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ON THE ASSESSMENT MODE OF SOME SAFETY COEFFICIENTS USING BREAKING POLYNOMIAL CRITERIA

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Abstract: *Starting of the characteristic expressions of some breaking polynomial criteria, known and used in practice, it is highlighted how to assess the safety coefficients used in some practical cases. It is obvious that the decision belongs to the user given the experience in the adequate technical domain. In this regard it must not neglect the fact in that the breakage is produced most often in unpredictable moments, conditioned by multiple factors, dependent on material, on manufacturing technologies of finished products, respective the operating conditions.*

Keywords: *Safety coefficients, breaking criteria*

1. INTRODUCTION

The industrial practice has shown many times that some deterioration of the mechanical equipments, in general, and those under pressure, from the process industries, in particular, occur in unwanted moments, sometimes becoming real material and human disasters. No matter how evolved the theoretical knowledge and the experimental procedures, there are still mysteries in many practical cases. It is necessary, therefore, to capitalize the obtained results in practical concretizations, on materials tested under operational conditions, obviously more aggressive than the common. The presence of some safety coefficients (or, otherwise expressed, like uncertainty in some industrial states) are useful both for the experimental models and the more for the methods of design, implementation and concrete use.

The need for these measures is the more important for the anisotropic materials, such as composites, but also for metallic materials much better known in response in usual conditions.

2. Polynomial/tensor criteria

The mathematical expression of these types of criteria tries to overcome the shortcomings of other quadratic criteria, which do not distinguish the stretching and compression solicitations.

According to [1-3], ***Gol'denblat I. I.* şi *Kopnov V. A.*** (see the paper published in Mehanika Polimerov, vol. 1, 1965, p. 70-78, for composite of plastic material armed with fiberglass) proposed the first polynomial criterion, written as a general form: $(i,\ j,\ k\ = 1, 2, \cdots, 6)$:

$$f\left(\sigma_{ij}\right) = \sum_{i=1}^{6}\left(F_i\cdot\sigma_i\right)^{\alpha} + \sum_{j=1}^{6}\sum_{i=1}^{6}\left(F_{ij}\cdot\sigma_i\cdot\sigma_j\right)^{\beta} + \\ + \sum_{i=1}^{6}\sum_{j=1}^{6}\sum_{k=1}^{6}\left(F_{ijk}\cdot\sigma_i\cdot\sigma_j\cdot\sigma_k\right)^{\gamma} + \cdots \tag{1}$$

where the $\alpha,\ \beta,\ \gamma, \cdots$ exponents are experimentally determined values (constants of material).

A simpler expression (with $\alpha = \beta = \gamma = 1{,}0$), retaining only the first three terms of the (1) equality, according to the papers [4 - 6], is presented under the form (*Tennyson R. C* – [7]):

$$f\left(\sigma_{ij}\right) = \sum_{i=1}^{6} F_i\cdot\sigma_i + \sum_{j=1}^{6}\sum_{i=1}^{6} F_{ij}\cdot\sigma_i\cdot\sigma_j + \\ + \sum_{i=1}^{6}\sum_{j=1}^{6}\sum_{k=1}^{6} F_{ijk}\cdot\sigma_i\cdot\sigma_j\cdot\sigma_k, \tag{2}$$

with $i,\ j,\ k\ = 1, 2, \cdots, 6$.

Usually the influence of the F_{ijk} size, compared to the other terms is neglected, so that the equality which is turned account for practical applications is presented under the form [2, 3, 5, 8, 9, 10]:

$$f\left(\sigma_{ij}\right) = \sum_{i=1}^{6} F_i \cdot \sigma_i + \sum_{j=1}^{6} \sum_{i=1}^{6} F_{ij} \cdot \sigma_i \cdot \sigma_j , \quad (3)$$

considering the notations: $\sigma_1, \sigma_2, \sigma_3$ – normal stresses, respectively:

$$\sigma_4 = \tau_{23} ; \sigma_5 = \tau_{31} ; \sigma_6 = \tau_{12} .$$

The breaking corresponds to the $f\left(\sigma_{ij}\right) \rangle 1$ condition [3], while **the operating safety** is ensured if $f\left(\sigma_{ij}\right) \leq 1$.

