CRITICAL STRESSES, CRITICAL GROUPS OF STRESSES AND STRENGTHS OF TUBULAR STRUCTURES WITHOUT AND WITH CRACKS

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One analysis the strength of tubular samples and tubular junctions without and with cracks. Non-linear behaviour is considered. Strength calculation has been proposed for: – un-cracked and cracked tubular specimens mixed-mode loaded; – un-cracked and cracked tubular joints mixed-mode loaded. The obtained relationships for strength calculation take into account the deterioration, the residual stress, as well as the scattering of mechanical characteristics involved in the loading process. The relationships proposed in the paper were verified against results reported in literature.

Keywords: mixed-mode loading; critical stresses; crack; tubular sample; tubular branch junction.

1. Introduction

The calculation of the deterioration and failure stress of cracked tubular sample is useful in structural integrity assessment of pressure equipment, particularly of piping, as well as for tubular mechanical structures.

The plastic limit loads of cylindrical tubes have been analyzed in the papers [1-8], which cover the case of cracked pipes having mean radius-to-thickness ratios greater than five, as well as less than five for thick-walled pipes [9].

In general, the limit load was arbitrarily defined as the load which provides yielding (local or global). For example, the papers [8] and [10] provides plastic limit load solutions of cylinders with part-through surface cracks, and under combined axial tension, internal pressure and global bending, using elastic-perfectly plastic material behavior [8]. Both circumferential and axial cracks, external and internal cracks, are considered. On the other side the paper [9] presents plastic limits loads parameters for cracked thick-walled pipes with axial and circumferential through-wall and surface cracks. In the plastic limit analyses,

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generally, the materials were assumed to be elastic–perfectly plastic. In reality the materials behavior beyond the yield stress is non-linear.

This paper presents a non-linear, deterioration dependence, of the critical stresses and critical loading parameters for tubular sample and branch pipe junction without and with cracks, mixed – mode loaded. Both, axial and circumferential surface cracks are considered. The deterioration is calculated for thin-walled cylinders under a single loading (axial force, global bending or internal pressure), as well as under combined loading (axial force and global bending, internal pressure and global bending, internal pressure and axial force).

2. State - of - the - art for cracked structure sample strength calculation

The failure condition of materials with cracks is obtained by superposing crack participation and stress, σ, participation. For example, Morozov has proposed the following criterion of rupture [11; 12],

$$\left(\frac{K_I}{K_{Ic}}\right)^2 + \left(\frac{\sigma}{\sigma_{cr}}\right)^2 = 1, \tag{1}$$

where K_I is the stress intensity factor in the case of mode I failure; K_{Ic} is the toughness; σ_{cr} is the critical stress of the specimen without cracks (may be the yield stress or the ultimate stress).

For flat plates with cracks, under the same stress σ, the ratio

$$K_I / K_{Ic} = Y \cdot \sigma \cdot \sqrt{\pi \cdot c} \Big/ \left(Y \cdot \sigma \cdot \sqrt{\pi \cdot c_{cr}}\right) = \sqrt{c / c_{cr}}, \tag{2}$$

where $2c_{cr}$ is the critical crack length under stress σ. The last two relations yield the critical stress for a cracked specimen (eq. (3) in Table 1).

The bending stress in a welded structure with a crack of depth a is given by eq. (4) as it was reported in [13; 14], where $\sigma_b(a)$ and σ_b are the bending stress component for cracked and un-cracked joints, respectively; t - is the structure thickness. Andreikiv [15] proposed the failure criterion (5), where ε, ε_{cr} is the effective and the critical strain, respectively, while m is the exponent determined experimentally. From equations (2) and (5) one obtains the critical specific strain of the cracked specimen given by eq. (6).

Table 1

Mechanical characteristics for cracked sample

$\sigma_{cr}(c) = \sigma_{cr} \cdot \left(1 - c/c_{cr}\right)^{0.5}$	(3)
$\sigma_b(a) = \sigma_b \cdot \left(1 - a/t\right)$	(4)

$\left(\frac{K_I}{K_{Ic}}\right)^{2m} + \left(\frac{\varepsilon}{\varepsilon_{cr}}\right)^{m} = 1$	(5)
$\varepsilon_{cr}(c) = \varepsilon_{cr} \cdot \left[1 - \left(\frac{c}{c_{cr}}\right)^{m}\right]^{\frac{1}{m}}$	(6)

3. A general proposal of strength calculation in the case of non – linear behavior

Let us consider the nonlinear, power law, behavior of the specimen, under normal stress, σ, and shear stress, τ,

$$\sigma = M_\sigma \cdot \varepsilon^k \text{ and } \tau = M_\tau \cdot \gamma^{k_1}, \tag{7}$$

where ε is the strain; γ is the shear stress; M_σ, M_τ, k and k_1 are material constants.

