEF and to prolong their service life over the rated resource, it is necessary to monitor rates of damage growth in the most hazardous zones of structural elements (to evaluate their worked-out life), as well as to predict the development of such processes up to limiting states (to evaluate their residual life) [1].

Sudden strength malfunctions of structural elements result from the degradation of initial strength properties of structural materials due to damage accumulation under the effect of physical fields of various natures. In view of locality of degradation processes, durability of structural elements is determined by durability of their most hazardous zones – zones of the highest rates of degradation of the physical mechanical characteristics of structural materials. The parameters of such zones can differ considerably due to the difference in the properties of the materials themselves, the structural particularities, the exploitation conditions, the production technology, *etc*.

The currently available methods for evaluating service life of structural elements do not account for realistic processes taking place in materials. Elastic analysis used in the rated approach does not make it possible to account for realistic characteristics of viscoplastic deformation of a material, which, to a considerable degree, determine service life of structural elements [1]. In a general case, strength of structures has to take into account both time and history of loading. Consequently, the failure criterion will be closely connected with the defining relations describing the failure process.

In this connection, it becomes vital to develop new methods for evaluating service life of structural elements based on related equations of thermal viscoplasticity, equations of damage accumulation and failure criteria with their comprehensive substantiation by conducting the related full-scale and numerical experiments with laboratory samples and numerically analyzing processes of deformation and failure of structural elements in their exploitation conditions [1-7].

The most effective tool for these purposes is mathematical modeling of degradation processes of structural materials, using modern models and methods of mechanics of damaged media (MDM) and fracture mechanics [2, 4-9]. Values of damage degree of the material in accessible zones, estimated by modeling, must be updated, using periodic non-destructive inspection of the state of the material in accessible zones with the help of modern physical methods, during shut-downs or maintenance of the facility [9].

In [7], in the framework of MDM, a mathematical model of MDM was developed, which describes damage accumulation processes in structural materials (metals and their alloys) due to degradation mechanisms, determined by growing creep strains under multiaxial stressed states and arbitrarily complex regimes of thermal mechanical loading.

In what follows, this model is used for numerically analyzing the carrying capacity of a nuclear power plant (NPP) vessel in the event of a hypothetical emergency.

Defining relations of MDM

The main assumptions of the introduced version of MDM are [2, 7]:

– the material of the medium is initially isotropic and free of damage (only the anisotropy due to deformation processes is taken into account; the anisotropy of elastic properties due to damage processes in the material is not accounted for),
– components of strain tensors e_{ij} and strain rates $\dot{e}_{ij}$ are a sum of *momentary* and *time* components; a *momentary* component consists of elastic components e_{ij}^{e}, $\dot{e}_{ij}^{\prime e}$, independ-

ent of the deformation history and determining the final state of the process, and of plastic components e_{ij}^{p}, $\dot{e}_{ij}'^{p}$, depending on the history of deformation process; a time component (of creep strains e_{ij}^{c}, $\dot{e}_{ij}'^{c}$) describes time-dependence of deformational processes under low-rate loading,

- the evolution of equipotential creep surfaces is described by the change of its radius C_C and displacement of its center ρ_{ij}^{c};
- the change of the volume of the body element is elastic, *i. e.*, $e_{ii}^{p} = e_{ii}^{c} = 0$,
- deformation processes characterized by small deformations are considered,
- the only structural parameter characterizing the damage degree of the material at the macro-level is scalar parameter ω – damage degree, $\omega_0 \le \omega \le \omega_f$, and
- the effect of the accumulated damage degree on the deformation process of the material is taken into account by introducing effective stresses $\tilde{\sigma}_{ij}$.

A damaged medium model consists of three interconnected parts:

- relations determining viscoplastic behavior of the material, with accounting for the dependence on the failure process,
- equations describing damage accumulation kinetics, and
- a criterion of strength of the damaged material.

