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The Principle of Critical Energy as a Transdisciplinary Principle with Interdisciplinary Applications

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Additional information is available at the end of the chapter

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Abstract

The principle of critical energy (PCE) is a transdisciplinary principle that may be used in all chapters of sciences for superposition and/or cumulation of different external actions (mechanical, thermal, magnetic, electrical, chemical, etc.) It may be used for lifetime evaluation of engineering structures, as well as for living organisms, by taking into account the influences due to pollution, due to internal deterioration, due to preloading or residual stresses, etc. In this paper, we explain what PCE is, how it may be practically used and the interdependences between the terms comprised in its general relation. PCE was applied for solving problems of superposition of external actions and internal deteriorations in the following chapters of sciences: mechanical engineering, thermomechanical-chemical loadings, multiple pollution, medical field and viscoelasticity. It was compared with synergy theory and with catastrophe theory.

Keywords: Transdisciplinarity, interdisciplinarity, principle of critical energy, superposition and cumulation of load actions, multiple pollution, application in medical field, viscous and elastic behaviour, synergy

1. Introduction

The principle of critical energy (PCE) is the fourth principle of Energonics [1–3], a field of science that stands for energy in action. It was discovered and formulated in 1984 [4].

The principle of critical energy has allowed so far the finding of solutions to many problems of superposition and/or cumulation of actions or their effects on engineering structures [1–17], or on living organisms that find themselves under stress, abused and/or medically treated [2, 13].

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The criterion of truth in scientific research is the experiment. For this reason, down below there have been presented the predictions resulting from the application of the principle of critical energy in comparison to experimental results. In this way, the critical energy principle has been validated by the experimental data reported in the literature by various authors.

The principle of critical energy has been used, for example, to solve the problems of superposition and/or cumulation of the effects of actions definitory for such disciplines/chapters of engineering sciences as mechanical engineering, electrical and electromagnetic engineering, chemical engineering, etc. The question is whether we are dealing in this case with an interdisciplinary or a transdisciplinary issue?

Interdisciplinarity means bringing together elements of two or more academic disciplines in order to solve a specific theoretical or practical problem. The result would not be possible without the 'cooperation' of different academic disciplines, out of which use is made of elements that have been time proven. Creation, in this case, refers to the combination of knowledge already extant in the academic fields under scrutiny.

Transdisciplinarity essentially means concerns that go beyond any discipline ('trans' = beyond) or away from a particular discipline, concerns based on the existing academic disciplines and finally capable of generating new areas of knowledge. The new concepts in the field can be retrieved and applied to other areas or academic disciplines.

Consequently, the PCE features transdisciplinarity but in conjunction with just one more academic discipline it becomes interdisciplinary.

2. The principle of critical energy

The principle of critical energy is stated as follows [2, 4]:

'The critical state in a process or phenomenon is reached when the sum of the specific energy amounts involved, considering the sense of their action, becomes equal to the value of the critical specific energy characterizing that particular process or phenomenon'.

The principle of critical energy allows the calculation of the effect produced upon a physical body by the simultaneous or successive action of several external actions or loads Y_j (where j =1; 2; 3...). The mathematical expression of the principle of critical energy was stated as follows (1):

$$\sum_j \left(\frac{E_j}{E_{j,cr}} \right) \cdot \delta_j = 1, \tag{1}$$

where E_j is the specific energy (expressed in J/kg, J/m^3 or J/m^2) introduced in the material by loading Y_j, while $E_{cr,j}$ is the critical value of the specific energy E_j. If $E_j = E_{j,cr}$ the critical state is reached, namely, fracture, excessive deformation, buckling, and so on:

$$\delta_j = \begin{cases} 1, \text{if the specific energy acts in the direction of the process;} \\ 0, \text{if it has no effect upon the respective process;} \\ -1, \text{if it opposes the evolution of the process.} \end{cases} \tag{2}$$

The expression under the sum in relation (1) represents the participation of the specific energy introduced by the action or load Y_j and is written as:

$$P_j = \left(\frac{E_j}{E_{j,cr}} \right) \cdot \delta_j, \tag{3}$$

thus, the sum in the left part of relation (10) is called the total participation of specific energy:

$$P_T = \sum_j P_j, \tag{4}$$

where P_T is a sum of dimensionless variables calculated with respect to the critical state; this particularity gives a high degree generality of the Eq. (4).

