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Creep Failure Time of Thin-Walled Pipes under Combined Internal Pressure, Bending, and Tension

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Долговечность тонкостенных труб при ползучести в условиях совместного нагружения внутренним давлением, изгибом и растяжением

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Выполнен расчет долговечности в условиях ползучести для прямолинейных тонкостенных труб, подвергнутых совместному нагружению внутренним давлением, растягивающей силой и изгибающим моментом. Расчет времени до разрушения при ползучести осуществляется с использованием эквивалентных напряжений, которые определяются согласно смешанному критерию "отложенного разрушения", связывающему максимальные нормальные напряжения с интенсивностью тангенциальных напряжений. Полученные расчетные результаты хорошо согласуются с данными, приведенными в литературных источниках для труб, подвергнутых комбинированному нагружению. Предложенный подход позволяет рассчитать время до разрушения при ползучести для тонкостенных труб, совместно нагружаемых внутренним давлением, растягивающей силой и изгибающим моментом.

Ключевые слова: разрушение при ползучести, внутреннее давление, плоский изгиб, тонкостенная труба, одноосное растяжение.

Introduction. Elements of steam and gas turbines, jet engines, steam boilers, rockets, oil and gas processing plants widely use thin-walled pipes. These elements can be subjected to creep; therefore the creep analysis is of great interest [1]. The time to failure t_{RT} of a thin-walled pipe under internal pressure p, axial force N, and bending moment M_b is the objective of this study.

In [2–4], a mixed plane-stress criterion of delayed failure was established and experimentally validated for metal and polymeric materials. The criterion has the form of a two-parameter linear interpolation relating two stress invariants that represent ductile and brittle fracture and accounting for the signs of the principal stresses. However, Golub used the concept of unified limit stress diagram to model creep–fatigue interaction [5]. In addition, experimental analysis of high-temperature creep, fatigue and damage has been performed in [6]. A technique of constructing unified deformation and damage diagrams based on the conditions of proportional similarity is substantiated.

Creep deformation and damage of high-speed steel HS 6-5-3 was investigated by numerical simulation by Hofter et al. [7]. Whereas, Cole and Bhadeshia [8] tried to estimate the creep rupture strength of heat resistant steels and welds. Cole deals with quantitative methods for the design of steel weld metals for elevated temperature applications.

A series of fatigue tests under uniaxial and torsional loading at constant room temperature was carried out in [9]. A cyclic constitutive and damage model is presented to describe the characterization of stress strain response and damage evolution for these fully reversed strain-controlled tests.

Tinga et al.[10] have proposed a damage model for single crystal Ni-base superalloys that integrates time-dependent and cyclic damage into a generally applicable time-incremental damage rule. Yang et al. [11] have proposed a simple stress-controlled fatigue-creep damage evolution model based on the ductility dissipation theory and effective stress concept of continuum damage mechanism, where damage constants can be obtained through fatigue-creep tests directly.

An advanced elasto-viscoplastic model for the time-varying response of ultra-high molecular weight polyethylene (UHMWPE) was used by Bischoff [12] to explore the effects of loading frequency and creep time on the material behavior during cyclic loading. Whereas, an integral computational method has been developed to provide the initial values to a subsequent fitting of creep data based on non-linear and iterative methods by Rieiro et al. [13]. Kachanov [14] has suggested a theoretical model for the time to rupture with the account of embrittlement.

A method for the estimation of the time to failure under creep conditions proposed by Zharkova and Botvina [15] is based on the approach of a phase transition theory and the similarity of fracture mechanisms.

The equivalent-stress methods of long-term strength analysis of pipes are the most efficient and widely used in current design practice. The accuracy of calculations strongly depends on the adequacy of the equivalent stresses to the stress and failure modes of the pipe and on the degree of agreement between the material constants and long-term strength characteristics obtained under uniaxial tension

1. **Analysis**. This paper is focused on thin-walled pipe subjected to internal pressure, axial load, and bending.

1.1. ***The Failure of Thin-Walled Pipes under Internal Pressure [2]***.

