Strength of Pressure Equipment Components Taking into Account the Deterioration Concept

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Relationships for critical and allowable normal stress and shear stress were proposed, as well as the strength conditions with respect to critical state and with respect to allowable state, respectively, in the case of static loading and cyclic loading, taking into account the concept of deterioration. Values for the deterioration were obtained against experimental data for tubular specimens, with only one load, with two loads acting simultaneously, as well as for samples with rectangular cross-section.

Keywords: critical stress, deterioration, strength criteria, static and fatigue loading, pressure equipment.

The interest in the evaluation of structures deterioration is correlated with critical stresses, with strength criteria, with lifetime and with the remaining lifetime which features two aspects: the necessity to avoid the risk of catastrophic fracture (a safety issue) and the need to extend the structure lifetime (an economic issue).

The assessment of deterioration due to cracks in tubular specimens and, generally, in mechanical structures is an important issue in design and maintenance of chemical, petrochemical and power plant components. Accordingly many works was published about the crack-like defects, and their influence about the structure safety [1-17].

The origin of deterioration in pressure equipment (as well as in gas turbines, ships, aircraft, locomotives, bridges etc.) is often to be found in the flaws “impressed” during their manufacturing (casting, stamping, forging, welding, riveting etc.) and/or the cracks “born” during use, particularly as a result of overloading. If not detected through periodical examination and repaired, the cracks propagate down to failure.

For example, several relationships have been proposed for the deterioration by the cyclic loading of a cracked structure [6-10]. The cracks represent the macroscopic measure of the deterioration from the microscopic scale.

But the use of the concept of deterioration as to evaluate the life time or the strength of mechanical structures may be find in the papers [5, 9, 14, 18 -32]. On the other side the concept of deterioration has been used to define the critical stresses or the critical state of the matter, as in the papers [21, 22, 33 - 39], or of the critical state of living organisms [25, 26, 30, 31, 35], or of the environment [25, 41 - 43].

In this paper the concept of deterioration is used to calculate the strength of a cracked structure. One puts into evidence: - the interdependence between the critical stresses and the deterioration in the case of static and cyclic loading, respectively; - the value of several sample deterioration due to crack in the case of static loading.

Critical stresses of the sample with a crack

One consider a tubular or a plate sample (Fig. 1) with a crack of depth \(a\) and a length \(2c\).

a. Statically loaded sample

Due to the crack, the strength, namely the critical stress diminishes.

One considers the general case of the nonlinear, power law, behavior of the structure material, under monotonic loading with the normal stress, \(\sigma\), or with the shear stress, \(\tau\),

\[
\sigma = M_{\sigma} \cdot \varepsilon^k \quad \text{and} \quad \tau = M_{\tau} \cdot \gamma^k
\]

(1)

where \(\varepsilon\) is strain, \(\gamma\) is shear strain, \(M_{\sigma}\), \(M_{\tau}\), \(k\) and \(k_1\) are constants of material.

The critical normal stress of the cracked sample statical loaded according to V.V. Jinescu is [4; 5; 21],

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Fig. 1. Sample with cracks: a. tubular sample with crack on the outer surface; b. tubular specimen with circumferential semi-elliptical crack on the outer surface; c. rectangular cross-section sample.

\[ \sigma_{cr}(a;c) = \sigma_{cr} \left[ 1 - D_{\sigma}(a;c) \right]^{\frac{1}{n+1}}, \]  

(2)

where \( a = 1/k \) and \( \sigma_{cr} \) is the critical normal stress of the crackless sample. The deterioration due to crack in this case is,

\[ D_{\sigma}(a;c) = D_{\sigma}(c) \left[ 1 + D_{\sigma}(a) \right], \]  

(3)

where,

\[ D_{\sigma}(a_0) = (a/a_{cr})^{\frac{a+1}{2}}, \]  

(4)

\( a = a_0 \) is the current or instantaneous crack depth of the sample normal stress loaded (Fig. 1) and \( a_{cr} = a_{cr,cr} \) is the critical value of \( a_0 \).