If the loading is caused by normal stress, one writes $P_j = P_j(\sigma)$. But in the case of shear stress, τ, loading $P_i = P_i(\tau)$. For multiaxial loading:

$$P_T = \sum_j P_j(\sigma) + \sum_i P_i(\tau)$$

For real materials whose mechanical characteristic values range inside a dispersion interval, the critical specific energy also ranges inside a dispersion interval. Consequently, the right part of relation (1) can be replaced by the condition $P_{cr}(t) \leq 1$. Relation (1), by taking into account the relations (3) and (4), becomes:

$$P_T = P_{cr}(t), \tag{5}$$

3. Practical use of PCE

The total participation of specific energies is a dimensionless value that expresses the loading level of any physical body by considering its behaviour.

For example, if a load featuring stress Y produces effect X upon a physical body, the interdependence between the two expresses the body behaviour. In general, one resorts to the law of non-linear behaviour, function of power

$$Y = C \cdot X^k, \tag{6}$$

where C and k are constants of the physical body. The specific energy in this case is:

$$E = \int_0^X Y \cdot dX = \frac{C \cdot X^{k+1}}{k+1}. \tag{7}$$

Expressed as a result of loading Y, relation (8) becomes:

$$E = \frac{Y^{(1/k)+1}}{(k+1) \cdot C^{1/k}}. \tag{8}$$

The specific critical energy corresponds to $Y = Y_{cr}$, so that:

$$E_{cr} = \frac{Y_{cr}^{(1/k)+1}}{(k+1) \cdot C^{1/k}}. \tag{9}$$

From relations (4), (9) and (10) one acquires the expression of the specific energy participation:

$$P(Y) = \left(\frac{Y}{Y_{cr}}\right)^{1/k+1} \cdot \delta_Y, \tag{10}$$

where δ_Y means the same thing as δ_j.

When several loads n act, written as Y_i, where $i = 1; 2; \dots n$ (Figure 1), the total participation of the specific energies of action is:
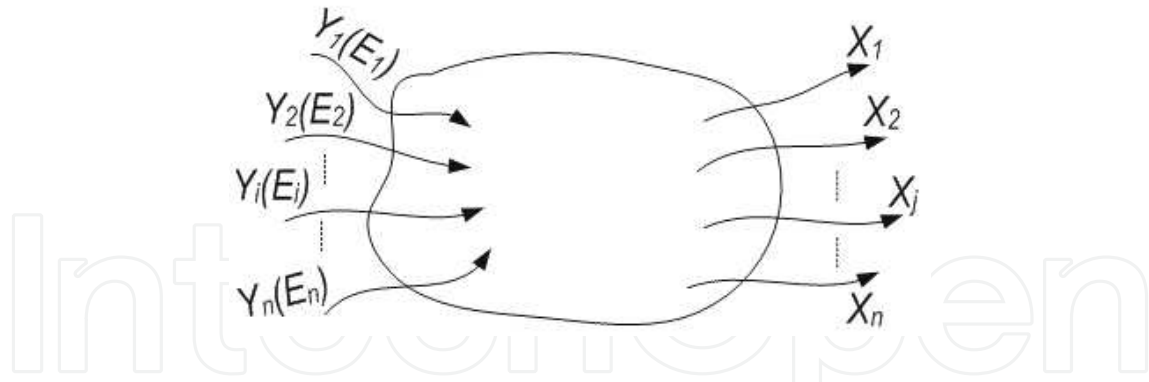
$$P_T = \sum_{i=1}^n P(Y_i). \tag{11}$$

Figure 1. Loading with stresses $Y_i(E_i)$, carrying specific energies E_i, produces upon the physical body effects X_j.

If for all loads Y_i, the behaviour of the material is given by a relation of the form (7), where the values of constants C_i and k_i are different, Eq. (12) becomes:

$$P_T = \sum_{i=1}^{n} \left(\frac{Y_i}{Y_{i,cr}} \right)^{\alpha_i + 1} \cdot \delta_{Yi}, \tag{12}$$

where $\alpha_i = 1/k_i$, and δ_{Yi} stands for δ_j.