It is allowed that $F_4 = F_5 = F_6 = 0$ and $F_{14} = F_{15} = F_{16} = F_{24} = F_{25} = F_{26} = = F_{34} = F_{35} = F_{36} = F_{45} = F_{56} = F_{64} = 0$,

like simplifications resulting from the fact that in the main axis system of the material, the shear resistance is independent of sign. However, it is considered that the F_i and F_{ij} factors are symmetrical tensors [8].

For an **orthotropic material** the (3) equality is converted to [5, 6, 8, 9, 11]:

$$\begin{aligned} f\left(\sigma_{ij}\right) &= F_1 \cdot \sigma_1 + F_2 \cdot \sigma_2 + F_3 \cdot \sigma_3 + F_{11} \cdot \sigma_1^2 + \\ &+ F_{22} \cdot \sigma_2^2 + F_{33} \cdot \sigma_3^2 + F_{44} \cdot \sigma_4^2 + F_{55} \cdot \sigma_5^2 + \\ &+ F_{66} \cdot \sigma_6^2 + 2 \cdot F_{12} \cdot \sigma_1 \cdot \sigma_2 + 2 \cdot F_{13} \cdot \sigma_1 \cdot \sigma_3 + \\ &+ 2 \cdot F_{23} \cdot \sigma_2 \cdot \sigma_3 . \end{aligned} \quad (4)$$

The F_i, F_{ij} $\left(i, j = 1, 2, \cdots, 6\right)$ sizes can be determined by the stresses at limit/breaking, through **unidirectional tests**.

For **the plane state of stresses** ($\sigma_3 = \sigma_4 = \sigma_5 = 0$), the (3) equality becomes [6]:

$$\begin{aligned} f\left(\sigma_{ij}\right) &= F_1 \cdot \sigma_1 + F_2 \cdot \sigma_2 + F_6 \cdot \sigma_6 + \\ &+ F_{11} \cdot \sigma_1^2 + F_{22} \cdot \sigma_2^2 + F_{66} \cdot \sigma_6^2 + \\ &+ 2 \cdot F_{12} \cdot \sigma_1 \cdot \sigma_2 + 2 \cdot F_{16} \cdot \sigma_1 \cdot \sigma_6 + \\ &+ 2 \cdot F_{26} \cdot \sigma_2 \cdot \sigma_6 . \end{aligned} \quad (5)$$

In the [6] paper, for the case of a **transversal isotropic material** - special case of the orthotropy, with the 2 – 3 plan of symmetry, is specified that: $F_2 = F_3$; $F_{12} = F_{13}$; $F_{22} = F_{33}$; $F_{55} = F_{66}$, and from the shear condition $F_{44} = 2 \cdot \left(F_{22} - F_{23}\right)$, so that the (4) equality becomes:

$$\begin{aligned} f\left(\sigma_{ij}\right) &= F_1 \cdot \sigma_1 + \left(F_2 + 2 \cdot F_{12} \cdot \sigma_1\right) \cdot \left(\sigma_2 + \sigma_3\right) + \\ &+ F_{11} \cdot \sigma_1^2 + F_{22} \cdot \left(\sigma_2^2 + \sigma_3^2\right) + 2 \cdot F_{23} \cdot \sigma_2 \cdot \sigma_3 + \\ &+ 2 \cdot \left(F_{22} - F_{23}\right) \cdot \sigma_4^2 + F_{55} \cdot \left(\sigma_5^2 + \sigma_6^2\right) \leq 1 . \end{aligned} \quad (6)$$

In the [8, 9] papers the method of determining the F_1, F_{11} factors is shown, considering $\sigma_1 \neq 0$ and all the others stresses $\sigma_i = 0$, in the case of uniaxial solicitation of **stretching** or **compression**. It is deduced that [8]:

$F_1 \cdot X_T + F_{11} \cdot X_T^2 = 1$ - for stretching;

$F_1 \cdot X_C + F_{11} \cdot X_C^2 = 1$ - for compression,

after that the corresponding tensors result [5, 8, 9]:

$$F_1 = 1 / X_T + 1 / X_C ; F_{11} = -1 / \left(X_T \cdot X_C\right) . \quad (7)$$

Similarly, with the others non-null stresses, the expressions are established[5, 8, 9, 12]:

$$F_2 = 1 / Y_T + 1 / Y_C ; F_{22} = -1 / \left(Y_T \cdot Y_C\right) ;$$
$$F_3 = 1 / Z_T + 1 / Z_C ; \quad (8)$$

$$F_{33} = -1 / \left(Z_T \cdot Z_C\right) ; F_{44} = -1 / Q^2 ;$$
$$F_{55} = -1 / R^2 ; \; F_{66} = -1 / S^2 . \quad (9)$$

The F_{12}, F_{13} and F_{23} factors, called **interaction constants**, too [8], can be determined from three independent trials, where $\sigma_1 = \sigma_2$, $\sigma_1 = \sigma_3$, $\sigma_2 = \sigma_3$, the others stresses being null. If it is accepted that $\sigma_1 = \sigma_2 = \sigma$, the others stresses being null, the tensor criterion predicts the breaking (at limit) when **[61]**:

$$\begin{aligned} f\left(\sigma_{ij}\right) &= \left(F_1 + F_2\right) \cdot \sigma + \\ &+ \left(F_{11} + F_{22} + F_{12}\right) \cdot \sigma^2 = 1 . \end{aligned} \quad (10)$$

In this equality considering successive that the stress values are X_T, X_C, Y_T , Y_C and σ and replacing the F_1, F_2, F_{11}, F_{22} sizes with the (7) and (8) corresponding expressions we reach to [8, 9]:

$$F_{12} = \frac{1}{2}\cdot\left[\begin{array}{c}\frac{1}{\sigma^2} - \frac{1}{\sigma}\cdot\left(\frac{1}{X_T} + \frac{1}{X_C} + \frac{1}{Y_T} + \frac{1}{Y_C}\right) + \\ + \frac{1}{X_T\cdot X_C} + \frac{1}{Y_T\cdot Y_C}\end{array}\right]. \tag{11}$$

For a **plane state of stresses**, where $F_{12} = 0$, the (5) equality becomes [8, 12]:

$$f\left(\sigma_{ij}\right) = F_1\cdot\sigma_1 + F_2\cdot\sigma_2 + F_{11}\cdot\sigma_1^2 + \\ + F_{22}\cdot\sigma_2^2 + F_{66}\cdot\sigma_6^2. \tag{12}$$

When $F_{12} \neq 0$, the (5) equality, at limit, takes the form [8]:

$$f\left(\sigma_{ij}\right) = F_1\cdot\sigma_1 + F_2\cdot\sigma_2 + F_{11}\cdot\sigma_1^2 + F_{22}\cdot\sigma_2^2 + \\ + F_{66}\cdot\sigma_6^2 + 2\cdot F_{12}\cdot\sigma_1\cdot\sigma_2 = 1, \tag{13}$$

where following some adequate calculations the equality is established **[8-10, 13]**:

$$F_{12} = -0{,}5\cdot\sqrt{F_{11}\cdot F_{22}}, \tag{14}$$

the other sizes being the (7) expressions.

