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Calculation of the local critical state taking into account the deterioration and the residual stresses

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Abstract. The critical state of structures simultaneous loaded with different loads is analised taking into account the principle of critical energy. The general case is considered when the material behavior is non-linear according to the power law.
The critical state is correlated with the deterioration produced by cracks and with the residual stresses. General relationships have been deduced for the correlation of loads or stresses acting on a cracked structure having residual stresses. The theoretical relationships were verified against results reported in literature.

Keywords: critical local stress; critical local load; principle of critical energy; deterioration; crack; residual stresses.

1. Introduction

The objectives of this paper are as follows:

a. to establish relationships for:
- the critical local loads and critical local stresses of a structure, taking into account the deterioration and the residual stresses;
- local deterioration for cracked structure, on the basis of experimental data;

b. to establish relationships for the superposition of different stresses with the consideration of critical local loads,
- in the case of loading with two different loads;
- in the case of tubular junctions loaded by internal pressure and bending moment.

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All these cases will be solved by using the principle of critical energy

2. Principle of critical energy (PCE)

For structures without cracks and without residual stress, superposition or cumulation of loads is currently solved in the classical way, using a stregth theory [1]-[3], or by summing up the reported loads at a given power, as a result of applying the principle of critical energy [4] - [19].

In this paper, the load's superposition of the mechanical structures is evaluated on the basis of the critical energy principle. The principle of critical energy formulated on the basis of the concept of the specific energy participation postulates [20],

"During the evolution of a phenomenon or process, the critical state is reached when the total participation of the specific energies involved becomes equal to the critical participation."

PCE introduces concept of specific energy participation, a dimensionless variable.

The total participation of specific energies, introduced by loads Y_i takes into account the sense of the external load in relation to the evolution of the process or phenomenon analyzed, as a sum of the individual participations P_i corresponding to each load Y_i.

$$P_T = \sum_i P_i(Y_i). \tag{1}$$

One consider the general case of nonlinear behavior power function, according to the relationship:

$$Y = C \cdot X^k \tag{2}$$

where Y is the external load, X - the effect of the load, C and k - constants of the material.

The total participation of specific energies for the behavior described by the power law is [7; 8],

$$P_T(t) = \sum_i \left(\frac{Y_i}{Y_{i,cr}} \right)^{\alpha_i + 1} \cdot \delta_{Y_i}, \tag{3}$$

where it has been considered the general case when the total participation is time dependent (t); $Y_{i,cr}$ is the critical value of Y_i; the exponent $\alpha_i = 1/k_i$ depends on the behavior of the material under load and δ_Y is 1, if the load Y acts in sense of the evolution of phenomenon or process; 0 if it has no effect; -1, if the Y load opposes the evolution of the phenomenon or process.

The critical participation $P_{cr}(t)$ is a dimensionless value, time-dependent (t), also dependent by total deterioration $(D_T(t))$ and by residual stress participation (P_{res}),

$$P_{cr}(t) = P_{cr}(0) - D_T(0) - P_{res}, \tag{4}$$

where $D_T(t)$ is the sum of the individual deteriorations calculated in relation to the critical state, produced by cracks, pretension, corrosion, erosion, creep, hydrogen, neutrons, etc.

The residual stress' participation in relation to the critical state is,

$$P_{res} = \left(\frac{\sigma_{res}}{\sigma_u}\right)^2 \cdot \delta_{res}\,, \tag{5}$$

where σ_{res} is the residual stress, σ_u - ultimate stress, and δ_{res} has the meaning of $\delta_{y,i}$, the factor of external load beeing σ_{res} instead of Y_i.

$P_{cr}(0)$ is the critical participation at moment t=0; it is a stochastic value because the values of the mechanical characteristics are stochastic.

In *design*, a unique values of mechanical characteristics is used such as $P_{cr}(0)=1$.

Evaluation of the result of the loading. If:

$$\left.\begin{aligned} &P_T(t) < P_{cr}(t) \text{ - the loading is subcritical;}\\ &P_T(t) \geq P_{cr}(t) \text{ - the loading is critical or overcritical.}\end{aligned}\right\} \tag{6}$$

3. Calculation of deterioration, critical local load and critical local stress of a structure with cracks

Here are reproduced some results obtained in the paper [20].