(a) Relations of thermal creep

The relation between tensor components of stresses and elastic strains is established based on the equations of thermal elasticity:

$$\sigma = 3K\left[e - \alpha T)\right], \quad \dot{\sigma} = 3K\left[\dot{e} - \dot{\alpha}T - \alpha\dot{T})\right] + \frac{\dot{K}}{K}\sigma$$
$$\sigma_{ij}' = 2Ge_{ij}'^{e}, \quad \dot{\sigma}_{ij} = 2G\dot{e}_{ij}'^{e} + \frac{\dot{G}}{G}\sigma'_{ij}, \quad e_{ij}'^{e} = e_{ij}' - e_{ij}^{p} - e_{ij}^{c} \tag{1}$$

where σ, e are spherical, and σ_{ij}', e_{ij}' are deviatoric tensor components of stresses σ_{ij} and strains e_{ij}, respectively, $G(T)$ is shear modulus, $K(T)$ is volumetric elasticity modulus, $\alpha(T)$ is thermal expansion coefficient – a function of temperature T.

To describe creep processes, a family of equipotential creep surfaces, F_c, is introduced in the stress space, which has common center, ρ_{ij}^{c}, and different radii, C_c, defined by a current stressed state [2, 7]:

$$F_c^{(i)} = S_{ij}^{c}S_{ij}^{c} - C_c^2 = 0, \quad S_{ij}^{c} = \sigma_{ij}' - \rho_{ij}^{c}, \quad i = 0,1,2,... \tag{2}$$

According to the associated law:

$$\dot{e}_{ij}^{c} = \lambda_c \frac{\partial F_c^{(i)}}{\partial S_{ij}^{c}} = \lambda_c S_{ij}^{c} \tag{3}$$

where λ_c corresponds to current surface $F_c^{(i)}$ determining current stressed state S_{ij}^{c}.

Among these equipotential surfaces, a surface of radius $\bar{C}_c$ can be chosen, corresponding to the zero creep rate:

$$F_c^{(0)} = \bar{S}_{ij}^{c}\bar{S}_{ij}^{c} - \bar{C}_c^2 = 0, \quad \bar{S}_{ij}^{c} = \bar{\sigma}_{ij}' - \rho_{ij}^{c} \tag{4}$$

where $\bar{S}_{ij}^{c}$ and $\bar{\sigma}_{ij}'$ is a set of stressed states corresponding (to a certain tolerance) to the zero creep rate.

It is postulated that:

$$\bar{C}_c = \bar{C}_c\left(\chi_c, T\right), \quad \dot{\chi}_c = \sqrt{\frac{2}{3}\dot{e}_{ij}^c, \dot{e}_{ij}^c}, \quad \chi^c = \int_o^t \dot{\chi}^c \mathrm{d}t, \quad \lambda_c = \lambda_c\left(\psi_c, T\right)$$

$$\psi_c = \left[\frac{\sqrt{S_{ij}^c S_{ij}^c} - \bar{C}_c}{C_c}\right], \quad \lambda_c = \begin{cases} 0, \psi_c \le 0 \\ \lambda_c, \psi_c > 0 \end{cases} \tag{5}$$

where $\bar{C}_c$ and λ_c are experimentally determined functions of temperature T.

The evolutionary equation for changing the co-ordinates of the creep surface center is assumed to have the following form [7]:

$$\dot{\rho}_{ij}^c = g_1^c \dot{e}_{ij}^c - g_2^c \rho_{ij}^c \dot{\chi}_c \tag{6}$$

where g_1^c and $g_2^c > 0$ are experimentally determined material parameters.

By concretely defining relation (3), the law of orthogonality can be represented:

$$\dot{e}_{ij}^c = \lambda_c\left(\psi_c, T\right) S_{ij}^c = \lambda_c \psi_c S_{ij}^c = \lambda_c \left(\frac{\sqrt{S_{ij}^c S_{ij}^c} - \bar{C}_c}{C_c}\right) S_{ij}^c \tag{7}$$

whence the expression for the deformation trajectory length will assume the following form [7]:

$$\dot{\chi}_c = \sqrt{\frac{2}{3}} \dot{e}_u^c = \sqrt{\frac{2}{3}} \lambda_c \left(\sqrt{S_{ij}^c S_{ij}^c} - \bar{C}_c\right) \tag{8}$$