1.1.1. *Failure under Internal Pressure*. Golub et al. [2] have derived a formula to evaluate the creep time for pipes under internal pressure

$$\sigma_1 = \frac{pD_m}{2h}, \qquad \sigma_2 = \frac{pD_m}{4h}, \qquad \sigma_3 = 0, \tag{1}$$

$$t_{RT} = \frac{1}{B[(1+\alpha)\lambda]^m \left(\dfrac{p}{2}\right)^m}, \tag{2}$$

where

$$\lambda = \frac{D_m}{2h}. \tag{3}$$

The material constant α is

$$\alpha = \frac{2\sigma_t - \lambda p_t}{\sigma_t}. \tag{4}$$

1.1.2. *Failure under Internal Pressure and Axial Load*. For a rectilinear thin-walled pipe under internal pressure p and axial tensile force N, the equilibrium conditions for the pipe yield:

Case (a): $\delta \le \lambda/2$,

$$\sigma_1 = \frac{pD_m}{2h}, \qquad \sigma_2 = \frac{pD_m}{4h} + \frac{N}{\pi D_m h}, \qquad \sigma_3 = 0 \tag{5}$$

for $\dfrac{N}{\pi D_m h} \le \dfrac{pD_m}{4h}$.

The creep time is given as

$$t_{RT} = \frac{1}{B}\left[\frac{\sqrt{3\lambda^2 + 4\delta^2} + (2\sqrt{3}\lambda - \sqrt{3\lambda^2 + 4\delta^2})\alpha}{\sqrt{3}}\right]^{-m}\left(\frac{p}{2}\right)^{-m}, \tag{6}$$

where

$$\frac{N}{\pi D_m hp} = \delta, \tag{7}$$

$$\alpha = \frac{\lambda(2\sqrt{3}\sigma_t - \sqrt{3\lambda^2 + 4\delta^2}\, p_t)}{(2\sqrt{3}\lambda - \sqrt{3\lambda^2 + 4\delta^2})\sigma_t}. \tag{8}$$

Case (b): $\delta \ge \lambda/2$. The equilibrium conditions for the pipe yield

$$\sigma_1 = \frac{pD_m}{4h} + \frac{N}{\pi D_m h}, \qquad \sigma_2 = \frac{pD_m}{2h}, \qquad \sigma_3 = 0 \tag{9}$$

for $\dfrac{N}{\pi D_m h} \ge \dfrac{pD_m}{4h}$.

The formula for creep time is

$$t_{RT} = \frac{1}{B}\left[\frac{\sqrt{3\lambda^2 + 4\delta^2} + (\sqrt{3}\lambda + 2\sqrt{3}\delta - \sqrt{3\lambda^2 + 4\delta^2})\alpha}{\sqrt{3}}\right]^{-m}\left(\frac{p}{2}\right)^{-m} \tag{10}$$

and

$$\alpha = \frac{(\lambda + 2\delta)(2\sqrt{3}\sigma_t - \sqrt{3\lambda^2 + 4\delta^2}\, p_t)}{2[\sqrt{3}(\lambda + 2\delta) - \sqrt{3\lambda^2 + 4\delta^2}\,]\sigma_t}. \tag{11}$$

1.1.3. *Failure under Internal Pressure and Bending*. For a rectilinear thin-walled pipe under internal pressure p and bending moment M_b, the equilibrium conditions for the pipe are:

Case (a): $\xi \leq \lambda/2$,

$$\sigma_1 = \frac{pD_m}{2h}, \qquad \sigma_2 = \frac{pD_m}{4h} + \frac{2M_b}{\pi D_m^2 h}, \qquad \sigma_3 = 0 \tag{12}$$

for $\dfrac{2M_b}{\pi D_m^2 h} \leq \dfrac{pD_m}{4h}$.

The creep time is given as

$$t_{RT} = \frac{1}{B}\left[\frac{\sqrt{3\lambda^2 + 4\xi^2} + (2\sqrt{3}\lambda - \sqrt{3\lambda^2 + 4\xi^2})\alpha}{\sqrt{3}}\right]^{-m}\left(\frac{p}{2}\right)^{-m}, \tag{13}$$

$$\alpha = \frac{\lambda(2\sqrt{3}\sigma_t - \sqrt{3\lambda^2 + 4\xi^2}\, p_t)}{(2\sqrt{3}\lambda - \sqrt{3\lambda^2 + 4\xi^2})\sigma_t}, \tag{14}$$

where

$$\xi = \frac{2M_b}{\pi D_m^2 hp}. \tag{15}$$

Case (b): $\xi \geq \lambda/2$. The equilibrium condition

$$\sigma_1 = \frac{pD_m}{4h} + \frac{2M_b}{\pi D_m^2 h}, \qquad \sigma_2 = \frac{pD_m}{2h}, \qquad \sigma_3 = 0 \tag{16}$$

for $\dfrac{2M_b}{\pi D_m^2 h} \geq \dfrac{pD_m}{4h}$.