In recent works [16 - 18], on the basis of principle of critical energy (PCE), were proposed the following relations for the critical stresses of specimens with cracks:

$$\left.\begin{aligned} \sigma_{cr}(a;c) &= \sigma_{cr} \cdot \left[1 - D(a_\sigma;c)\right]^{\frac{1}{\alpha+1}}; \\ \tau_{cr}(a;c) &= \tau_{cr}\left[1 - D(a_\tau;c)\right]^{\frac{1}{\alpha_1+1}}, \end{aligned}\right\}, \tag{8}$$

where the total deterioration $D(a_\sigma;c)$ depends on the crack depth, $a \equiv a_\sigma$, and the crack length $2c$ in the direction perpendicular to the normal stress σ, while deterioration $D(a_\tau;c)$ depends on the depth of the crack, $a \equiv a_\tau$, and the crack length $2c$ in the direction of shear stress τ.

The relations proposed in the literature [8-10] for yield loading in tubular specimens with cracks, generally can be written as in eq. (8), namely

$$Y_L = Y_y \cdot \left[1 - (D(a;c))^{0.5}\right], \tag{9}$$

where Y_L is the limit load of the cracked tubular specimen; Y_y is the limit load of the crackless tubular specimen.

4. Strength of un-cracked tubular sample mixed – mode loaded

Piping systems, as well as pressure equipment with nozzles, are always subjected to combined pressure and loadings (bending moment, torsional moment, forces…), thus the studies need to be carried out of combined loadings. Generally some mechanical structures and their components are stressed by simultaneous or successive applied loads. These loads together represent a loading group. If under group of loads the critical state is achieved, the group is named critical group of loads.

a. *Un-cracked tubular structures. General case.* Consider a certain structure whose nonlinear material behaves according to relations (7). Under a group of loads such as $F_i\ (i=1;2;\ 3...\ n)$, the total participation of specific energies introduced into the structure material is written as [19],

$$P_T = \sum_i \left(F_i / F_{i,cr} \right)^{\alpha+1} \cdot \delta_F , \qquad (10)$$

where $F_{i,cr}$ is the critical value of the generalized load F_i, while $\delta_F = 1$ if F_i acts in the direction of the process and $\delta_F = -1$, if it opposes the evolution of the process. The PCE introduces the term *critical participation* $P_{cr}(t)$, a time (t) dependent variable [20],

$$P_{cr}(t) = P_{cr}(0) - D_T(t) - P_{res} , \qquad (11)$$

where [21],

$$D_T(t) = \sum_i D_i(t), \qquad (12)$$

is the total deterioration, a dimensionless parameter time dependent, a sum of the partial deteriorations, $D_i(t)$, due to different loads/actions (corrosion, aging, erosion, crack, creep, fatigue, hydrogen, neutrons etc…).

$P_{cr}(0)$ is the value of $P_{cr}(t)$ at $t = 0$; it takes values between $P_{cr,\min}(0) > 0$ and $P_{cr,\max}(0) \le 1$, depending on the scatter of the material mechanical characteristics involved in the loading process. If the mechanical characteristics are deterministic values, than $P_{cr}(0) = 1$. The residual stress (σ_{res}) influence is introduced through the participation of residual stress specific energy, P_{res} [20].

For crackless structures and no residual stresses $P_{cr}(t) = P_{cr}(0)$; the critical state is reached when $P_T = P_{cr}(0)$. Consequently, the group of static loads becomes critical if,

$$\sum_i \left(F_i / F_{i,cr} \right)^{\alpha+1} \cdot \delta_F = P_{cr}(0). \qquad (13)$$

b. If a tubular structure is under loads (Fig. 1) p (pressure), F (force) and M_b (bending moment) relation (13) becomes,

$$\left(\frac{p}{p_{cr}} \right)^{\alpha+1} + \left(\frac{F}{F_{cr}} \right)^{\alpha+1} \cdot \delta_F + \left(\frac{M_b}{M_{b,cr}} \right)^{\alpha+1} \cdot \delta_M = P_{cr}(0), \qquad (14)$$

where $\delta_M = 1$ in the section where M_b causes elongation and $\delta_M = -1$ in the section where M_b produces compression.