The critical participation of specific energies, a time-dependent dimensionless variable, has the general expression [2, 12]:

$$P_{cr}(t) = P_{cr}(0) - D_T(t) - P_{res}, \tag{13}$$

where $P_{cr}(0)$ is the initial value of the critical participation at $t=0$.

The value of $P_{cr}(0)$ depends on the probability of achieving the critical condition at $t=0$. Generally, $P_{cr}(0) \in [P_{cr,\min}(0); P_{cr,\max}(0)]$, where $P_{cr,\min}(0) > 0$ and $P_{cr,\max}(0) \leq 1$. The critical participation $P_{cr}(0)$ expresses the value distribution of physical characteristics (e.g. tensile strength, σ_u, yield stress, σ_y, etc.). If one considers as deterministic (fixed; statistical averages) values of the critical physical characteristics $Y_{i,cr}$, then $P_{cr}(0)=1$.

For the *deterministic values* of the physical characteristics $Y_{i,cr}$ one replaces $P_{cr}(0)=1$, so that relation (14) becomes:

$$P_{cr}(t) = 1 - D_T(t) - P_{res}. \tag{14}$$

Relation (14) is used to interpret the experimental data, and relation (15) is used to calculate structures with deterministic calculation methods [12].

The total damage $D_T(t)$, a dimensionless value, depends on the duration of exposure, t, and one calculates it by using the general relation [3, 7, 12]:

$$D_T(t) = \sum_k D_k(t),$$ (15)

where $D_k(t)$ is the deterioration produced by loading or by cause k: crack $D(a;c)$, pre-loading $D(-t)$, corrosion $D(t_{cs})$, creep $D(t_c)$, hydrogen action $D(H^+)$, neutron action $D(n)$, magnetic action $D(B)$, vibration action $D(\omega)$, radiation flow action $D(\Phi)$, pollutant action $D(c)$, etc.

In the manufacturing of engineering components (by plastic deformation, welding, moulding, forging, etc.) there are induced residual stresses, σ_{res}, that map out the participation [2],

$$P_{res} = \left(\frac{\sigma_{res}}{\sigma_u} \right)^2 \cdot \delta_{res},$$ (16)

where $\delta_{res} = 1$ if the residual stresses act in the direction of the process taking place in the body under load and $\delta_{res} = -1$ if not.

The practical use of the results obtained lie in comparing, for a certain given moment t (Figure 2), the values of $P_T(t)$ and $P_{cr}(t)$. If

$$P_T(t) < P_{cr}(t) - \text{subcritical loading;}$$
$$P_T(t) = P_{cr}(t) - \text{critical loading;}$$ (17)
$$P_T(t) > P_{cr}(t) - \text{overcritical loading.}$$

After equalizing the expressions of participations (13) and (14),

$$\sum_{i=1}^{n} \left(\frac{Y_i}{Y_{i,cr}} \right)^{\alpha_i + 1} \cdot \delta_{Yi} = P_{cr}(0) - D_T(t) - P_{res},$$ (18)

one obtains the time life t_l, or the duration down to the moment when the body under load is destroyed (Figure 2).