The creep time is

$$t_{RT} = \frac{1}{B}\left[\frac{\sqrt{3\lambda^2 + 4\xi^2} + (\sqrt{3}\lambda + 2\sqrt{3}\xi - \sqrt{3\lambda^2 + 4\xi^2})\alpha}{\sqrt{3}}\right]^{-m}\left(\frac{p}{2}\right)^{-m}, \tag{17}$$

$$\alpha = \frac{(\lambda + 2\xi)(2\sqrt{3}\sigma_t - \sqrt{3\lambda^2 + 4\xi^2}\, p_t)}{2[\sqrt{3}(\lambda + 2\xi) - \sqrt{3\lambda^2 + 4\xi^2}\,]\sigma_t}. \tag{18}$$

1.2. ***Formulation of the Problem and the Proposed Initial Relations***. Consider a long rectilinear thin-walled pipe of circular cross section under creep conditions. Denote the diameter of the median surface by D_m and wall thickness, which is constant, by h. It is assumed that $2h << D_m$.

The pipe is subjected to internal pressure p in combination with axial tensile force N and bending moment M_b. Under creep, the external load remains constant. The ends of the pipe are not restrained, and its deformation is free. The material of the pipe is homogeneous, isotropic, and incompressible, and its initial state is elastic. The time to failure t_{RT} of the pipe is found using the approach of Golub et al. [2] based on the concept of equivalent stress as some scalar characteristic of the initial stress of the pipe. The equivalent stress relates the failure of the pipe under arbitrary stress and the failure of a cylindrical specimen under uniaxial tension. Therefore

$$t_R = \frac{1}{B(\sigma_t)^m} \Rightarrow t_{RT} = \frac{1}{B(\sigma_{eq})^m}, \tag{19}$$

where t_R and σ_t are the time to failure and failure stress of smooth cylindrical specimens under uniaxial tension, σ_{eq} is the equivalent stress, and B and m are material constants determined from standard uniaxial-tension creep-rupture tests on smooth cylindrical specimens. In what follows, we consider that for the values of B and m found, the delayed-failure patterns of smooth specimens and thin-walled pipes are identical. If the standard long-term strength curve has breaks, the values of B and m are calculated for each section of the curve.

The combination of internal pressure, tension, and bending induces plane stress in thin-walled pipes. A mixed delayed-failure criterion in the following form ([3])

$$\sigma_{eq} = \begin{cases} \alpha\sigma_{\max} + (1-\alpha)s_i & \text{for} \quad \sigma_1 > \sigma_2 > 0,\ \sigma_3 = 0, \\ 2\beta\tau_{\max} + (1-\beta)\tau_{oct} & \text{for} \quad \sigma_1 > 0,\ \sigma_2 = 0,\ \sigma_3 < 0 \end{cases} \tag{20}$$

can be used as the equivalent stress σ_{eq}.This criterion accounts for the signs of the principal stresses and relates the maximum normal stress $\sigma_{\max}$,

$$\sigma_{\max} = \sigma_1, \tag{21}$$

the intensity of tangential stresses,

$$s_i = \frac{1}{\sqrt{3}}\sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}, \tag{22}$$

the double maximum tangential stress $2\tau_{\max}$,

$$2\tau_{\max} = \sigma_1 - \sigma_2, \tag{23}$$

and the octahedral tangential stress τ_{oct},

$$\tau_{oct} = \frac{\sqrt{2}}{3}\sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}, \tag{24}$$

where σ_1 and σ_2 are the principal normal stresses ($\sigma_1 > \sigma_2$), and α and β are experimentally determined material constants reflecting the effect of the plane stress mode (σ_2 is any nonzero second principal stress). When thin-walled pipes are subjected to internal pressure in combination with tension and bending, the signs of the principal stresses coincide. Substituting the first relation in (20) into Eq. (19) and taking into account (21) and (22), we obtain an equation for the time to failure in terms of the principal stresses

$$t_{RT} = B\left[\frac{\sqrt{3}\alpha\sigma_1 + (1-\alpha)\sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}}{\sqrt{3}}\right]^{-m}, \qquad (25)$$

which in fact determines the time of occurrence of local failure.