From eq. (8), the expression for λ_c for the three parts of the creep curve will be written [7]:

$$\lambda_c = \begin{cases} 0, \psi_c \le C_c \vee \chi_c = 0 \\ \lambda_c^I, 0 \le \chi_c \le \chi_c^{(1)} \\ \lambda_c^{II}, \chi_c^{(1)} \le \chi_c \le \chi_c^{(2)} \\ \lambda_c^{III}, \chi_c^{(2)} \le \chi_c \le \chi_c^{(3)} \end{cases} \tag{9}$$

where:

$$\lambda_c^I = \lambda_c^{(0)}\left(1 - \frac{e_{11}^c}{e_{11}^{c(1)}}\right) + \lambda_c^{(1)} \frac{e_{11}^c}{e_{11}^{c(1)}}, \quad \lambda_c^{II} = \frac{3}{2} \frac{\dot{e}_{11}^{est}}{\left(\sigma_{11}' - \frac{3}{2}\rho_{11}^c - \bar{\sigma}_c\right)}, \quad \lambda_c^{III} = \lambda_c^{II}\left(\omega\right)$$

are determined in the experiments with a uniaxial stressed state of a laboratory specimen [7].

In eq. (9): $\lambda_c^{(0)}$ and $\lambda_c^{(1)}$ are values of λ_c in the initial and final points of the first part of the creep curve of the material; $e_{11}^{c(1)}$, $e_{11}^{c(2)}$, and $e_{11}^{c(3)}$ are boundaries of the parts of the creep curve for a uniaxial stresses state where $\dot{e}_{11}^{c(beg)}$ is creep rate at an initial time, $\dot{e}_{11}^{c(est)}$ is creep rate at the part of the steady-state creep (the 2nd part of the creep curve), and ω is value of the damage degree of the material:

$$\bar{\sigma}_c = \sqrt{2/3}\bar{C}_c$$

is creep limit for a uniaxial stressed state [7].

Equations (1)-(9) describe the transient and steady-state parts of the creep curve for multiaxial stressed states and the main effects of the creep process under alternating loading.

At the stage of the development of defects scattered over the volume, the effect of the damage degree on the physical mechanical characteristics of the material is observed. In the first approximation, this effect can be accounted for, based on the concept of a degrading continuum, by introducing effective stresses [2, 9]:

$$\tilde{\sigma}'_{ij} = F_1(\omega)\sigma'_{ij} = \frac{G}{\tilde{G}}\sigma'_{ij}, \quad \tilde{\sigma} = F_2(\omega)\sigma = \frac{K}{\tilde{K}}\sigma \tag{10}$$

where $\tilde{G}$, $\tilde{K}$ are effective moduli of elasticity determined using McKenzie's formulas [9]:

$$\tilde{G} = G(1-\omega)\left[1 - \frac{(6K+12G)}{(9K+8G)}\omega\right] \tag{11}$$

$$\tilde{K} = \frac{4GK(1-\omega)}{4G+3K\omega} \tag{12}$$

Effective internal variable $\tilde{\rho}_{ij}^c$ is determined in a similar way:

$$\tilde{\rho}_{ij}^c = F_1(\omega)\rho_{ij}^c = \frac{G}{\tilde{G}}\rho_{ij}^c \tag{13}$$

(b) Evolutionary equations of damage accumulation

The rate of damage accumulation process during creep is postulated to be determined by the following evolutionary equation [2, 7]:

$$\dot{\omega} = f_1(\beta)\, f_2(\omega)\, f_3(W_c)\, f_4(\dot{W}_c) \tag{14}$$

where functions f_i, $i = 1\ldots4$ account for: voluminosity of the stressed state [$f_1(\beta)$], level of the accumulated damage [$f_2(\omega)$], accumulated relative energy of damage spent on the formation of defects [$f_3(W_c)$], and rate of change of damage energy [$f_4(\dot{W}_c)$].