In the general case of statistical value distribution of critical characteristics $Y_{i,cr}$ between a minimum $(Y_{i,cr})_{\min}$ value and a maximum $(Y_{i,cr})_{\max}$ one, the initial critical participation is itself a statistical distribution and consequently, it lies probabilistically between the corresponding curves written as $P_{cr,\min}(t)$ and $P_{cr,\max}(t)$.
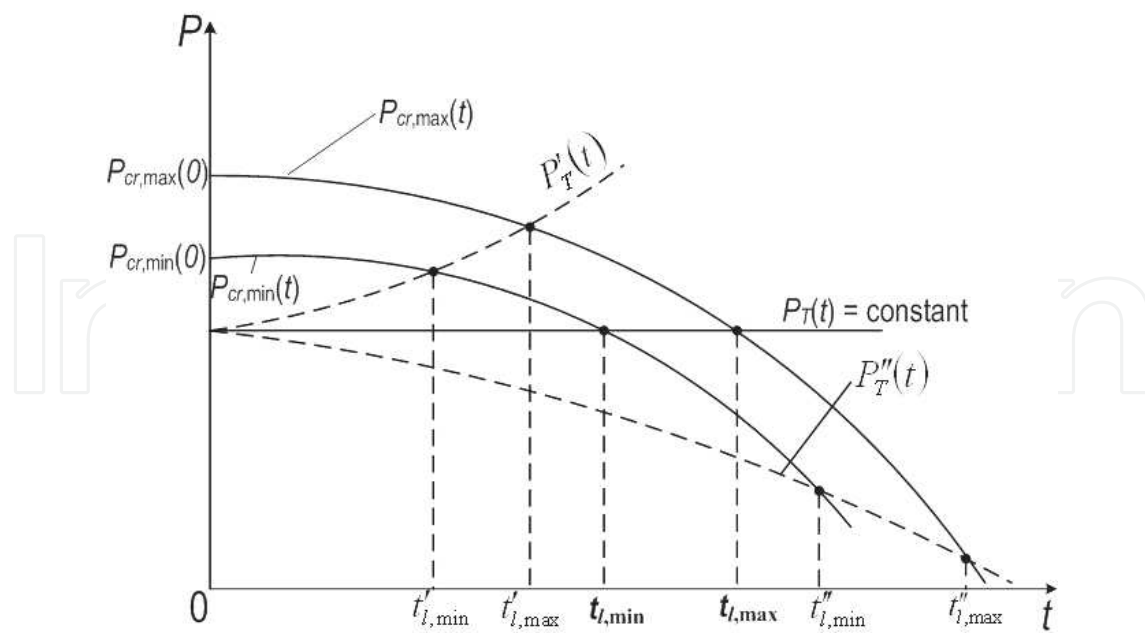
Figure 2. Lifetime with critical characteristics featuring probabilistic variables. $P_{cr,min}(t)$ corresponds to maximum probability and $P_{cr,max}(t)$ corresponds to the minimum probability of recovery of a value of the critical characteristic (e.g. the maximum probability of survival and the minimum probability of survival, respectively).

If $P_T(t)=$ constant, the lifetime lies between values $t_{l,min}$ and $t_{l,max}$, if $P_T(t)=P'(t)$ rises in time, then the lifetime decreases and it lies between $t'_{l,min}$ and $t'_{l,max}$. Similarly, if the total participation $P_T(t)=P''(t)$ decreases in time, the lifetime rises and it lies between $t''_{l,min}$ and $t''_{l,max}$.
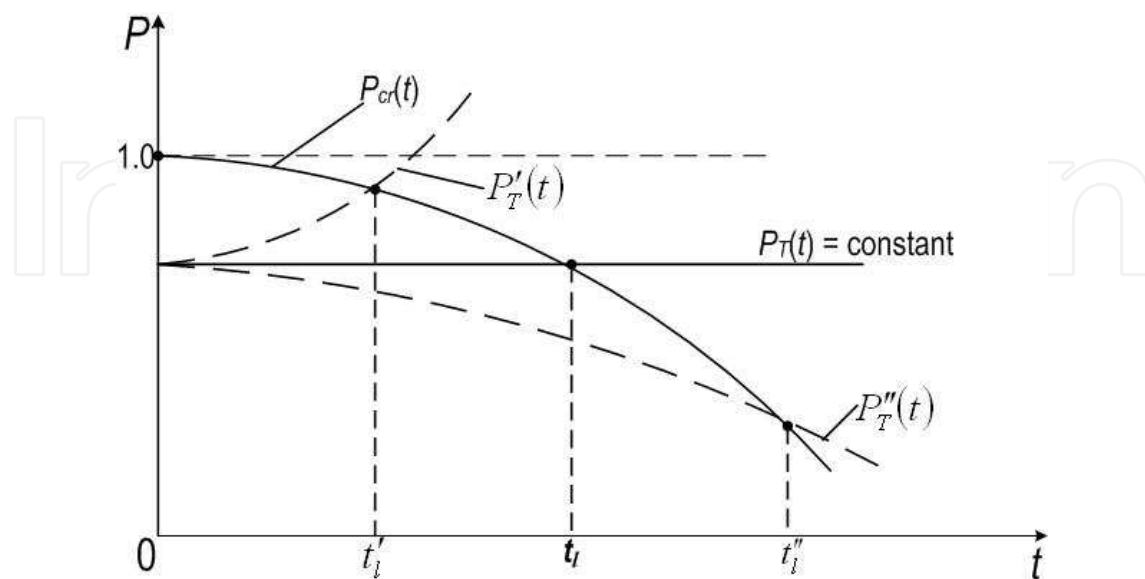

Figure 3. Lifetime when critical characteristics are deterministic variables.