1.2.1. *Failure under Internal Pressure, Tension, and Bending*. Consider a rectilinear thin-walled pipe with the edge plates under internal pressure p and both axial load N and bending moment M_b. We assume that the pipe is long. The plane stress state in the median surface of the pipe is membrane and statically determinate. The equilibrium conditions yield

$$\sigma_1 = \sigma_\varphi = \frac{pD_m}{2h}, \qquad \sigma_2 = \sigma_z = \frac{pD_m}{4h} + \frac{N}{\pi D_m h} + \frac{2M_b}{\pi D_m^2 h},$$
$$\sigma_3 = \sigma_r = 0 \qquad (26)$$

for $\dfrac{N}{\pi D_m h} + \dfrac{2M_b}{\pi D_m^2 h} \le \dfrac{pD_m}{4h}$, and where σ_φ is the hoop stress, σ_z is the axial stress, and σ_r is the radial stress, while,

$$\sigma_1 = \frac{pD_m}{4h} + \frac{N}{\pi D_m h} + \frac{2M_b}{\pi D_m^2 h}, \qquad \sigma_2 = \frac{pD_m}{2h}, \qquad \sigma_3 = 0 \qquad (27)$$

for $\dfrac{N}{\pi D_m h} + \dfrac{2M_b}{\pi D_m^2 h} \ge \dfrac{pD_m}{4h}$.

Case (a): $\delta + \xi \le \lambda/2$. Substituting Eq. (26) into Eq. (25) yields the time to failure $\delta + \xi \le \lambda/2$,

$$t_{RT} = \left\{\left[3\left(\frac{D_m}{2h}\right)^2 + 4\left(\frac{N}{\pi D_m hp}\right)^2 + 4\left(\frac{2}{\pi D_m^2 h}\frac{M_b}{p}\right)^2 + 4\left(\frac{2N}{\pi D_m hp}\frac{2M_b}{\pi D_m^2 hp}\right)\right]^{1/2} + \right.$$

$$+\left[\frac{\sqrt{3}D_m}{h} - \left(3\left(\frac{D_m}{2h}\right)^2 + 4\left(\frac{N}{\pi D_m hp}\right)^2 + 4\left(\frac{2}{\pi D_m^2 h}\frac{M_b}{p}\right)^2 + \right.\right.$$

$$+\,4\left(\frac{2N}{\pi D_m hp}\frac{2M_b}{\pi D_m^2 hp}\right)\Bigg)^{1/2}\Bigg]\alpha\Bigg\}^m \left(\frac{p}{2\sqrt{3}}\right)^m \tag{28}$$

or

$$t_{RT}=\Bigg[\frac{\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi}}{\sqrt{3}}+$$

$$+\frac{(2\sqrt{3}\lambda-\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi})\alpha}{\sqrt{3}}\Bigg]^{-m}\left(\frac{p}{2}\right)^{-m}, \tag{29}$$

where λ, δ, and ξ are dimensionless parameters, describing variation in the stressed state of the thin-walled pipe under internal pressure, axial load and bending, which are obtained from Eqs. (3), (7) and (15), respectively.

The material constant α in Eqs. (28) and (29) is determined from the following relation [3]:

$$\alpha=\frac{\lambda[2\sqrt{3}\sigma_t-(\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi})p_t]}{[2\sqrt{3}\lambda-\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi}]\sigma_t}, \tag{30}$$

where σ_t and p_t are experimentally determined values of averaged long-term strength (in view of the statistical properties of the material) for a cylindrical specimen under uniaxial tension and a thin-walled pipe under internal pressure, which correspond to the same time to failure.

Case (b): $\delta+\xi\geq\lambda/2$. Substituting Eq. (27) into Eq. (25) yields the time to failure $\delta+\xi\geq\lambda/2$,

$$t_{RT}=\Bigg\{\Bigg[3\left(\frac{D_m}{2h}\right)^2+4\left(\frac{N}{\pi D_m hp}\right)^2+4\left(\frac{2}{\pi D_m^2 h}\frac{M_b}{p}\right)^2+8\left(\frac{N}{\pi D_m hp}\frac{2M_b}{\pi D_m^2 hp}\right)\Bigg]^{1/2}+$$

$$+\Bigg[2\sqrt{3}\left(\frac{D_m}{4h}+\frac{N}{\pi D_m hp}+\frac{2M_b}{\pi D_m^2 hp}\right)-\Bigg(3\left(\frac{D_m}{2h}\right)^2+4\left(\frac{N}{\pi D_m hp}\right)^2+$$