The critical shear stress of the cracked sample statically loaded is,

\[ \tau_{cr}(a;c) = \tau_{cr} \left[ 1 - D_{\tau}(a;c) \right]^{\frac{1}{n+1}}, \]  

(5)

where \( a = 1/k \) and \( \tau_{cr} \) is the critical shear stress of the crackless sample. The deterioration due to crack is,

\[ D_{\tau}(a;c) = D_{\tau}(c) \left[ 1 + D_{\tau}(a) \right], \]  

(6)

where

\[ D_{\tau}(a_0) = (a/a_{cr})^{\frac{a+1}{2}}, \]  

(7)

\( a = a_0 \) is the current or instantaneous crack depth of the sample shear stress loaded; \( a_{cr} \) is the critical value of \( a_0 \).

b. Cyclically loaded sample

Cyclic loading is characterized by:

\[ \sigma_a = 0.5(\sigma_{\text{max}} - \sigma_{\text{min}}) \] - the normal stress amplitude; \( \sigma_{\text{m}} = 0.5(\sigma_{\text{max}} + \sigma_{\text{min}}) \) - the mean normal stress;

\[ \tau_a = 0.5(\tau_{\text{max}} - \tau_{\text{min}}) \] - the shear stress amplitude; \( \tau_{\text{m}} = 0.5(\tau_{\text{max}} + \tau_{\text{min}}) \) - the mean shear stress,

where \( \sigma_{\text{max}}, \sigma_{\text{min}} \) is the maximum and minimum normal stress, respectively; \( \tau_{\text{max}}, \tau_{\text{min}} \) is the maximum and minimum shear stress, respectively.

In the case of cyclically loaded sample \( \sigma_{cr} = \sigma_{-1}(N) \) is the fatigue normal strength for a crackless sample after fully reversed stress under \( N \) cycles. Similarly \( \tau_{cr} = \tau_{-1}(N) \) is the fatigue shear strength. If \( N > N_0 \), where \( N_0 \) is the basic number of cycles or the knee point of the fatigue curve (\( \sigma - N \) or \( \tau - N \)), \( \sigma_{cr} = \sigma_{-1} \) and \( \tau_{cr} = \tau_{-1} \), are the fatigue limits.

As to calculate the depth of the crack on may use the exponential crack growth equation [38; 39],

\[ a = a_e \exp\left( k_e \cdot N \right), \]  

(8)
where \( N \) is the number of accumulated cycles, \( k_u \) is a coefficient that characterizes the crack growth rate, which is related to the geometry specimen material and load [39]. \( a \) is the crack length and \( a_i \) is the initial crack length related to material defect or other microstructural features.

Under cyclic loading with normal stresses of a cracked sample, the critical stresses for a sample cyclically loaded according to V.V. Jinescu and al. [4] are,

\[
\sigma_{cr}(a,N) = \sigma_{cr}(N) \left[ 1 - \left( \frac{\sigma_m}{\sigma_{cr,m}} \right)^{n_1} \delta_{\sigma_m} - D_\sigma(a;c) \right]^{\frac{1}{n_1}} \]
\[
\tau_{cr}(a,N) = \tau_{cr}(N) \left[ 1 - \left( \frac{\tau_m}{\tau_{cr,m}} \right)^{n_1} \delta_{\tau_m} - D_\tau(a;c) \right]^{\frac{1}{n_1}},
\]

where \( \sigma_{cr,m} = \sigma_u \) (ultimate stress) or \( \sigma_y \) (yield stress), depending on whether fracture occurs when \( \sigma_y \leq \sigma_{max} < \sigma_u \) or when \( \sigma_{max} < \sigma_y \). Similarly for shear stress ( \( \tau_{cr,m} = \tau_u \) or \( \tau_y \)). \( \delta_{\sigma_m} = 1 \) if \( \sigma_m > 0 \) and \( \delta_{\sigma_m} = -1 \) if \( \sigma_m < 0 \). Similarly \( \delta_{\tau_m} = 1 \) if \( \tau_m > 0 \) and \( \delta_{\tau_m} = -1 \) if \( \tau_m < 0 \).

c. The use of critical stresses

As to use the critical stresses calculated with the above relationships ((2); (5); (9)), the deterioration ((3) and (6)) must be calculated. These critical stresses are used in connection with the principle of critical energy [14; 18; 21; 37], applied here to pressure equipment design.