The loading state becomes critical if $P_T(t) = P_{cr}(t)$, where from results,

$$\sum_i \left(\frac{Y_i}{Y_{i,cr}}\right)^{\alpha_{i+1}} \cdot \delta_{Y_i} = P_{cr}(0) - D_T(t) - P_{res}(t). \tag{7}$$

Since, generally, the stresses are directly proportional to the applied loads, $\sigma_i \sim Y_i$, the relation (7) may be written on the bases of the stresses, as follows,

$$\sum_i \left(\frac{\sigma_i}{\sigma_{i,cr}}\right)^{\alpha_{i+1}} \cdot \delta_{\sigma_i} = P_{cr}(0) - D_T(t) - P_{res}(t) \tag{8}$$

where $\sigma_{i,cr}$ is the critical value of σ_i in analysed case, and $\delta_{\sigma_i} = \delta_{Y_i}$.

a. Cracks with depth a and length 2c or with angular extension 2θ (Fig. 1). The crack width is negligible.

For a structure builded from a material with known mechanical characteristics $(P_{cr}(0)=1)$, without residual stresses, whose deterioration is produced only by a crack having a depth a and a length $2c$ from relationship (8), by replacing $D_T(t) = D(a;c)$ results,

$$\sum_i \left(\sigma_i/\sigma_{i,cr}\right)^{\alpha_i+1} \cdot \delta_{\sigma_i} = 1 - D(a;c). \tag{9}$$

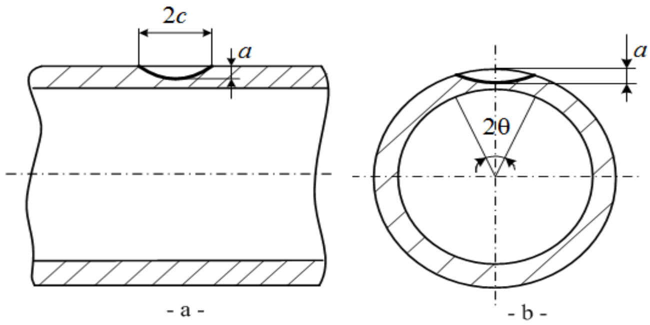


Fig. 1. Cracks at the outer surface, of a tubular specimen , of depth a, length 2c (a) or angular extension 2θ (b).

$\sigma_{i,cr}(a;c)$ is *the critical stress of the structure with crack.* By replacing the stress σ in the relation (9) with its value $\sigma_{i,cr}(a;c)$at breaking of the crackt specimen, the deterioration caused by the crack, obtains,

$$D(a;c) = 1 - \sum_i \left(\sigma_{i,cr}(a;c)/\sigma_{i,cr}\right)^{\alpha_i+1} \cdot \delta_{\sigma_i}, \tag{10}$$

where $\sigma_{i,cr}$ is the critical stress of the specimen without crack.

Table 1 lists the deterioration values calculated with the relationship (10), based on the experimental data obtained from the testing of steel specimens with crack. [22; 23].

b.From the relationship (9) written for uniaxial loading with stress σ, the critical local stress of the structure with crack (*a; c*), obtains

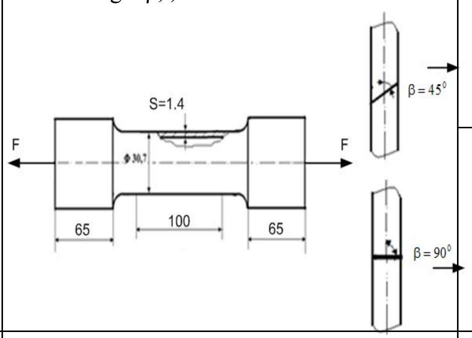
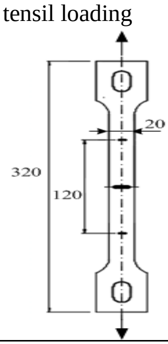
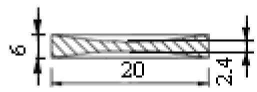
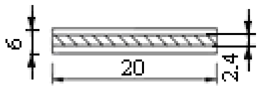
$$\sigma_{cr}(a;c) = \sigma_{cr} \cdot [1 - D(a;c)]^{\frac{1}{\alpha+1}}, \tag{11}$$

where σ_{cr} is the critical stress of the crackless structure.