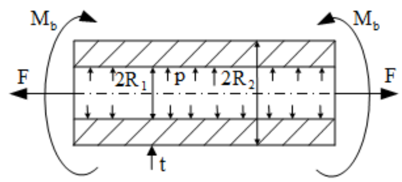

Fig. 1.Tubular specimen loaded with internal pressure, *p*, tensile axial force, *F*, and bending moment M_b.

In interpreting the experimental data, in general, one can see that $P_{cr}(0) \neq 1$ is a random value. Consequently, the critical group is not a single value but a stochastic distribution between $\mathrm{P}_{\mathrm{cr,min}}(0)$ and $P_{cr,\max}(0)$, depending on the probability of structure material failure. These justify the scatter of experimental data. Several test points may be outside the upper $(P_{cr,\max}(0))$ and lower $(P_{cr,\min}(0))$ bounds. This may be caused by inaccuracy of material property and experimental measurement. The proposed criterion (14) for critical group of loads is an effective criterion for the fracture of defect – free tubular sample.

c. *For simultaneous loading with p and M_b* equation (14) becomes,

$$\left(\frac{p}{p_{cr}}\right)^{\alpha+1} + \left(\frac{M_b}{M_{b,cr}}\right)^{\alpha+1} \cdot \delta_M = P_{cr}(0). \tag{15}$$

For linear-elastic loading $(\sigma_{\max} \leq \sigma_y)$, $\alpha = 1/k = 1$. If one adds to the above $P_{cr}(0) = 1$ corresponding to the deterministic values of the mechanical characteristics, then the relationship (15) is converted to,

$$\left(\frac{p}{p_{cr}}\right)^{2} + \left(\frac{M_b}{M_{b,cr}}\right)^{2} = 1. \tag{16}$$

This relationship was obtained on experimental data with tube specimens made from carbon steel (St 20) and austenitic steel (12X18H10T). For critical parameters the following relations have been proposed [23],

$$p_{cr} = \frac{2}{\sqrt{3}} \cdot \sigma_{0.2} \cdot \ln\beta \quad \text{and} \quad M_{b,cr} = 2 \cdot \sigma_{0.2} \cdot S_s, \tag{16}$$

which is the yield pressure and the yield bending moment, respectively, i.e. the values of those loads that determine the transition to a plastic state of the section to the outer radius, where the maximum stress becomes equal to the yield stress.

Stress $\sigma_{0.2} = \sigma_y$ is the yield stress corresponding to a residual strain of 0.2%; S_s is the static moment of the area section and $\beta = R_2/R_1$ (Fig. 1)

d. *For simultaneous loading with axial force and bending moment,* if force F produces elongation $(\delta_F = 1)$, then in the section where $\sigma_b > 0$ $(\delta_M = 1)$ eq. (14) becomes,

$$\left(\frac{F}{F_{cr}}\right)^{\alpha+1} + \left(\frac{M_b}{M_{b,cr}}\right)^{\alpha+1} = P_{cr}(0). \tag{17}$$

e. *For simultaneous loading under internal pressure and tensile axial force*, relation (14) becomes,

$$\left(\frac{p}{p_{cr}}\right)^{\alpha+1} + \left(\frac{F}{F_{cr}}\right)^{\alpha+1} = P_{cr}(0). \tag{18}$$

In the eqs. (17) and (18), for a linear-elastic material one replaces $\alpha = 1/k = 1$ and for deterministic values of the mechanical characteristics of the material, one replaces $P_{cr}(0) = 1$.

5. Strength of cracked tubular samples mixed – mode loaded

In the case of mechanical samples with cracks the deterioration $D_T(t) \neq 0$. If the damage is caused by a crack with depth a and length $2c$, then $D_T(t) \equiv D(a;c)$ or $D_T(t) \equiv D(a;\theta)$, where $2c$ is the length of the axial crack, while 2θ is the angle at the centre of the circumferential crack on the tube element (Fig. 2). For structures with cracks one should replace $P_{cr}(0)$ with $P_{cr}(t) = [P_{cr}(0) - D(a;c)]$ in all previous relationships.