$$+\,4\left(\frac{2}{\pi D_m^2 h}\frac{M_b}{p}\right)^2+\;8\left(\frac{N}{\pi D_m hp}\frac{2M_b}{\pi D_m^2 hp}\right)\Bigg)^{1/2}\Bigg]\alpha\Bigg\}^m\left(\frac{p}{2\sqrt{3}}\right)^m \tag{31}$$

or

$$t_{RT}=\Bigg[\frac{\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi}}{\sqrt{3}}+$$

$$+\frac{[\sqrt{3}(\lambda+2\delta+2\xi)-\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi}\,]\alpha}{\sqrt{3}}\Bigg]^{-m}\left(\frac{p}{2}\right)^{-m}. \qquad (32)$$

The material constant α is determined from [3],

$$\alpha=\frac{(\lambda+2\delta+2\xi)\{2\sqrt{3}\sigma_t-(\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi})p_t\}}{2[\sqrt{3}(\lambda+2\delta+2\xi)-2\sqrt{3\lambda^2+4\delta^2+4\xi^2+8\delta\xi}\,]\sigma_t}, \qquad (33)$$

where the notation is the same as in (30).

Substitute in Eq. (29) with $\delta=0$ and $\xi=0$ (i.e., pipe is under internal pressure only) yields to the same Eq. (2). Otherwise substitute in Eq. (29) with $\delta=0$ yields the same Eq. (13), while substituting with $\xi=0$ yields Eq. (6). Similarly substitute in Eq. (30) with $\delta=0$ and $\xi=0$ yields the same Eq. (4), substituting in Eq. (30) with $\xi=0$ yields the same Eq. (8) and substituting with $\delta=0$ yields the same Eq. (14) (i.e., as in [2]).

Substitute in Eq. (32) with $\delta=0$ yields the same Eq. (17), while substituting with $\xi=0$ yields Eq. (10). While substituting in Eq. (33) with $\xi=0$ yields the same Eq. (11), and substituting with $\delta=0$ yields the same Eq. (18) (i.e., in agreement with [2]).

The critical state between cases (a) and (b) is when $\delta+\xi=\lambda/2$, substitute with this value in Eqs. (29) and (32) yields the same following equation:

$$t_{RT}=\frac{1}{B}\left[\frac{4(\delta+\xi)(1+0.732\alpha)}{\sqrt{3}}\right]^{-m}\left(\frac{p}{2}\right)^{-m}. \qquad (34)$$

While substituting with $\delta+\xi=\lambda/2$ in Eqs. (30) and (33) yields the same following equation for α:

$$\alpha=\frac{\{\sqrt{3}\sigma_t-2(\delta+\xi)p_t\}}{0.732\sigma_t}. \qquad (35)$$

2. **Results and Discussion**. The time to creep failure of thin-walled pipes under internal pressure combined with axial load and bending is introduced in the previous section. These analytical solutions are concerned with long rectilinear thin-walled pipe, in order to predict the time failure of the pipe according to the parameters of the stressed state, as well as the internal pressure of the pipe.

The results are given in Figs. 1–10. Figures 1 and 2 show the results obtained for internal pressure versus failure time for 1Kh13N16B steel. For 1Kh13N16B steel (Figs. 1 and 2) there is a slight increase in failure time with $\delta=2.5$ and $\xi=0.8$ as compared to the case when $\delta=\xi=0$. There is a noticeable increase in failure time (77%) when pipes under internal pressure are subjected to combined axial load and bending (Fig. 2). The values of B, m, λ, δ, and ξ used in the calculation are summarized in Table 1.

Table 1

The Materials Used ([2])

Material	T, °C	B, $\text{MPa}^{-m}\cdot\text{h}^{-1}$	m	λ	δ	ξ	α
Steel Kh18N10T	850	$2.710\cdot10^{-7}$	3.04	11.50	5.75	1.50	0.8430
Steel 1Kh13N16B	700	$1.078\cdot10^{-13}$	4.95	4.10	2.50	0.80	0.1900
Steel 1Kh18N9T	800	$3.396\cdot10^{-26}$	15.41	20.50	10.00	1.65	0.9126
	700	$1.567\cdot10^{-15}$	6.23	7.15	3.50	0.90	0.8596
Steel 20	500	$3.117\cdot10^{-17}$	6.58	9.60	9.50	2.00	0.1619