It is known on the Pellini-Puzak diagram of experimental analysis of the behavior at the low temperature of the cracked steels [24] that the ultimate stress is reduced, sometimes reaching less thanyield stress $(\sigma_u(a;c) < \sigma_y)$, in which case the material behaves brittle. This validates the relation (11).

Also based on PCE, it was established the expression of critical stress for a specimen with crack with depth *a*, depending on the stress intensity factor in mode I fracture, K_I, and separately, depending on the crack tip opening displacement (CTOD), δ_I [12]:

Table 1. **Deterioration values for specimens with crack on tensile loaded [21 - 23]**

No		**a/s**	**θ/π**	**Deterioration D(a;c)**
1.	• Tubular specimen with nonpenetrated circumferential crack at an angle β, , on external surface 	0.5	1.0	0.2278
		0.5	1.0	0.9811
		Crack length (2c = 20 mm)		**Deterioration D(a;c)**
2.	• Rectangular specimen (20x6 mm) on tensil loading 			0.994
				0.914
				0.99

$$\left.\begin{aligned}\sigma_{cr}(a;c) &= \sigma_{cr}\cdot\left[1-\left(\frac{K_I}{K_{IC}}\right)^{\alpha+1}\right]^{\frac{1}{\alpha+1}}\\ \sigma_{cr}(a;c) &= \sigma_{cr}\cdot\left[1-\left(\frac{\delta_I}{\delta_{IC}}\right)^{k+1}\right]^{\frac{1}{\alpha+1}}\end{aligned}\right\} \tag{12}$$

where $\alpha = 1/k$ and k is the exponent of the behavior law (2) written for stresses $(\sigma = M_\sigma \cdot \varepsilon^k)$ where ε is the strain; M_σ and k constants of the material; K_{Ic} is the fracture toughness *in mode I of fracture (critical value of K_I); δ_{Ic}* critical value of δ_I. *The* first relation (12) contains the concept of stress intensity factor, K_I, which when applied in the area of linear behavior (k = 1), lead to,

$$\sigma_{cr}(a;c)=\sigma_{cr}\cdot\left[1-\left(\frac{K_I}{K_{IC}}\right)^2\right]^{0,5}, \qquad (13)$$

in which case $D(a;c)=(K_I/K_{IC})^2$.

The relations (12) şi (13) take into account only the depth of the crack, a, because $K_I \sim \sqrt{a}$. Relationships proposed in this paper through the concept of deterioration take into account both, the depth *a* and the length *2c* of the crack.

c. For a single load, Y, in the particular case when $P_{cr}(0)=1$, $P_{res}(t)=0$, and the deterioration $D_T(t)=D(a;c)$ is determined only by the crack, the relation (11) becomes $(Y/Y_{cr})^{\alpha+1}=1-D(a;c)$. On this basis the local critical load of structure with cracks, is,

$$Y_{cr}(a;c)=Y_{cr}\cdot[1-D(a;c)]^{\frac{1}{\alpha+1}}, \qquad (14)$$

where Y_{cr} is the critical load for the structure without crack.

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4. Deterioration of a structure with a quasi-crack.

Generally, the influence of the cracks width is negligible, this is whay the deterioration only depends on the depth and the length of the crack. The quasi-crack are crack that have a relatively small width *e* (*e* ≤ 1 mm); they are very narrow channels. In this case, the deterioration depends on all three dimensions, $D_T=D(a;c;e)$.

Critical values for structures without residual stresses $(P_{res}=0)$ is calculated by the relations,

$$\left.\begin{aligned} Y_{i,cr}(a;c;e)&=Y_{i,cr}\cdot[P_{cr}(0)-D(a;c;e)]^{\frac{1}{\alpha_i+1}}\\ \sigma_{i,cr}(a;c;e)&=\sigma_{i,cr}\cdot[P_{cr}(0)-D(a;c;e)]^{\frac{1}{\alpha_i+1}}\end{aligned}\right\} \qquad (15)$$

From the second relation (15) it can calculate the deterioration based on the experimental results with specimens without or with cracks, namely,

$$D(a;c;e)=\left[P_{cr}(0)-\left(\frac{\sigma_{i,cr}(a;c;e)}{\sigma_{i,cr}}\right)^{\alpha_i+1}\right] \tag{16}$$

Generally, one uses a deterministic value for the critical stress of the specimen without crack $(\sigma_{i,cr})$, which requires consideration of $P_{cr}(0)=1$. In relation (16) $\sigma_{cr}(a;c;e)$ is the critical stress for the specimen with a quasi-crack, and σ_{cr} is the statistic average of critical stress for a non-cracked specimen.