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The paper [2] introduces the idea of the presence of a c_s safety coefficient, having the same value both the normal stresses and for the shear stresses, **<u>of mechanical nature</u>**, so that the (13) equality becomes:

$$A_1\cdot c_s^2 + A_2\cdot c_s - 1 = 0, \tag{15}$$

where:

$$A_1 = F_{11}\cdot\sigma_1^2 + F_{22}\cdot\sigma_2^2 + F_{66}\cdot\tau_{12}^2 + 2\cdot F_{12}\cdot\sigma_1\cdot\sigma_2; \\ A_2 = F_1\cdot\sigma_1 + F_2\cdot\sigma_2. \tag{16}$$

Solving the (15) equation the adoption of the positive value for the safety coefficient is permitted:

$$c_{s1} = \left(-A_2 + \sqrt{A_2 + 4\cdot A_1}\right)/\left(2\cdot A_1\right), \tag{17}$$

respectively:

$$c_{s2} = \left|\left(-A_2 - \sqrt{A_2 + 4\cdot A_1}\right)/\left(2\cdot A_1\right)\right|. \tag{18}$$

How $\left|c_{s2}\right| \rangle \left|c_{s1}\right|$, the user will decide which of the two values is accepted.

Developing the previous problem in the case of simultaneous of **<u>the thermal stresses</u>** and/or **<u>stresses caused by humidity</u>**, alongside those mechanical, too, the (15) equality adjusts the form:

$$A_1^*\cdot\left(c_s^*\right)^2 + A_2^*\cdot\left(c_s^*\right) - 1 = 0, \tag{19}$$

with the corresponding notations:

$$A_1^* = F_{11}\cdot\left[\begin{array}{c}\sigma_1^2 + k_T^2\cdot\sigma_{1T}^2 + k_H^2\cdot\sigma_{1H}^2 + \\ + 2\cdot\left(\begin{array}{c}k_T\cdot\sigma_1\cdot\sigma_{1T} + k_H\cdot\sigma_1\cdot\sigma_{1H} + \\ + k_T\cdot k_H\cdot\sigma_{1T}\cdot\sigma_{1H}\end{array}\right)\end{array}\right] +$$

$$+ F_{22}\cdot\left[\begin{array}{c}\sigma_2^2 + k_T^2\cdot\sigma_{2T}^2 + k_H^2\cdot\sigma_{2H}^2 + \\ + 2\cdot\left(\begin{array}{c}k_T\cdot\sigma_2\cdot\sigma_{2T} + k_H\cdot\sigma_2\cdot\sigma_{2H} + \\ + k_T\cdot k_H\cdot\sigma_{2T}\cdot\sigma_{2H}\end{array}\right)\end{array}\right] +$$

$$+ F_{66}\cdot\left[\begin{array}{c}\tau_{12}^2 + k_T^2\cdot\tau_{12T}^2 + k_H^2\cdot\tau_{12H}^2 + \\ + 2\cdot\left(\begin{array}{c}k_T\cdot\tau_{12}\cdot\tau_{12T} + k_H\cdot\tau_{12}\cdot\tau_{12H} + \\ + k_T\cdot k_H\cdot\tau_{12T}\cdot\tau_{12H}\end{array}\right)\end{array}\right] +$$

$$+ 2\cdot F_{12}\cdot\left(\begin{array}{c}\sigma_1\cdot\sigma_2 + k_T\cdot\sigma_1\cdot\sigma_{2T} + k_H\cdot\sigma_1\cdot\sigma_{2H} + \\ + k_T\cdot\sigma_2\cdot\sigma_{1T} + k_T^2\cdot\sigma_{1T}\cdot\sigma_{2T} + \\ + k_T\cdot k_H\cdot\sigma_{1T}\cdot\sigma_{2T} + k_H\cdot\sigma_2\cdot\sigma_{1H} + \\ + k_T\cdot k_H\cdot\sigma_{2T}\cdot\sigma_{1H} + k_T\cdot k_H\cdot\sigma_{1H}\cdot\sigma_{2H}\end{array}\right); \tag{20}$$

$$A_2^* = F_1\cdot\left(\sigma_1 + k_T\cdot\sigma_{1T} + k_H\cdot\sigma_{1H}\right) + \\ + F_2\cdot\left(\sigma_2 + k_T\cdot\sigma_{2T} + k_H\cdot\sigma_{2H}\right). \tag{21}$$

The solutions of the (19) equation takes the form:

$$c_{s1}^* = \left|\left(-A_2^* + \sqrt{A_2^* + 4\cdot A_1^*}\right)/\left(2\cdot A_1^*\right)\right|; \tag{22}$$

$$c_{s2}^* = \left|\left(-A_2^* - \sqrt{A_2^* + 4\cdot A_1^*}\right)/\left(2\cdot A_1^*\right)\right|. \tag{23}$$

In this case, too, the user will choose the convenient variant of the safety coefficient value.