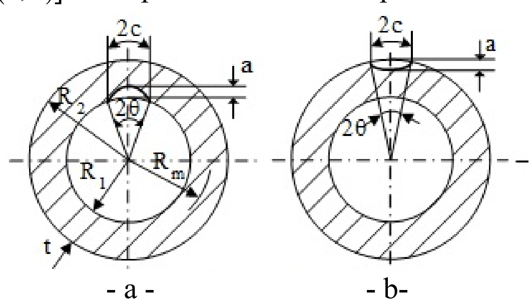

Fig. 2. Circumferential cracks in tubular samples with semi-elliptical cross section (a; b) at inner surface (a) and outer surface (b).

For the linear-elastic behavior of the structure material $\alpha = 1/k = 1$, in the section under the highest load, relations (15), (17) and (18) become:

$$\left.\begin{aligned}&\left(\frac{p}{p_{cr}}\right)^2+\left(\frac{M_b}{M_{b,cr}}\right)^2=P_{cr}(0)-D(a;\theta);\\&\left(\frac{F}{F_{cr}}\right)^2+\left(\frac{M_b}{M_{b,cr}}\right)^2=P_{cr}(0)-D(a;\theta);\\&\left(\frac{p}{p_{cr}}\right)^2+\left(\frac{F}{F_{cr}}\right)^2=P_{cr}(0)-D(a;\theta),\end{aligned}\right\}\qquad(19)$$

where one considered: - tensile axial force ($\delta_F=1$); - the sections where the bending moment produces tensile stresses ($\delta_M=1$). The right member in these relationships takes values ranging

$$P_{cr,max}(t)=P_{cr,max}(0)-D(a;\theta)\quad\text{and}\quad P_{cr,min}(t)=P_{cr,min}(0)-D(a;\theta)\qquad(20)$$

Any of the eqs. (19) describes a quarter of a circle with radius $[P_{cr}(0)-D(a;\theta)]^{0.5}$.

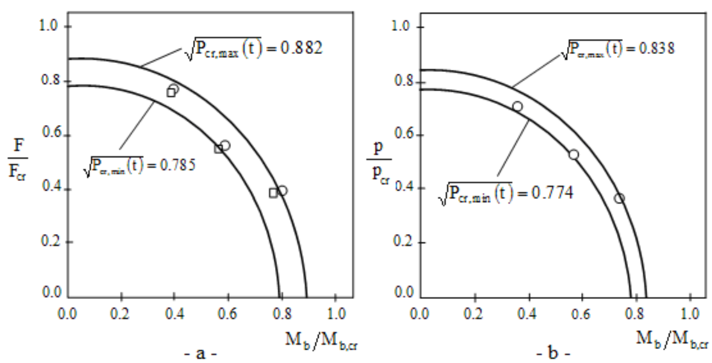

Fig. 3. The interdependence between F/F_{cr} and $M_b/M_{b,cr}$ for a tube specimen, when $a/t=0.1$ and $\theta/\pi=0.1$ (a) and between p/p_{cr} and $M_b/M_{b,cr}$ in case $a/t=0.75$ and $\theta/\pi=0.4$ (b) Curves are drawn with relations (19). Experimental points were taken from work [8].

The interpretation of the experimental data [8] on tubular specimens based on relations (19) emphasizes the dependence of the kind represented in Fig. 3. For example, with loading featuring an axial force and bending moment (Fig. 3, a), the points fall between the circles with radius $\sqrt{P_{cr}(t)}=0.785$ and 0.882. With loading featuring an internal pressure and bending moment (Fig. 3, b) the experimental points fall between circles of radius $\sqrt{P_{cr}(t)}=0.774$ and 0.838. As shown in figure 3 the results agree very well eq. (19), which takes into account the crack depth (a/t) and the crack extension (θ/π).

The general criterion (14), obtained in the paper, where $P_{cr}(0)$ is replaced by $P_{cr}(t)$ and its particular cases (19) are able to take into account the influence of deterioration upon the value of the critical participation.

6. Strength of tubular branch junction loaded with internal pressure and bending moment

A branch junction (Fig. 4) was assumed to be subjected to combined pressure and bending. The mean radius of the pipe is denoted $R_m = 0.5(R_1 + R_2)$ and that of the branch pipe by $r_m = 0.5(r_1 + r_2)$.