Figure 2 shows the variation of the deterioration calculated with the relation (16) for cracked steel specimens with rectangular section subjected to tensile stress.

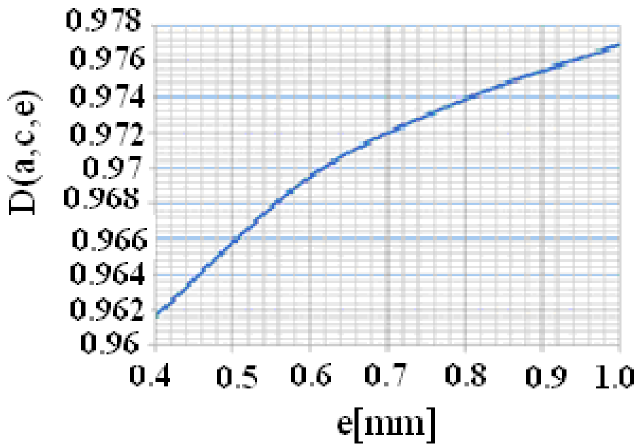

Fig. 2. Variation of deterioration in relation to the width *e* of the penetrated quasi-crack (a = s) of specimens with rectangular section (width 20 mm and thickness s = 2 mm) subjected to tensile stress .The quasi-crack is perpendicular to the direction of the stress [25].

4. Loads superpositions

One takes into account cracked structures without residual stress. Accordingly, $P_{cr}(t)=1-D(a;c)$.

a. Single load or single stress loading

Accordingly, the relations (7) and (8) become,

$$\left.\begin{aligned}(\sigma/\sigma_{cr}(a;c))^{\alpha+1}&=1;\\(Y/Y_{cr}(a;c))^{\alpha+1}&=1,\end{aligned}\right\} \tag{17}$$

which means that in fulfilling these conditions, either σ or Y achieves *the critical state.*

b. Simultaneous action of two different loads, Y_1 and Y_2; the relation (7) becomes,

$$\left(\frac{Y_1}{Y_{1,cr}}\right)^{\alpha_1+1}+\left(\frac{Y_2}{Y_{2,cr}}\right)^{\alpha_2+1}\cdot\delta_{Y_2}=1-D(a;c), \quad (18)$$

where $Y_{1,cr}$ and $Y_{2,cr}$ are the critical values for the non-cracked structure. Considering critical local stresses for the structure with crack (14), relation (18) becomes,

$$\left(\frac{Y_1}{Y_{1,cr}(a;c)}\right)^{\alpha_1+1}+\left(\frac{Y_2}{Y_{2,cr}(a;c)}\right)^{\alpha_2+1}\cdot\delta_{Y_2}=1. \quad (19)$$

where generally,

$$\left.\begin{aligned} Y_{i,cr}(a;c)&=Y_{i,cr}\cdot\left[P_{cr}(0)-D(a;c)\right]^{\frac{1}{\alpha_i+1}};\\ \sigma_{i,cr}(a;c)&=\sigma_{i,cr}\cdot\left[P_{cr}(0)-D(a;c)\right]^{\frac{1}{\alpha_i+1}}.\end{aligned}\right\} \quad (20)$$

c. Tubular junction with crack, loaded by internal pressure and bending moment.

In this case, $Y_1=p$ and$Y_2=M_b$. For the ideal - plastic behavior of the material ($k_1=k_2=1$ and $\alpha_1=\alpha_2=2$ in relations (18) and (19)), the interaction of the pressure and the bending moment is given by,

$$\left(\frac{p}{p_{cr}}\right)^2+\left(\frac{M_b}{M_{b,cr}}\right)^2\cdot\delta_b=1-D(a;\theta), \quad (21)$$

$$\left(\frac{p}{p_{cr}(a;\theta)}\right)^2+\left(\frac{M_b}{M_{b,cr}(a;\theta)}\right)^2\cdot\delta_b=1, \quad (22)$$

where $\delta_b=\delta_{Y_2}=1$because the calculation it is made for the fibre on which bending moment produces stretching.