In equation (14):

$$f_1(\beta) = \exp(\beta), \quad f_2(\omega) = \begin{cases} 0, & W_c \le W_c^a \\ \omega^{1/3}(1-\omega)^{2/3}, & W_c > W_c^a \wedge \omega \le \dfrac{1}{3} \\ \dfrac{\sqrt[3]{16}}{9}\omega^{-1/3}(1-\omega)^{-2/3}, & W_c > W_c^a \wedge \omega > \dfrac{1}{3} \end{cases} \tag{15}$$

$$f_3(W_c) = \frac{W_c - W_c^a}{W_c^f}, \quad f_4(\dot{W}_c) = \frac{\dot{W}_c}{W_c^f}, \quad \dot{W}_c = \rho_{ij}^c \dot{e}_{ij}^c, \quad W_c = \int_0^t \dot{W}_c\, \mathrm{d}t \tag{16}$$

where β is parameter of voluminosity of stressed state, $\beta = \sigma/\sigma_u$, W_c^a is value of damage energy W_c at the end of the stage of nucleation of scattered defects during creep (at the end of the second part of the creep curve), and W_c^f is value of the energy, corresponding to the formation of a macroscopic crack (the end of the third part of the creep curve).

The duration of the microdefect nucleation phase will be correlated with the value of parameter W_c^a .

When the dimensions of microdefects become comparable with the mean distance between them, the process of merging begins (breakage of the remaining gaps of continuity between the defects). In the present paper, a detailed model of merging of cavities was not constructed, but, to account for this process, the kinetic equation, due to term $f_2(\omega)$, was formulated in such a way that, when the damage degree reaches the value of ω = 1/3, relation $\dot{\omega} = f_1(\omega)$ accounts for the avalanche-like increase of the damage degree value.

(c) Criterion of strength of the damaged material

The criterion of the ending of the phase of the development of scattered microdefects (the stage of the formation of a macrocrack) is assumed to be the condition when the damage degree reaches its critical value:

$$\omega = \omega_f \leq 1 \tag{17}$$

By integrating evolutionary equation of damage accumulation (14)-(16) together with defining relations of thermal viscoplasticity (1)-(13) and failure criterion (17) according to a known history of thermal mechanical loading in a given elementary volume of the material, one can determine the time of formation of a macroscopic crack in the process of degradation of the material according to the long-term strength mechanism.

Results of the numerical analysis

In the event of a serious emergency at reactor plants, with a complete or partial meltdown of the core, the only barrier for radioactive materials is the reactor vessel. The meltdown of the core is accompanied by meltdown of the internal structures of the vessel. The interaction of the melted core and the internal structures with the reactor vessel results in excessive heating and possible melting through of the vessel wall. As a rule, reactor vessels are made of pearlitic steel, which, when heated over 600 ºC, loses considerably its physical mechanical characteristics, the dominating mechanism of its deformation being creep of the material.

The breach of integrity of the reactor vessel in the event of a serious emergency with the meltdown of the core may take place for two reasons:

– melting-through of the reactor vessel and
– exhaustion of the carrying capacity of the vessel as a result of the degradation of the initial strength properties of the structural material, mainly due to creep effects.

In what follows, the results of numerically analyzing the carrying capacity of a NPP reactor vessel in the event of a hypothetical emergency for the long-term strength mechanism are presented. The reactor vessel is made of steel 15X2HMFA.

The calculation scheme is represented by an axisymmetric structure of a reactor vessel, consisting of a cylindrical wall and an elliptic bottom. An emergency was modeled by applying internal hydrostatic pressure, p_1, varying from zero at a height of h = 1.5 m from the lowest point of the bottom and modeling the forcer effect from the meltdown, internal pressure, p_2, and temperature, T, varying in the limits of the considered part of the reactor vessel from 184-1510 ºC.

Two values of temperature, T, over the area at the apex of the outer surface of the elliptic bottom were used in calculations:

– T = 594 ºC, the 1st version of the calculation – fig. 1(a), taken from [8] and
– T = 800 ºC, the 2nd version of the calculation – fig. 1(b), taken from [10].