- For static loading:
  - the strength conditions are [18; 19],

\[
P(\sigma) < 1 \text{ or } P(\tau) < 1,
\]

where the specific energy participations with respect to the static critical state due to loading with normal stress, \( \sigma \), and with shear stress, \( \tau \), respectively, are:

\[
P(\sigma) = \left( \sigma / \sigma_{cr}(a;c) \right)^{n_1} \text{ or } P(\tau) = \left( \tau / \tau_{cr}(a;c) \right)^{n_1}.
\]

The stresses \( \sigma \) and \( \tau \) are the effective applied normal stress and effective applied shear stress, respectively;

- the allowable conditions are, as follows,

\[
P'(\sigma) \leq 1 \text{ or } P'(\tau) \leq 1,
\]

where the specific energy participations with respect to allowable state in the case of static loading, are:

\[
P'(\sigma) = \left( \sigma / \sigma_{al}(a;c) \right)^{n_1} \text{ or } P'(\tau) = \left( \tau / \tau_{al}(a;c) \right)^{n_1}.
\]

The allowable stresses are defined as:

\[
\sigma_{al}(a;c) = \sigma_{cr}(a;c) / c_\sigma \text{ and } \tau_{al}(a;c) = \tau_{cr}(a;c) / c_\tau,
\]

where \( c_\sigma > 1 \) and \( c_\tau > 1 \) are coefficients of safety with respect to allowable state.

- For cyclically loading:
  - the strength conditions are:

\[
P(\sigma_a) < 1 \text{ or } P(\tau_a) < 1,
\]

where the specific energy participations with respect to critical state, in the case of cyclic loading are [14]:

\[
P(\sigma_a) = \left( \sigma_a / \sigma_{cr,a}(a;N) \right)^{n_1} \text{ or } P(\tau_a) = \left( \tau_a / \tau_{cr,a}(a;N) \right)^{n_1}.
\]

The critical stresses \( \sigma_{cr,a}(a;N) \) and \( \tau_{cr,a}(a;N) \) calculates with the relationships (8):

- the allowable conditions are:
where the specific energy participation with respect to allowable state are as follows:

\[ P^*(\sigma_a) = \left( \frac{\sigma_a}{\sigma_{al}(a; c)} \right)^{1+\epsilon} \]  \text{or}  \[ P^*(\tau_a) = \left( \frac{\tau_a}{\tau_{al}(a; c)} \right)^{1+\epsilon}. \]

In relationships (17) the allowable normal stress and the allowable shear stress, respectively, are:

\[ \sigma_{al}(a; c) = \frac{\sigma_{cr}(a; N)}{c_{\sigma}}, \text{and} \quad \tau_{al}(a; c) = \frac{\tau_{cr}(a; N)}{c_{\tau}}, \]

where \( c_{\sigma} > 1 \) and \( c_{\tau} > 1 \) are coefficients of safety with respect to allowable state.

The deterioration due to crack depends on crack shape, crack depth and crack length. As to use the relationships established in the paper, the deterioration due to crack must be obtained.

The deterioration of tubular samples

The deterioration due to only one load

We further analyze the loads: under internal pressure, \( p \), and separately under axial force, \( F \). In all cases, the loading occurred down to the yield point, the latter being considered the limit stress \( (\sigma_{cr} = \sigma_y) \).

a. In cylindrical shells under internal pressure, the maximum stress is the hoop or circumferential stress,

\[ \sigma_0 = p \cdot \left( R_m / s \right). \]

where \( R_m = 0.5(R_e + R_i) \) is the mean radius of the section and \( s \) is the wall thickness. Consequently, with \( \sigma = \sigma_0 \) and \( \sigma_{cr} = \sigma_{0,cr} \), for a static loaded shell, one gets

\[ \frac{p_{cr}(a; c)}{p_{cr}} = \frac{\sigma_{cr}(a; c)}{\sigma_{cr}}. \]

Figure 2 shows (processed according to [1]) the dimensionless ratio variation \( \sigma_{cr}(a; c)/\sigma_{cr} \) (where \( \sigma_{cr} = \sigma_y \)) depending on the dimensionless variable \( c / \sqrt{R_m \cdot s} \), for four values of the reported crack depth \( a/s = 0.25; 0.5; 0.75 \) and 1.0.