In the case of the previous expressions the following notations have been used: σ_{1T}, σ_{2T} – thermal normal stresses; σ_{1H}, σ_{2H} – normal stresses due to humidity; τ_{12T}, τ_{12H} – shear stresses due to the thermal effect, respective that developed of the humidity; k_T, k_H – selection factors, with unitary values when the presence of the stresses is accepted, respectively with null values, as appropriate, when the respective effect is not taken into consideration.

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Criterion *Karkkainen L. R. – Sankar V. B. – Tzeng T. J.* (2007)

In the paper [1002], accepting the $(8.85)_3$ formulation is proceeded to the utilization of the effect of the developed loads in the transversal sections under the external actions (*Karkkainen L. R., Sankar V. B., Tzeng T. J* – Journal of Composite Materials, vol. 41, nr. 16, 2007, p. 1917 – 1937), so that the safety condition at the structure deterioration appear (at limit):

$$F_1\cdot\left(N_x+N_y\right)+F_{11}\cdot\left(N_x^2+N_y^2\right)+F_{12}\cdot N_x\cdot N_y+$$
$$+F_{33}\cdot N_{xy}^2+F_{44}\cdot\left(M_x^2+M_y^2\right)+F_{66}\cdot M_{xy}^2=1, \quad (24)$$

where the N_x, N_y normal unitary forces and the N_{xy} shear unitary force, respective the M_x, M_y unitary bending moments, and the M_{xy}. torsion unitary moment are present. As a rule the conditions can be used [14]:

$$F_1=1/F_{1t}-1/F_{1c};\quad F_{11}=1/\left(F_{1t}\cdot F_{1c}\right);$$
$$F_{33}=1/F_3^2; \quad (25)$$

$$F_{44}=F_{55}=1/F_4^2;\quad F_{66}=1/F_6^2, \quad (26)$$

where F_3, F_4, F_6 are determined experimentally loads for solicitations to stretch/compression, shear or bending and torsion [14].

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<u>**Note**</u>: For the composites with carbon or glass fibers, S. *Liu K. S., Tsai W.S.* (Composite Science and Technology, vol. 58, nr. 7, 1998, p. 1023 – 1032) recommends [14]: $-0{,}9\cdot\sqrt{F_{11}\cdot F_{22}}\ \langle\ F_{12}\ \langle\ 0$ or, in general, $F_{12}=-0{,}5\cdot\sqrt{F_{11}\cdot F_{22}}$.

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The security conditions at deterioration, written compact, have the forms [14]:

$$F_1\cdot\left(N_x+N_y\right)+F_{11}\cdot\left(N_x^2+N_y^2\right)+$$
$$+F_{12}\cdot N_x\cdot N_y+F_{33}\cdot N_{xy}^2\ \langle\ 1; \quad (27)$$

$$F_{44}\cdot max\left\{M_x^2,M_y^2\right\}+F_{66}\cdot M_{xy}^2\ \langle\ 1; \quad (28)$$

$$max\left\{N_x/F_x;N_y/F_y\right\}+$$
$$+max\left\{\left|M_x\right|,\left|M_y\right|\right\}/F_4\ \langle\ 1, \quad (29)$$

where the helpful expressions was used [14]:

$$F_x=\left[1/\left(2\cdot F_{11}\right)\right]\cdot\left[\begin{array}{c}-\left(F_1+F_{12}\cdot N_x\right)\pm\\ \pm\sqrt{\begin{array}{c}\left(F_1+F_{12}\cdot N_y\right)^2-\\ -4\cdot F_{11}\cdot\left(\begin{array}{c}F_1\cdot N_y+\\ +F_{11}\cdot N_y^2+\\ +F_{33}\cdot N_{xy}^2-1\end{array}\right)\end{array}}\end{array}\right]; \quad (30)$$

$$F_y=\left[1/\left(2\cdot F_{11}\right)\right]\cdot\left[\begin{array}{c}-\left(F_1+F_{12}\cdot N_x\right)\pm\\ \pm\sqrt{\begin{array}{c}\left(F_1+F_{12}\cdot N_x\right)^2-\\ -4\cdot F_{11}\cdot\left(\begin{array}{c}F_1\cdot N_x+\\ +F_{11}\cdot N_x^2+\\ +F_{33}\cdot N_{xy}^2-1\end{array}\right)\end{array}}\end{array}\right]. \quad (31)$$

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Considering a unique safety coefficient both for normal unitary forces and for the shear forces, the (27) expression becomes:

$$A_{1N}\cdot c_{sN}^2+A_{2N}\cdot c_{sN}-1=0, \quad (32)$$

with the corresponding notations:

$$A_{1N}=F_{11}\cdot\left(N_x^2+N_y^2\right)+F_{12}\cdot N_x\cdot N_y+F_{33}\cdot N_{xy}^2;$$
$$A_{2N}=N_x+N_y, \quad (33)$$

where the effective loads created under the action of the external loads, without producing of some bending unitary or torsion moments are presented. By solving the (32) equation the solutions are obtained:

$$\left(c_{sN}\right)_1=\left|\left(-A_{2N}+\sqrt{A_{2N}^2+4\cdot A_{1N}}\right)/\left(2\cdot A_{1N}\right)\right|; \quad (34)$$

$$\left(c_{sN}\right)_2=\left|\left(-A_{2N}-\sqrt{A_{2N}^2+4\cdot A_{1N}}\right)/\left(2\cdot A_{1N}\right)\right|, \quad (35)$$

recommending the choice of the convenient value:

$$c_{sN}=max\left\{\left(c_{sN}\right)_1;\left(c_{sN}\right)_2\right\}. \quad (36)$$

In the case of the accepting and the presence of the rotations of the transversal sections of the plate, with the condition of one safety coefficient, the previous expressions adequately correct:

$$A^*_{1N} = F_{11}\cdot\left(N_x^2 + N_y^2\right) + F_{12}\cdot N_x\cdot N_y +$$
$$+ F_{33}\cdot N^2_{xy} + F_{44}\cdot\left(M_x^2 + M_y^2\right) + F_{66}\cdot M^2_{xy}; \quad (37)$$

respectively:

$$\left(c_{sN}\right)^*_1 = \left|\left(-A_{2N} + \sqrt{A^2_{2N} + 4\cdot A^*_{1N}}\right)\Big/\left(2\cdot A^*_{1N}\right)\right|; \quad (38)$$

$$\left(c_{sN}\right)^*_2 = \left|\left(-A_{2N} - \sqrt{A^2_{2N} + 4\cdot A^*_{1N}}\right)\Big/\left(2\cdot A^*_{1N}\right)\right|; \quad (39)$$

$$c^*_{sN} = max\left\{\left(c_{sN}\right)^*_1; \left(c_{sN}\right)^*_2\right\}. \quad (40)$$

CONCLUSIONS

This paper presents the general problem of the breaking polynomial criteria, respective the characteristic mathematical expression, adapted by different authors based on the nature of the tested anisotropic materials and the obtained result by adequate experimental research. Given the used criteria for exemplifying the content of the paper, the authors specify the expressions of some safety coefficient, whose values can be accepted by users. It is recommended, considering an ample bibliography, specific to the domain, direct research for the anisotropic materials, metal or composite, so the concrete practical data enable the certificated decisions.

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