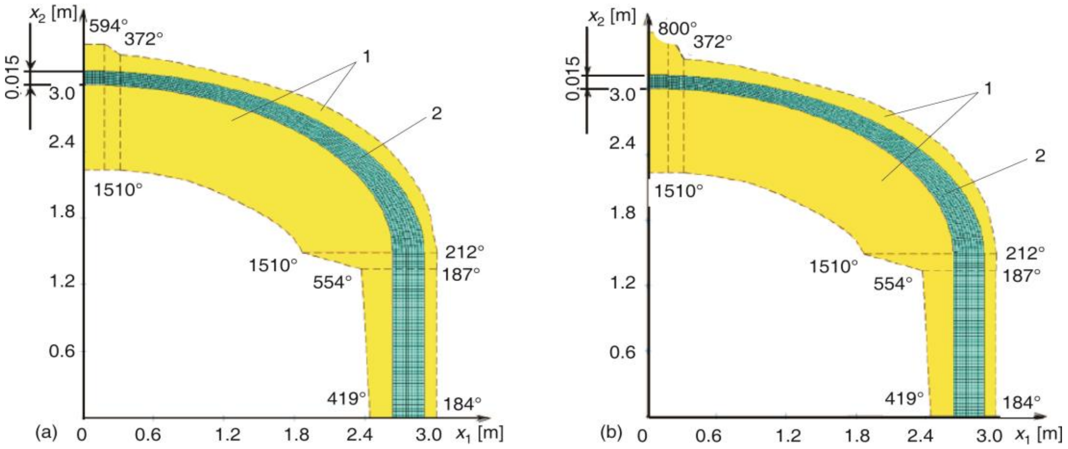

Figure 1. Two types of temperature distribution over the cross-section of the reactor vessel

The geometric dimensions and the temperature profile on the reactor vessel surface (the temperatures on the internal and external surfaces of the vessel) were used as boundary conditions for calculating temperature fields in the cross-section of the reactor vessel. The temperature field profiles in fig. 1 are shown in yellow – (1), the reactor vessel is shown in blue – (2).

Before modeling the emergency, the reliability of the developed MDM model was numerically assessed, and material parameters of steel 15X2HMFA were determined in the temperature range of 20 ºC to 1200 ºC. To this end, the experimental data given in [11] was used.

In [11], the results of experimentally studying processes of short-term transient creep of steel 15X2HMFA in the temperature range of up to 1200 ºC are presented. The creep process was numerically modeled up to the formation of a macroscopic crack, using physical mechanical characteristics and material parameters of the DMD model for steel 15X2HMFA summarized in the tab. 1.

Table 1. Physical-mechanical characteristics and material parameters of the MDM model of steel 15X2HMFA

T [°C]	K [MPa]	G [MPa]	$\bar{C}_c$ [MPa]	$\lambda_c^{(0)}$ [MPa^{-1}h^{-1}]	$\lambda_c^{(1)}$, [MPa^{-1}h^{-1}]	g_1^c [MPa]	g_2^c [MPa]	W_c^f [MJ/m^3]	W_c^a [MJ/m^3]	ω_f
600	138000	63500	110	0.000045	0.00009	30000	1000	26	11,2	0,8
800	34700	16000	29	0.00026	0.00052	3500	350	7	3,7	0,8
900	66700	30800	9	0.0002	0.000053	1000	300	2,6	1,24	0,8
1200	9170	4230	1.5	0.00027	0.00027	100	100	0,65	0,21	0,8

Figures 2 and 3 present the creep curves for:
– temperature T = 900 ºC and stresses σ_{11} = 20, 22, and 26.5 MPa, respectively, fig. 2, and
– temperature T = 1200 ºC and stresses σ_{11} = 4.5, 5.4, and 6.3 MPa, respectively, fig. 3.

In the pictures, the lines depict the results of numerical modeling, using defining relations of MDM (1)-(17), and the markers show the corresponding experimental data. Qualitative and quantitative agreement between the experimental and numerical data is observed,

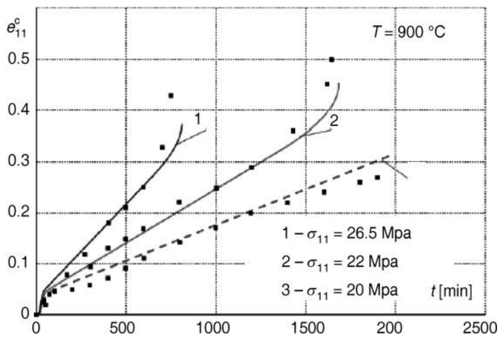

Figure 2. Comparison of calculated and experimental data on creep curves for temperature 900 °C