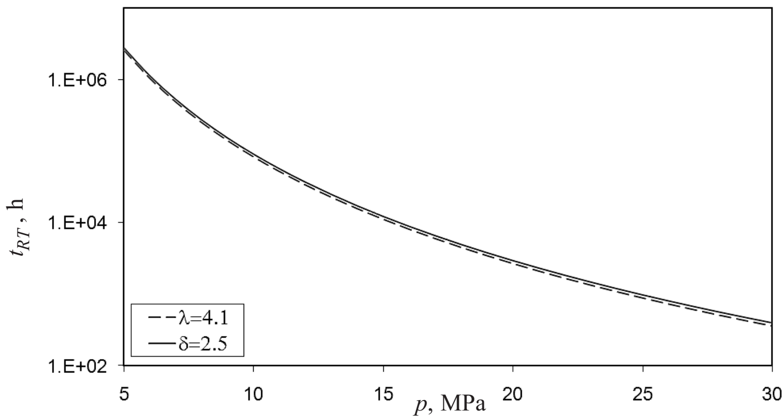

Fig. 1. The relationship between the internal pressure and the failure time for steel 1Kh13N16B with λ and δ. (Here and Figs. 2–10 data are show in Table 1.)

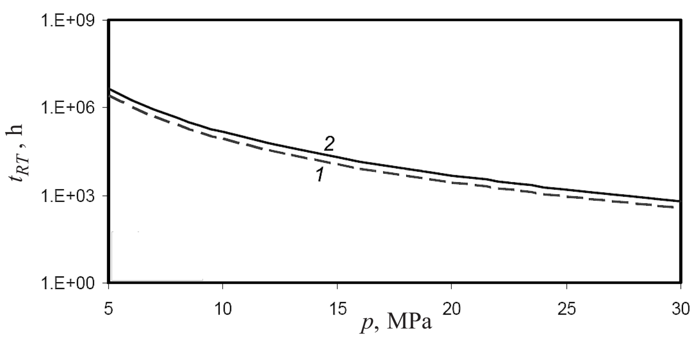

Fig. 2. The relationship between the internal pressure and the failure time for steel 1Kh13N16B with ξ, λ, and δ: (*1*) $\xi = 0.8$, (*2*) $\lambda + \delta + \xi$.

Figures 3 and 4 (steel 20) manifest a low failure time at high internal pressure compared with steel 1Kh13N16B at the same pressure, while a steel Kh18N10T have a very low failure time at the same internal pressure (Figs. 5 and 6). This is because the material has lower material proprieties and the pipes have larger parameters. The failure time increases by 140% for steel 20, while it increases by 21% for steel Kh18N10T at the same internal pressure, when the pipe is subjected to axial load and bending moment.

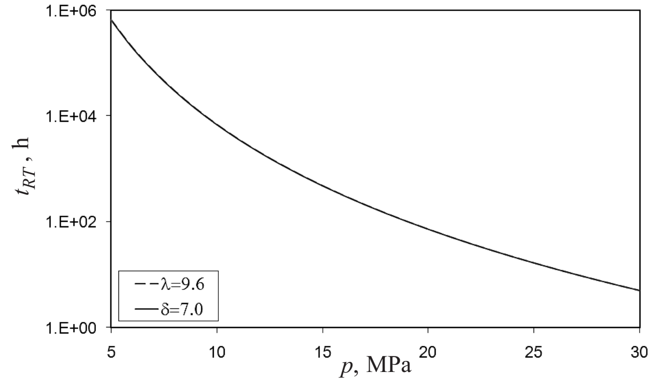

Fig. 3. The relationship between the internal pressure and the failure time for steel 20 with λ and δ. (Here and in Figs. 5, 7, and 9: solid and dashed lines practically coincide.)

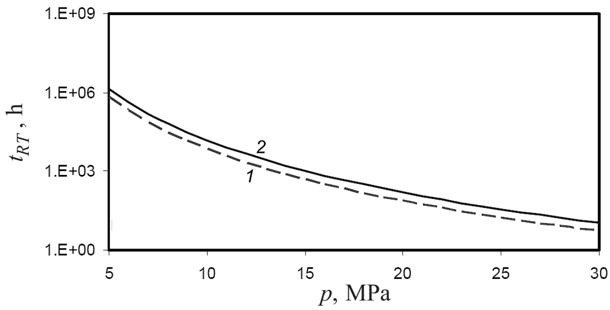

Fig. 4. The relationship between the internal pressure and the failure time for steel 20 with ξ, λ, and δ: (*1*) $\xi = 2.0$, (*2*) $\lambda + \delta + \xi$.