The tubular junction may have the crack at the base of the weld (Fig. 3, a), on the flank (4) or on the crotch (5). It is considered the tubular junction analyzed in the papers [23; 26], characterized by $2R_m/T=20$; $r_m/R_m=0.5$; $s=S$. The crack was considered penetrated ($a=S$), and the material - ideal plastic. Accordingly $\alpha_1=\alpha_2=1$ and $\sigma_{cr}=\sigma_y$ – yield stress.

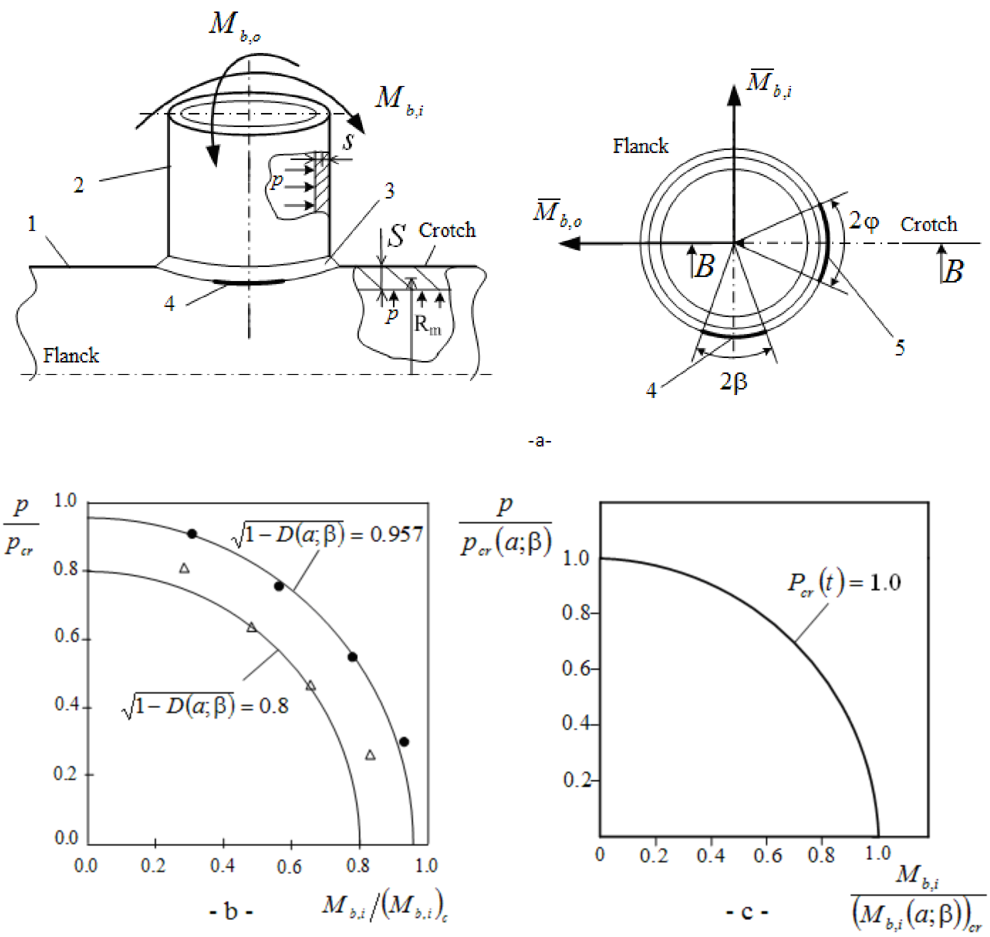

Fig. 3. *a* - tubular junction: 1 – run pipe; 2 – branch pipe; 3 – weld; 4 – crack on the flank; 5 – crack on the crotch;
b – the interaction between the reported pressure (p/p_{cr}) and the reported bending moment $\left(M_{b,i}/\left(M_{b,i}\right)_{cr}\right)$, for the penetrated crack (a=S) on the flank, with opening $2\beta = 49°$ (●); $2\beta = 140°$ (**Δ**) [26]. The curves were drawn with rel. (23) for $\delta_b = 1$. *c* – the interaction between the reported loads $p/p_{cr}(a;\beta)$ and $M_{b,i}/\left(M_{b,i}(a;\beta)\right)_{cr}$ drawn with relation (24) [21].