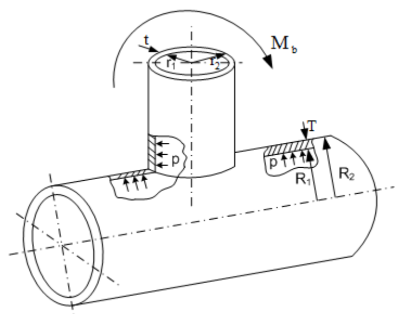

Fig. 4. The branch pipe junction used in the paper [22].

a. *Un-cracked tubular branch junction*. For un-cracked branch [24] with a medium bore branch with $r/R = 0.27$ ($r = 59.5$ mm, $R = 222.5$ mm, $t = 8$ mm; $T = 20$ mm) the limit load is given by the circular interaction curve, described by eq. (16). In this eq. $p_{cr} = p_L(M = 0)$ and $M_{b,cr} = M_L(p = 0)$ denote the plastic limit loads for un-cracked branch junction under internal pressure and under bending, respectively. An elastic-perfect plastic material was assumed $(\sigma_{max} \le \sigma_y)$.

For large bore branch $(r/R = 0.63)$ after Meyong et al. [24] the interaction of pressure and bending is slightly higher than the parabolic interaction curve described by the eq.

$$\left(\frac{p}{p_{cr}}\right)^2 + \frac{M_b}{M_{b,cr}} = 1, \tag{21}$$

but lower than the circular interaction given by eq. (16).

b. *Cracked tubular branch junction*. It is important to have information on limit loads of cracked branch junctions in structural integrity assessment of piping components. The paper [24] describes the effect of cracks on the plastic limit loads of branch junctions under combined pressure and bending. Limit loads for single loading [24] of a branch junction: - un-cracked branch, depending on the branch geometry, collapse can occur either in the intersection or in the pipe; - at through – wall cracks the limit loads decrease almost with increasing relative crack length.

The problem is to correlate the limit load with the deterioration due to crack, in the case of a single load, as well as in the case of combined loads. This may be obtained by using the eqs. (19). The relevant dimensions of the branches reported by Myeong et al are inscribed in Fig. 5 [24].

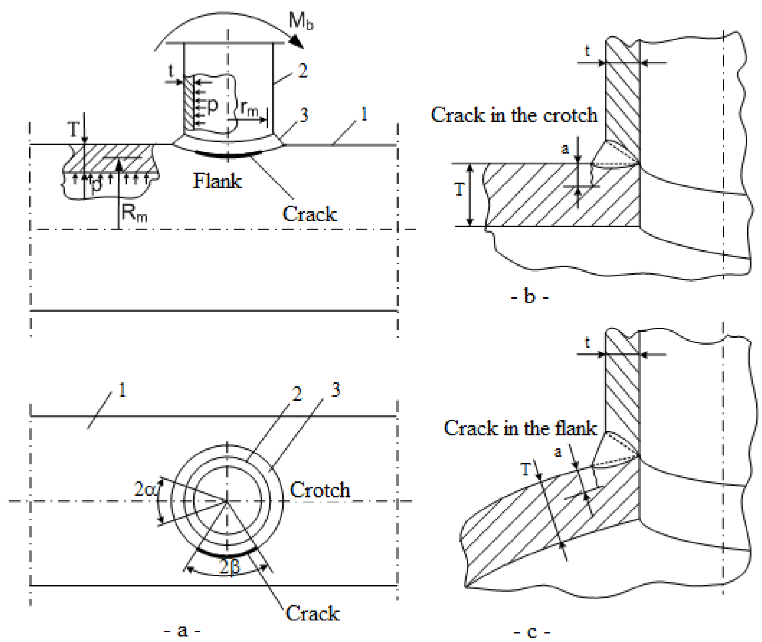

Fig. 5. A branch with a crack in the lower weld toe: 1 – run pipe; 2 – branch pipe; 3 – weld.

The limit loads as dimensionless variables (p/p_L and M_b/M_{bL}) for through – wall cracked branch junctions under combined pressure and in-plane bending to the branch pipe, for the crack in the crotch of the weld toe, is shown in Fig. 6, a. The curves correspond approximately to $\sqrt{P_{cr}} = 0.8$ and 0.9. By comparing these curves with the first eq. (19) one obtains $P_{cr} = P_{cr}(0) - D(a;\alpha)$.