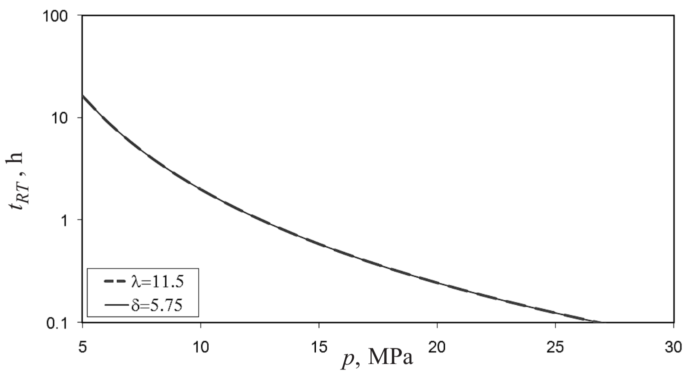

Fig. 5. The relationship between the internal pressure and the failure time for steel Kh18N10T with λ and δ: (*1*) $\lambda = 11.5$, (*2*) $\delta = 5.75$.

Steel 1Kh18N9T at 800 and 700°C (Figs. 7–10) manifests a high failure time with the same internal pressure, as compared to Figs. 1–6. The failure time for steel 1Kh18N9T at 800°C (Fig. 8) is very low compared with steel 1Kh18N9T 700°C (Fig. 10) at the same internal pressure. Steel 1Kh18N9T at 800°C manifests a very low failure time at high internal pressure (more than 2 MPa). The values of B, m, λ, δ, and ξ used in the calculation are summarized in Table 1.

Noteworthy is that, as follows from the structures of the equations derived Eqs. (29), (30), (32), and (33), the time to failure increases with decrease in

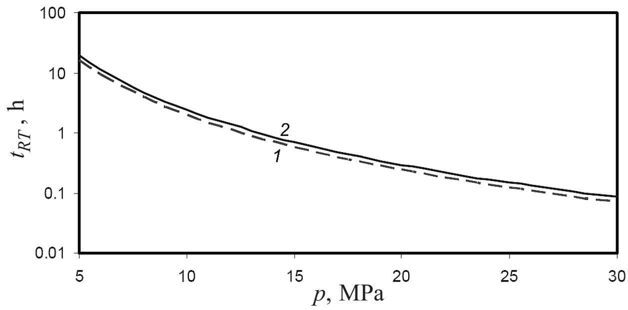

Fig. 6. The relationship between the internal pressure and the failure time for steel Kh18N10T with ξ, λ, and δ: (*1*) $\xi = 1.5$, (*2*) $\lambda + \delta + \xi$.

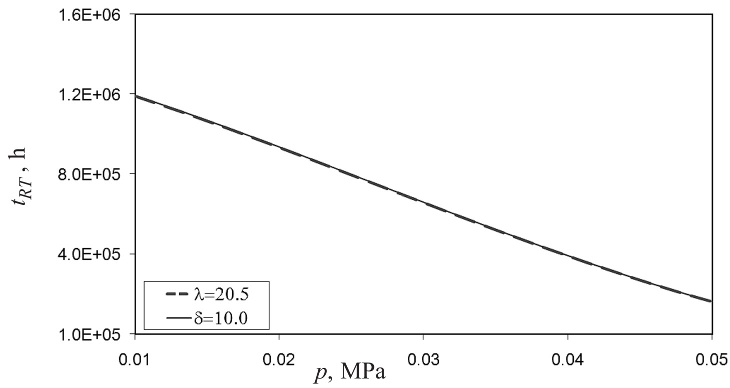

Fig. 7. The relationship between the internal pressure and the failure time for steel 1Kh18N9T (800°C) with λ and δ: (*1*) $\lambda = 20.5$, (*2*) $\delta = 10.0$.