- ***Crack at the base of the welding on the flank, with opening* 2β (Fig. 3,a).** Loading by internal pressure (p) and bending moment ($M_{b,i}$) in the plane of the geometrical axes of the junction elements,

$$\left(\frac{p}{p_{cr}}\right)^2 + \left(\frac{M_{b,i}}{\left(M_{b,i}\right)_{cr}}\right)^2 = 1 - D(a;\beta); \qquad (23)$$

$$\left(\frac{p}{p_{cr}(a;\beta)}\right)^2+\left(\frac{M_{b,i}}{\left(M_{b,i}(a;\beta)\right)_{cr}}\right)^2=1, \tag{24}$$

where the critical loads $p_{cr}\equiv p_Y$ and $\left(M_{b,i}\right)_{cr}\equiv\left(M_{b,i}\right)_Y$ correspond to reaching the yield stress.

The curves in Figure 3, b describe the interaction of the relation (23), where the denominator is the critical stress for the non-cracked material, and $D(a;\beta)$ depends on the crack opening 2β.

It is noted that: for $2\beta=49°$, $\sqrt{1-D(a;\beta)}=0.957$, and for $2\beta=140°$, $\sqrt{1-D(a;\beta)}=0.80$.

With relation (24), the graphical representation is a quarter of a circle with the radius 1.0 (Fig 3, c). The critical local stresses from the denominators (24) are calculated with the relations:

$$\left.\begin{aligned} p_{cr}(a;\beta)&=p_{cr}\cdot[1-D(a;\beta)]^{\frac{1}{\alpha+1}};\\ \left(M_{b,i}(a;\beta)\right)_{cr}&=\left(M_{b,i}\right)_{cr}\cdot[1-D(a;\beta)]^{\frac{1}{\alpha+1}}.\end{aligned}\right\} \tag{25}$$

- *The crack at the base of the welding, on the crotch, with opening 2φ* (Fig. 3,a).

In this case by loading by internal pressure (p) and bending moment ($M_{b,o}$), in relations (23) and (24), $M_{b,i}$ and $D(a;\beta)$ are replaced with $M_{b,o}$ and respectively $D(a;\varphi)$.

5. Discussions

From the analysis of relationships established in this paper it follows that the interaction of the reported stresses can be represented in two ways:

- according to critical stresses of the structure without cracks (p_{cr}; $M_{b,cr}$; F_{cr}...;Y_{cr}), the case of relations (18), (21) and (23), in which the deterioration caused by cracks is inserted into the right-hand member of the equation; one curve is obtained for each combination (a; c) or (a; β) or (a; φ);

- according to critical stresses of the structure with cracks ($p_{cr}(a;c)$; $M_{b,cr}(a;c)$; $F_{cr}(a;c)$...;$Y_{cr}(a;c)$), as in the relations (19), (22) and (24), in which case the right-hand member equals 1.0, basically a single curve is obtained.

The relation (19) and the diagram in figure 4 drawn on it has a general character, and can be applied not just to no-cracked structures ($(a=c=0$ and $Y_{1,cr}(a;c)=Y_{1,cr}$ and $Y_{2,cr}(a;c)=Y_{2,cr})$), but also to cracked structures

On the unique diagram of Fig. 4, also has been highlighted the case $\delta_{Y_2}=-1$.

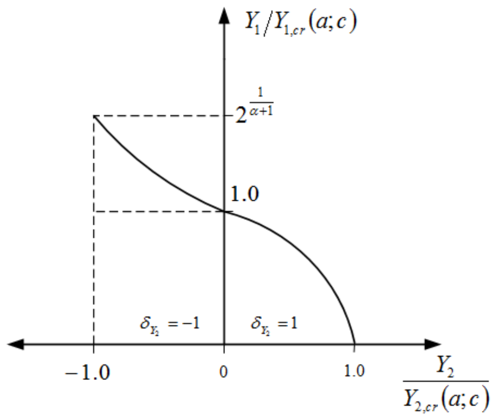

Fig. 4. Unique diagram according to relation (19)