In case critical characteristics $Y_{i,cr}$ feature deterministic values, critical participation $P_{cr}(0)=1$, which yields unique, precise values in the three cases analogous to Figure 2. One obtains lifetimes $t'_l < t_l < t''_l$ (Figure 3).

4. PCE application to solving problems of superposition or/and cumulation of loadings

The principle of critical energy generally refers to the effect of energy cumulation in a physical body, in connection with some phenomenon or process.

Load superposition means the simultaneous load actions upon the physical body. *Load cumulation means successive load actions in time.*

The discrimination between the superposition of effects and their cumulation is essential, especially if the effect of loading depends on the rate of applied load.

4.1. Applications in mechanical engineering

a.   One examines the superposition of effects under loading combining tensile stress, σ, bending stress, σ_b and torsion stress τ_t (Figure 4): $\sigma \sim F$; $\sigma_b \sim M_b$ and $\tau_t \sim M_t$.
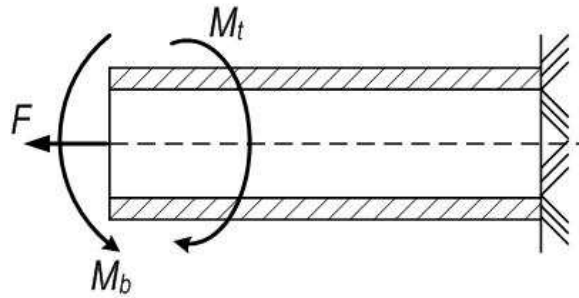

Figure 4. A tubular specimen loaded by axial force, *F*, bending moment, M_b and torsional moment, M_t.

The total participation is calculated with the general relation (12),

$$P_T = \left(\frac{\sigma}{\sigma_{cr}}\right)^{\alpha_\sigma+1} \cdot \delta_\sigma + \left(\frac{\sigma_b}{\sigma_b}\right)^{\alpha_b+1} \cdot \delta_{\sigma_b} + \left(\frac{\tau_t}{\tau_{t,cr}}\right)^{\alpha_t+1}. \tag{19}$$

Since $\sigma > 0$ (traction), $\delta_\sigma = 1$. In a stretched fibre, where $\sigma_b > 0$, $\delta_{\sigma_b} = 1$, the denominators represent the critical values of the stresses corresponding in the numerator. Generally $\alpha_\sigma = \alpha_b = \alpha_t = \alpha$, so that

$$P_{T,\max} = \left(\frac{\sigma}{\sigma_{cr}}\right)^{\alpha+1} + \left(\frac{\sigma_b}{\sigma_{b,cr}}\right)^{\alpha+1} + \left(\frac{\tau}{\tau_{t,cr}}\right)^{\alpha+1}. \tag{20}$$

If the loading state is bound not to exceed the yield stress, then one has to accept that the material features a linear elastic behaviour, in which case $k=1$ and $\alpha=1$; relation (20) becomes

$$P_{T,\max} = \left(\frac{\sigma}{\sigma_Y}\right)^2 + \left(\frac{\sigma_b}{\sigma_{b,Y}}\right)^2 + \left(\frac{\tau}{\tau_{t,Y}}\right)^2, \tag{21}$$

where σ_y, $\sigma_{b,y}$ and $\tau_{t,y}$ is the yield stress under tensile, bending and torsional stress, respectively.

Consider the particular case when loading occurs only under bending and torsional stress ($\sigma=0$). With the aid of the law of equivalence of processes and phenomena [2, 12, 18, 19] one obtained from relation (20), the equivalent bending stress:

$$\sigma_{b,ech} = \left(\sigma_b^{\alpha+1} + K \cdot \tau_t^{\alpha+1}\right)^{\frac{1}{(\alpha+1)}}. \tag{22}$$

$K = \dfrac{\sigma_{b,cr}^{\alpha+1}}{\tau_{t,cr}^{\alpha+1}}$ is a ratio of some mechanical characteristics of the material. In the linear elastic case, ($\alpha=1$) Eq. (22) becomes the known relation recommended by literature [20],

$$\sigma_{b,ech} = \left(\sigma_b^2 + K \cdot \tau_t^2\right)^{0.5}, \tag{23}$$

where K depends on the theory of strength used, not on the nature and behaviour of the material.

b. For engineering structures with cracks, PCE connects the mechanics of the deformable solids to fracture mechanics.