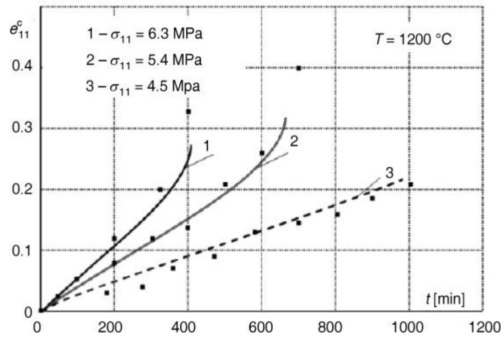

Figure 3. Comparison of calculated and experimental data on creep curves for temperature 1200 °C

both for the degree and character of the change of the deformations over all the three parts of the creep curve and for the time of formation of a macroscopic crack, which makes it possible to draw conclusions about the adequacy of the modeling process and the accuracy of the determined material parameters included in the developed defining relations of MDM.

The problem of evaluating long-term strength of a NPP reactor vessel under thermal dynamical loading was numerically solved in two steps.

At the first step, the stage at which the pressure and temperature increased up to their maximal values during a short period was analyzed (the duration of the heating stage was 1 minute).

At the second step, the pressure and temperature were kept constant.

A number of calculations were done, differing in the value of internal pressure, p_2.

Four values of pressure, p_2, were used in the calculations:

– the p_2 = 1.3, 1.35, 1.5, and 2 MPa for the version of the temperature field depicted in fig. 1(a) and
– the p_2 = 0.6, 0.7, 0.8, 1 MPa for the version of the temperature field shown in fig. 1(b).

At all the stages, the load acting on the bottom of the reactor vessel from the hydrostatic effect of the meltdown was modeled.

It is to be noted that the construction of the computational scheme took into account the zone of the elliptic bottom, where the material practically does not counteract the deformation because of its strong meltdown. For this reason, the thickness of the elliptic bottom in the computational scheme used was reduced by the depth of the meltdown zone, $T > 1200$ ºC.

The numerical analyses revealed that, for all the versions of the computations, from the viewpoint of long-term strength, the second stage (with the constant pressure and temperature), accompanied by the intensive development of creep strains and growth of defects, proved to be the most important one.

It was found, in particular, that for the values of $p_2 \leq 1.3$ MPa for the temperature field represented in fig. 1(a) and $p_2 \leq 0.6$ MPa for the temperature field in fig. 1(b), at time $t > 5$ hour for the first version of the analysis and $t > 57$ hour for the second one, the creep strain rate in the most heavily loaded zone of the reactor vessel, situated in the region of the apex of the elliptic bottom, was close to zero.

For the pressure values of $p_2 \geq 1.3$ MPa for the first version of the analysis and $p_2 \geq 1.3$ MPa for the second one, the deformation process of the loaded reactor vessel was accompanied by intensive changes of form due to the increasing creep of the material in the central part of the elliptic bottom.

Figure 4 shows the distribution of inelastic strain intensities over the cross-section of the vessel at different times for p_2 = 1.5 MPa and the temperature field, fig. 1(a). Whereas fig. 5 depicts analogous illustrations for p_2 = 1 MPa and the temperature field, fig. 1(b). It can be seen that the most *hazardous* zone (that with the highest level of the creep strain intensity) is localized in the central part of the elliptic bottom of the reactor vessel, where damage accumulation processes are especially intensive.