If the structure contains residual stresses, the right-hand member in relation (19) is replaced by $(1-P_{res}\cdot\delta_{res})$,

$$\left(\frac{Y_1}{Y_{1,cr}(a;c)}\right)^{\alpha_1+1}+\left(\frac{Y_2}{Y_{2,cr}(a;c)}\right)^{\alpha_2+1}\cdot\delta_{Y_2}=1-P_{res}\cdot\delta_{res}. \tag{26}$$

For $\delta_{res}=-1$ the interaction curve corresponds to higher values and for $\delta_{res}=1$, the curve corresponds to lower values than for $\delta_{res}=0$ (Fig. 5). The curves in Figure 5 contain both the influence of the crack *(a; c)* and the influence of the residual stresses.

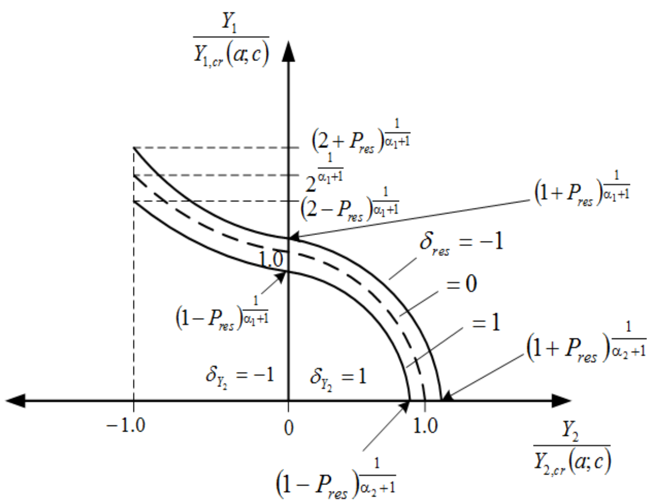

Fig. 5. Interdependence between reported stresses $Y_1/Y_{1,cr}(a;c)$ and $Y_2/Y_{2,cr}(a;c)$ in the case of non-linear behavior of the mechanical structure with $\alpha_1=\alpha_2=1$, considering the influence of residual stress, according to the relation (26).

If the influence of residual stress is introduced along with total damage, D_T, the expression of critical local stress becomes,

$$Y_{cr}(D_T;P_{res}) = Y_{cr} \cdot [1 - D_T - P_{res} \cdot \delta_{res}]^{\frac{1}{\alpha+1}}. \quad (27)$$

With this expression the relations (26) becomes

$$\left(\frac{Y_1}{Y_{1,cr}(D_T;P_{res})}\right)^{\alpha_1+1} + \left(\frac{Y_2}{Y_{2,cr}(D_T;P_{res})}\right)^{\alpha_2+1} \cdot \delta_{Y_2} = 1. \quad (28)$$

The graphical representation of this relationship is a curve that intersects coordinate axes at the coordinates equal 1.0; it is obtained a representation as in Figure 4 where the coordinates are $Y_1/Y_{1,cr}(D_T;P_{res})$ and $Y_2/Y_{2,cr}(D_T;P_{res})$.

6. Conclusions

Based on the principle of critical energy, for materials with non-linear behavior, power low, were deducted relations for the local critical state, as a result of the superposition of multiple loads. The influence of crack deterioration and residual stresses was considered.

It has been concluded that loads superposition that brings the structure into a critical state can lead to two kinds of expression, namely:

- by considering the deterioration in the right-hand member of relation for the critical state ((9); (11); (18); (21); (23)), in which case the graphical representation in the first dial is a quarter of the "circle" with the radius $(1 - D(a;c))^{\frac{1}{\alpha+1}}$;

- by considering the deterioration included in the value of the local critical stress (rel. (19); (22) şi (24)), in which case the graphical representation is a quarter of a circle with a radius equal to 1.0;

radius equal to 1.0

- by considering the deterioration and the residual stress in the right-hand member (rel. (7) şi (8)) or with the deterioration included in the expression of the local critical load and with the effect of the residual stress provided in the right-hand member like in relation (26) in which case the curves are plotted as in Fig. 5;

- by considering *both of deterioration and of residual stress* in the expression of the local critical load like in relation (27), in which case the relationship (28) is used, and the graphical representation is a unique curve.

The relationships established take into account *the sense of the action of each stress or load* (in favor of or against the deformation process).

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