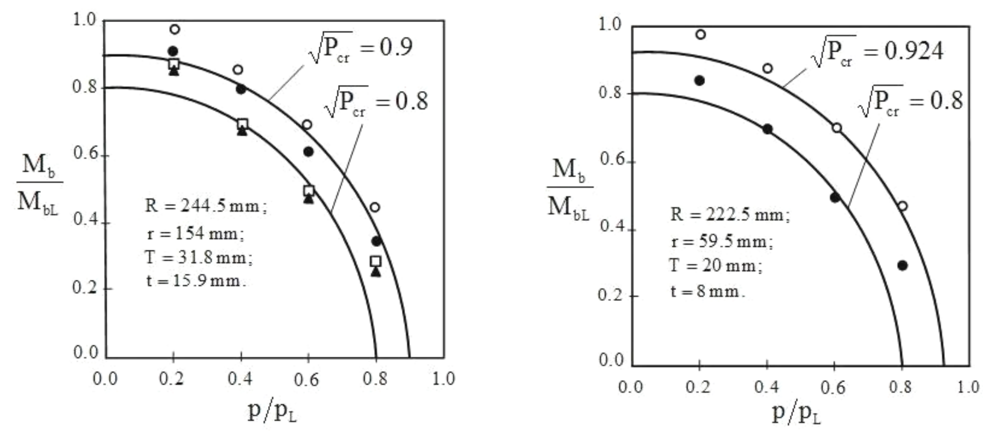

Fig. 6. The correlation: a - between M_b/M_{bL} and p/p_L for through wall cracked branch ($a/T = 1$) in the case of crack located in the lower weld toe on the crotch (Fig. 5): $\alpha/\pi = 0.125$ (○); $\alpha/\pi = 0.25$ (●); $\alpha/\pi = 0.44$ (□); $\alpha/\pi = 0.50$ (▲) [24];
b - between M_b/M_{bL} and p/p_L for surfaced cracked branches in the case of crack located in the lower weld toe flank ($\beta/\pi = 0.50$): $a/T = 0.50$ (○); $a/T = 1.0$ (●) [24].
The curves drawn with the first eq. (19).

With $P_{cr}(0) = 1$ for through wall ($a = T$) crack, one obtains the following mean values of deteriorations (Fig. 6, a):

$D(a;\alpha) = 1 - (0.9)^2 = 0.19$ - in the case of $P_{cr} = 0.9$, when $\alpha/\pi = 0.125 \ldots 0.25$;

$D(a;\alpha) = 1 - (0.8)^2 = 0.36$ - in the case of $P_{cr} = 0.8$, when $\alpha/\pi = 0.44 \ldots 0.50$.

Because $a/T = 1$, there results $D(a;\alpha) \equiv D(\alpha)$; the deterioration depends only on the crack length expressed through the angle 2α (Fig. 5, a).

In the case represented in Fig. 6, b where the crack is on the toe flank (Fig. 5, c), the correlation between the reported pressure, p/p_L, and reported bending moment, M_b/M_{bL}, may be done with the first eq. (19) with $\sqrt{P_{cr}} = 0.80$ and 0.924. For the crack length corresponding to angle $2\beta = \pi$ the deterioration $D(a;\beta) \equiv D(a)$ depends only on the crack depth (a/T). Consequently, the deteriorations are:

$D(a;\beta) = 1 - (0.80)^2 = 0.36$ for $\sqrt{P_{cr}} = 0.80$, where a/T = 1.0;

$D(a;\beta) = 1 - (0.924)^2 = 0.1462$ for $\sqrt{P_{cr}} = 0.924$, where a/T = 0.50.

The curves described with the first eq. (19) are in good agreement with the data reported by Myeong et al [24].

In the tubular branch junction considered here, the crack is in the run pipe (Fig. 5). The effect of a semi-elliptical crack in the branch pipe has been analyzed by finite element method, starting with the concepts of stress intensity factor [25]. Instead of the well known concepts of fracture mechanics in the paper we have used the concept of deterioration. This makes easier the strength calculation, especially in the case of mixed mode loading.

7. Conclusions

On the basis of principle of critical energy (PCE), there have been proposed relations for critical normal stress and for critical shear stress (8), depending on the damage caused by cracks, in the general case of the nonlinear behavior of the material structure (7).

Further were presented the strength calculation of crackless tubular specimens and branch pipe junction mixed-mode loaded ((13) and (14)). An analysis is made of the particular loading cases involving two different loads (internal pressure and bending moment; axial force and bending moment; axial force and internal pressure).

On the basis of PCE eqs. of the critical group were obtained, expressed in terms of forces, by considering the stochastic distribution of the mechanical characteristics of the materials (14). Work on particular cases yielded relations for loading with two different loads ((15), (17), (18)) of specimens without cracks in materials with nonlinear behavior. For the same groups of particular loads there have been deduced relations (19) for tubular specimens with cracks.

The relations obtained were verified against experimental data provided by literature for tubular specimens and for tubular branch junction.

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