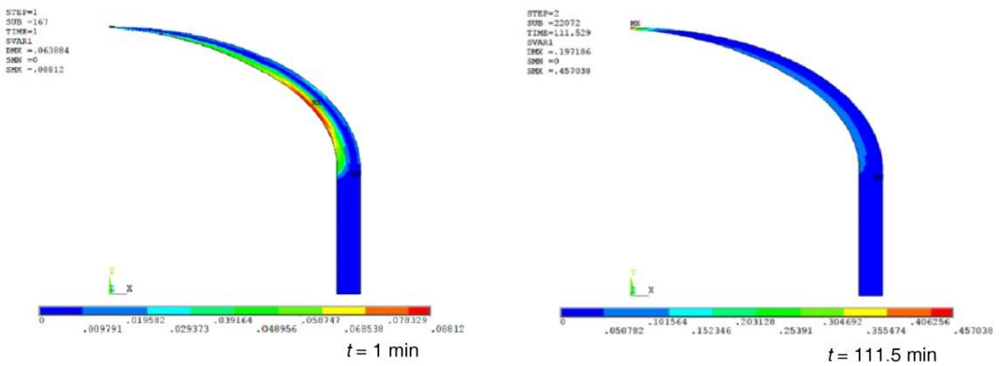

Figure 4. Distribution of inelastic strain intensities over the cross-section of the vessel at different times for p_2 = 1.5 MPa and the temperature field (fig. 1a)

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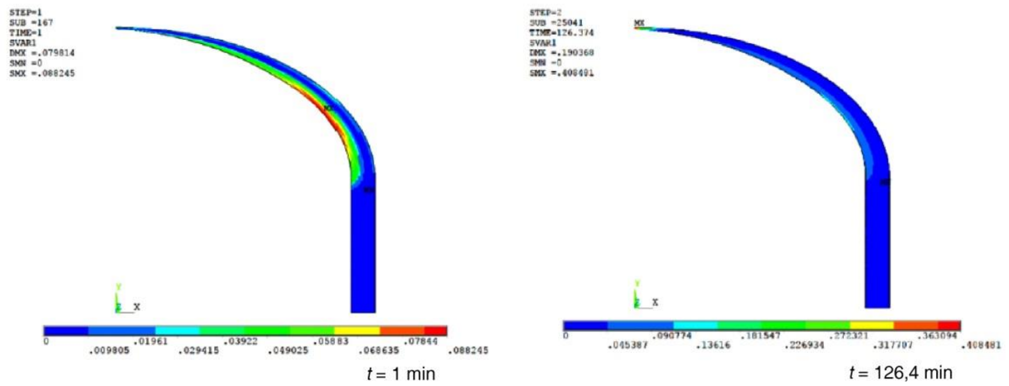

Figure 5. Distribution of inelastic strain intensities over the cross-section of the vessel at different times for p_2 = 1 MPa and the temperature field (fig. 1b)

vessel at the time when a macroscopic crack is formed for the first version of the analysis is presented in fig. 6, and for the second one in fig. 7. It can be seen that the macroscopic crack in both versions of the analysis is nucleated in the central part of the elliptic bottom, in the vicinity of the middle surface of the structural element (in figs. 6 and 7, the part of the zone where the macroscopic crack is formed is shown separately).

Figure 8 depicts damage level, ω, as a function of time of the process, t, in the zone of maximal hazard (point A in fig. 6) for the version of the temperature field, fig. 1(a) and different values of pressure, p_2. Figure 9 shows the analogous curves for the version of the temperature field depicted in fig. 1(b).

The analysis of the obtained numerical results revealed the following characteristic laws of the deformation process of a NPP reactor vessel:

– for the version of the temperature field presented in fig. 1, the maximal admissible value of pressure, p_2, not leading to the formation of a macroscopic crack for the long-term strength mechanism is, whereas for the temperature field shown in fig. 1(b) it is p_2 = 0.6 MPa and
– the numerical results on determining admissible values of pressures obtained in the present paper agree with the analogous results obtained in [10].

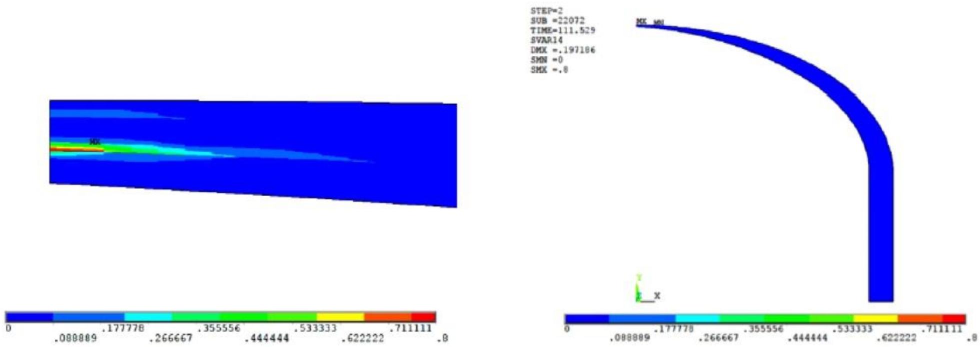

Figure 6. The distribution of the damage degree value over the cross-section of the reactor vessel at the time when a macroscopic crack is formed for the first version of the analysis