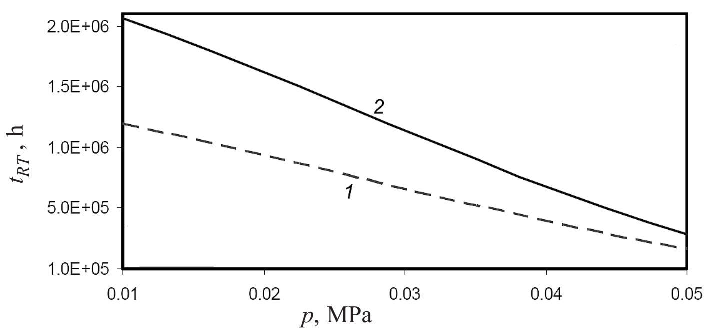

Fig. 8. The relationship between the internal pressure and the failure time for steel 1Kh18N9T (800°C) with ξ, λ, and δ: (*1*) $\xi = 1.65$, (*2*) $\lambda + \delta + \xi$.

thickness ratio λ and increase in the parameters δ and ξ, which specify the effects of the additional tensile force and bending moment.

Conclusions. The delayed-failure models constructed have allowed us to calculate the time to failure for thin-walled pipes under internal pressure combined with axial load and bending moment. There is a good agreement between the results of the present work in calculating the failure time and those obtained by Golub et al. [2]. We propose mathematical models that can be used to calculate the failure time for any rectilinear thin-walled pipes under internal pressure combined with axial load and bending moment. Results for failure time of pipes produced

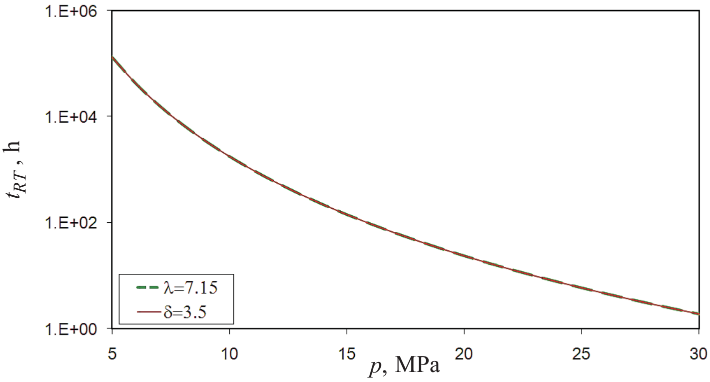

Fig. 9. The relationship between the internal pressure and the failure time for steel 1Kh18N9T (700°C) with λ and δ: (*1*) $\lambda = 7.15$, (*2*) $\delta = 3.5$.

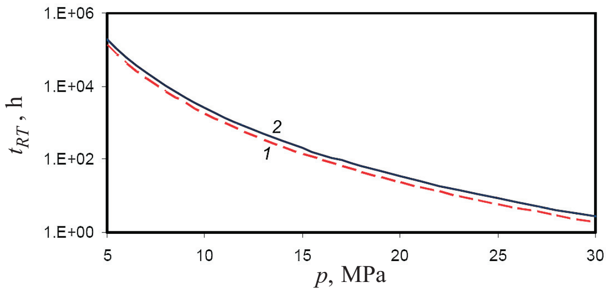

Fig. 10. The relationship between the internal pressure and the failure time for steel 1Kh18N9T (700°C) with ξ, λ, and δ: (*1*) $\xi = 0.9$, (*2*) $\lambda + \delta + \xi$.

from various steels are presented and compared with those results which are calculated using the analysis of Golub et al. [2]. In this paper, the equivalent stresses are used in the form of a mixed delayed-failure criterion relating the maximum normal stress and the intensity of tangential stresses and containing one material constant. The failure criterion chosen has been tested for a plane stress state with principal stresses of like sign. The present work can be applied to any material and thin-walled pipe of different dimensions, which makes the analysis a basic step for computer-aided creep failure analysis.

Резюме

Виконано розрахунок довговічності за умов повзучості для прямолінійних тонкостінних труб, що зазнають спільного навантаження внутрішнім тиском, розтяжною силою і згинальним моментом. Розрахунок часу до руйнування при повзучості проводили з використанням еквівалентних напружень, які визначаються згідно зі змішаним критерієм “відкладеного руйнування”, зв’язуючим максимальні нормальні напруження з інтенсивністю тангенціальних напружень. Отримані розрахункові результати добре узгоджуються з даними, наведеними в літературних джерелах для труб, що зазнають комбінованого навантаження. Запропонований підхід дозволяє розрахувати час до руйнування при повзучості для тонкостінних труб, що зазнають спільного навантаження внутрішнім тиском, розтяжною силою і згинальним моментом.

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