At present, the strength analysis of structures with cracks is done by using fracture mechanics concepts that are different from those of the mechanics of deformable solids. In the mechanics

of the deformable solids one makes use of such concepts as normal stress, shear stress, strain, etc.

In the mechanics of the deformable solids, the strength condition is expressed by inequality:

$$\sigma_{eq} \leq \sigma_{al}, \tag{24}$$

where σ_{eq} is the equivalent stress at the tip of the crack and σ_{al}, the allowable stress, calculated —generally—with the relationship:

$$\sigma_{al} = \min\left(\frac{\sigma_u}{c_u}; \frac{\sigma_y}{c_y}\right), \tag{25}$$

where σ_u is the ultimate stress; σ_y is the yield stress, while $c_u > 1$ and $c_y > 1$ are safety coefficients.

In fracture mechanics one resorts to the concepts of stress intensity factor, K_i, crack tip opening displacement, δ_i and the integral J_i, where $i = $ I, II, III, corresponds to the three accepted modes of failure (I, opening; II, sliding; III, tearing). The strength condition is expressed:

$$K_i \leq K_{i,al} \ \ \text{or} \ \ \delta_i \leq \delta_{i,al} \ \ \text{or} \ J_i \leq J_{i,al}, \tag{26}$$

where $K_{i,al}$, $\delta_{i,al}$ and $J_{i,al}$ are the allowable values of the variables K_i, δ_i and J_i.
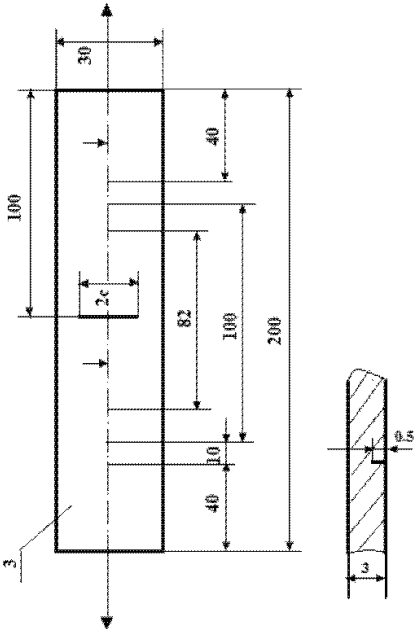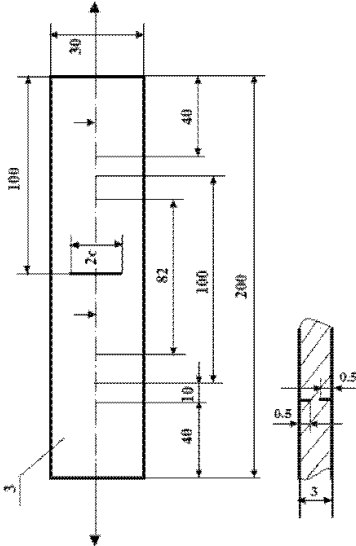
By introducing the concepts of *deterioration or damage*, with the aid of PCE there have been established the following relations of the critical stresses (ultimate stress, yield stress or allowable stress) for the structures with cracks that have characteristic dimensions a and $2c$:

$$\left. \begin{aligned} \sigma_{cr}(a;c) &= \sigma_{cr} \cdot \left[1 - D_\sigma(a;c)\right]^{\frac{1}{\alpha+1}} \\ \tau_{cr}(a;c) &= \tau_{cr} \cdot \left[1 - D_\tau(a;c)\right]^{\frac{1}{\alpha+1}} \end{aligned} \right\}, \tag{27}$$

where σ_{cr} and τ_{cr} are the critical normal and shear stresses of the structure without cracks; $D_\sigma(a;c)$ and $D_\tau(a;c)$ are the deterioration due to the crack (a, c) in the field of normal and shear stresses, respectively.