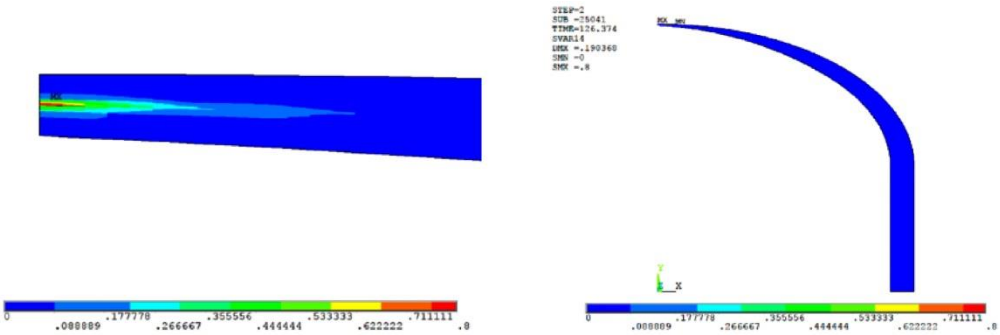

Figure 7. The distribution of the damage degree value over the cross-section of the reactor vessel at the time when a macroscopic crack is formed for the second version of the analysis

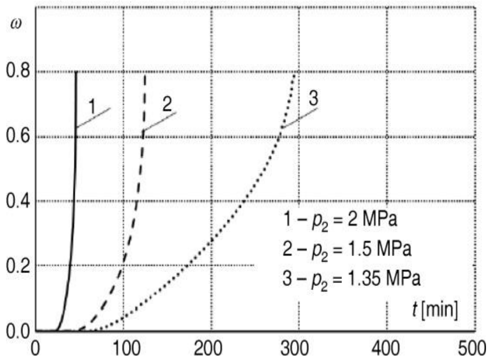

Figure 8. Damage level as a function of time of the process in the zone of maximal hazard for the version of the temperature field (fig. 1a)

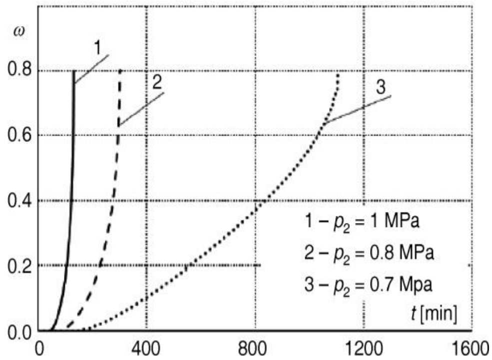

Figure 9. Damage level as a function of time of the process in the zone of maximal hazard for the version of the temperature field (fig. 1b)

Thus, the numerical analyses conducted in the present study and their comparison with the available experimental data make it possible to draw the conclusions about the adequacy of the defining relations of MDM in modeling degradation of materials of according to the long-term strength mechanism and the possibility of effectively using the developed defining relations of MDM for evaluating long-term strength of materials and structures.

Conclusions

A mathematical model of MDM has been developed, that describes processes of inelastic deformation and damage accumulation in structural materials (metals and their alloys) during the degradation of initial strength properties of materials according to the long-term strength mechanism.

Using the numerical modeling method and comparing the obtained results with experimental data, the reliability of the defining relations of MDM for creep has been assessed, which made it possible to draw the conclusions about the reliability of the developed modelling representations and the accuracy of the developed methodology of determining the material parameters contained in these relations.

The results of numerically analyzing the carrying capacity of a NPP reactor vessel in the event of a hypothetical accident are presented, that made it possible to note a number of characteristic features accompanying the process of deformation and failure of such facilities.

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