From relation (2) for \( \sigma < \sigma_y \) (linear-elastic behavior, \( k = 1 \) \( a + 1 = 2 \)), one gets the equation of deterioration,

\[ D_{\sigma}(a; c) = 1 - \left[ \frac{\sigma_{cr}(a; c)}{\sigma_{cr}} \right]^2. \]

![Fig. 2. a. Tubular specimens with axial rectangular cracks on the inner surface pressure loaded. b. Dependency of \( \sigma_{cr}(a; c)/\sigma_{cr} \) ratio for a tubular specimens (a) on reported length of axial crack \( c / \sqrt{R_m \cdot s} \), for four values of the \( a/s \) ratio (Processed according to [1]).](image)

From equation (21), based on the experimental data in Figure 2, there have been obtained the values of \( D_{\sigma}(a; c) \) shown in Figure 3. a. From equation (3) one determines the influence of crack length via the damage component,
wherein  \( D_a(a) \) was calculated with equation (4), where the material behavior under load \( \{\sigma < \sigma_y\} \) being linear-elastic, \( k = 1 \) and \( \alpha = 1 \). The variation of \( D_c(c) \) is shown in Figure 3, b, depending on the ratio \( c/\sqrt{R_m \cdot s} \) for four values of the reported depth \( a/s \).

\[
D_a(a) = D_a(a; c)/(1 + D_a(a)),
\]

(22)

\( \sigma \) and \( \sigma_{cr} \) being the yield stress.

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(3)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(4)

\[
\sigma_{cr}(a; \theta) = \frac{\sigma_{cr}}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(5)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(6)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(7)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(8)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(9)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(10)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(11)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(12)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(13)

\[
D_c(c) = \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right).
\]

(14)

The behavior of the tubular specimen material has been considered to be ideally-plastic, i.e. the maximum stress is the yield stress. Consequently, in this case \( k = 1 \) and \( \alpha = 1 \), from eq. 2 results,

\[
D_a(a; \theta) = \left( \frac{\sigma_{cr}(a; \theta)}{\sigma_{cr}} \left( \frac{a}{s} \right) \right)^2.
\]

(23)

From equation (3) one obtains,

\[
D_a(\theta) = \frac{D_a(a; \theta)}{1 + D(a)}.
\]

(24)

The variation of \( D_a(a; \theta) \) calculated with eq. (23) and of \( D_a(\theta) \) calculated with eq. (24) on the basis of the results inscribed in Fig. 4, b were represented in Figure 5, a, and b.

**Fig. 3.** Dependency of deterioration \( D_a(a; c) \) on the \( a/s \) ratio for four values of the reported crack axial length (a) and deterioration \( D_c(c) \) depending on \( c/\sqrt{R_m \cdot s} \) for four values of ratio \( a/s \) (b), in the case of internal pressure loading.

**Fig. 4.** Tubular specimen with circumferential semi-elliptical crack on the inner surface (a) under axial force \( F \) and the dependence of ratio \( \sigma_{cr}(a; \theta)/\sigma_{cr} \) on ratio \( a/s \), with three values of the dimensionless angle \( \theta/\pi \).
The deterioration due to effect superposition of two loads

In the case of specimens from materials considered ideal-plastic \((\alpha = 1)\) with an axial crack, the critical state under double load \(S_1\) and \(S_2\) results from the general relation \([14; 18]\),

\[
\left( \frac{S_{1,cr}(a; c)}{S_{1,cr}} \right)^2 + \left( \frac{S_{2,cr}(a; c)}{S_{2,cr}} \right)^2 = 1 - D(a; c).
\]  

(24)

where \(S_{1,cr}\) and \(S_{2,cr}\) are the critical loads of the crackless specimen under load \(S_1\) and load \(S_2\) respectively, whereas \(S_{1,cr}(a; c)\) and \(S_{2,cr}(a; c)\) are the critical loads of the cracked specimen under load \(S_1\), and \(S_2\) respectively.

For specimens with circumferential cracks, \(c\) in relationship (25) is replaced by \(\theta\). This general relationship is further applied to two particular loading cases.

- **Loading under internal pressure and bending moment** (Fig. 6). For a tubular specimen with circumferential crack (Fig. 1, b), the relationship for the calculation of damage is obtained from equation (25) in the form of

\[
D(a;\theta) = 1 - \left[ \left( \frac{p_{cr}(a;\theta)}{p_{cr}} \right)^2 + \left( \frac{M_{b,cr}(a;\theta)}{M_{b,cr}} \right)^2 \right].
\]  

(26)

By using relation (26) on the basis of three pairs of values of the reported loads, represented in Figure 7, the values of the damages are listed in Table 1.
Figure 7 shows the dependence of $p_{cr}(a;\theta)/p_{cr}$ and $M_{bc,cr}(a;\theta)/M_{bc,cr}$, processed according to [2]. The last column of the Table 1 features the average value of the damage.

The deterioration due to cracks in several rectangular cross-section sample (Figure 8) were experimentally obtained. Specimens with fully penetrated cracks, perpendicular to the specimen axis, were tested.

The sample material crackless is characterized by $\sigma_y = 295\text{MPa}$, $\sigma_u = 440\text{MPa}$ and $\alpha = 2.339$ [20]. The ultimate stress of cracked sample depends on the crack sizes $2c$ and $2c_1$. The size $2c = 23 \text{ mm}$ was the same for all cracks, but $2c_1$ was different: $2c_1 = 4.5, 5$ and $6.5 \text{ mm}$.

For all sample $a = s = 4 \text{ mm}$. The values of deterioration were calculated with the relationship (2) where from,

$$D_\sigma(a;c)=1-(\sigma_u(a;c)/\sigma_u)^{n+1},$$

(27)

where $\sigma_{cr}$ was replaced by $\sigma_u$ and $\sigma_{cr}(a;c)$ - by $\sigma_u(a;c)$.

The experimental data and the calculated $D_\sigma(a;c)$ values have been inscribed in the Table 2.

### Table 1
THE DAMAGE VALUES FOR THE LOADING IN FIGURE 6, WITH THREE PAIRS OF VALUES $p_{cr}(a;\theta)/p_{cr}$ AND $M_{bc,cr}(a;\theta)/M_{bc,cr}$, IF $a/s=0.75$ AND $\theta/\pi=0.40$, CALCULATED WITH EQUATION (26) ON THE BASIS OF THE DATA IN FIGURE 7

| $p_{cr}(a;\theta)/p_{cr}$ | $M_{bc,cr}(a;\theta)/M_{bc,cr}$ | $D(a;\theta)$ | $D(a;\theta)_{\text{mean value}}$ |
|---------------------------|-------------------------------|--------------|----------------------------------|
| 0.3578                    | 0.7287                        | 0.3410       | 0.3804                           |
| 0.5450                    | 0.5513                        | 0.3991       |                                  |
| 0.6887                    | 0.3544                        | 0.4010       |                                  |

### Table 2
EXPERIMENTAL RESULTS AND THE DETERIORATION CALCULATED WITH EQ. (27)

| The crack sizes:          | $\sigma_u(a;c) \text{MPa:}$ | $D_\sigma(a;c)$ |
|----------------------------|----------------------------|----------------|
|                            | (mean value)               |                |
| $2c=23 \text{ mm}$         | 192.82                     | 0.93634        |
| $2c_1=6.5 \text{ mm}$      |                            |                |
| $2c=23 \text{ mm}$         | 215.45                     | 0.9078         |
| $2c_1=5 \text{ mm}$        |                            |                |
| $2c=23 \text{ mm}$         | 254.09                     | 0.8401         |
| $2c_1=4.5 \text{ mm}$      |                            |                |
The deterioration decreases with the size of $2c_1$ increase.

Conclusions

The objective of the paper was to introduce the concept of deterioration in the calculus of the ultimate (critical) stress of pressure equipment with cracks.

Relationships for critical normal stress and for critical shear stress of a cracked component have been proposed (((2) and (5))). Strength criteria were proposed for statically (10) and for cyclically (14) loaded components. At the same time relationship for the allowable strength criteria were proposed, for static loading (12) and for cyclic loading (16).

The critical stresses as well as the allowable stresses, depends on the deterioration produced by the crack. On this account for several samples the deterioration produced by cracks were calculated on the basis of experimental data in the case of only one load (tubular sample and sample with rectangular section), and in the case of two different loads (tubular sample).

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Manuscript received: 23.05.2019