On the basis of relationships (27) one can experimentally determine the value of the deterioration. For example, Table 1 lists the values of deterioration $D_\sigma(a;c)$ calculated on the basis of the first relation (27), for some steel specimens:

$$D_\sigma\left(a;c\right) = 1 - \left(\frac{\sigma_{cr}\left(a;c\right)}{\sigma_{cr}}\right)^{\alpha+1}.$$

	Dimensions in mm	2c, mm	$\sigma_u(a;c),$ [MPa]	D(a,c)
		10	439.722	0.1045
		20	429.701	0.1652
Sample with a crack on one side		30	391.698	0.3704
		10	421.756	0.2113
		20	390.027	0.3786
Sample with cracks on both sides		30	379.444	0.4285
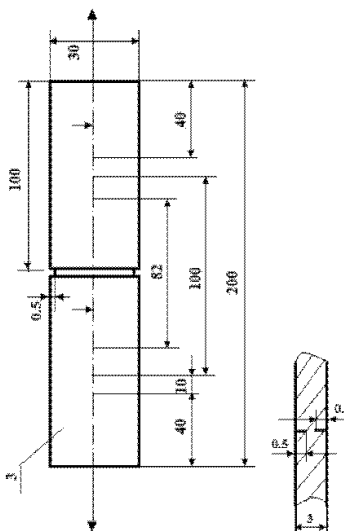
	Dimensions in mm		2c, mm	$\sigma_u(a;c)$, [MPa]	D(a,c)
Sample with around crack			29	330.447	0.6250

Table 1. The deterioration $D(a,c)$ due to crack of some steel specimens elongational loaded. The ultimate stress of the crackless specimen σ_u=455.934 [MPa]

Analogously, for the critical load of the structure with cracks one established the general relation:

$$Y_{i,cr}\left(a;c\right) = Y_{i,cr} \cdot \left[1 - D_{Y_i}\left(a;c\right)\right]^{\frac{1}{\alpha+1}},\tag{28}$$

where $Y_{i,cr}$ is the critical load for the structure without cracks; $D_{Y_i}(a;c)$ is the deterioration due to the crack within the load range (force, bending moment, torque, pressure, etc.).

The strength condition of a structure with cracks, after using PCE,

$$\sigma_{eq} \leq \sigma_{al}\left(a;c\right),\tag{29}$$

which is similar to the relationship (25) from the mechanics of deformable solids; it differs from Eq. (25) in that the allowable stress depends on the crack characteristic parameters, through the concept of deterioration,

$$\sigma_{al}\left(a;c\right) = \frac{\sigma_{cr}\left(a;c\right)}{c_\sigma},\tag{30}$$

where

$$\sigma_{cr}(a;c) = \sigma_u(a;c) = \sigma_u \cdot \left[1 - D_\sigma(a;c)\right]^{\frac{1}{\alpha+1}}. \tag{31}$$

The equivalent stress is calculated in the same way as in relationship (25).

The use of relations (29)–(31) requires the determination of deterioration value $D_\sigma(a;c)$ as it was done in works [7, 15–17, 21–24].

The method of calculating presented may replace the calculation based on the concepts of fracture mechanics (26). The connection with fracture mechanics lies only in the calculation of deterioration based on crack geometry.

4.2. Thermomechanical-chemical application

One examines the superposition of actions under static loads featuring constant stress σ in creep conditions of a body lying in a corrosive environment for time t_{cs}. The total participation of an action featuring stress σ is calculated with relation (12):

$$P_T = \left(\frac{\sigma}{\sigma_{cr}}\right)^{\alpha+1}, \tag{32}$$

where $\delta_\sigma = \delta_{Y_i} = 1$.

The influence of loading beyond creep temperature and corrosion influence intervene in calculating the total deterioration:

$$D_T(t) = D(t_c;T_c) + D(t_{cs}), \tag{33}$$

where $D(t_c;T_c)$ is the deterioration resulting from loading at temperature (creep temperature) over interval t_c, and $D(t_{cs})$ is the damage caused by corrosive action over interval t_{cs} [3, 7].

The critical stress that takes into consideration the deterioration results from the second equation (17), from relations (13) and (32):

$$\sigma_{cr}(D) = \sigma_{cr} \cdot \left[1 - D_T(t) - P_{res}\right]^{\frac{1}{\alpha+1}}, \tag{34}$$

where σ_{cr} is the critical stress of the undamaged material ($D_T(t)=0$) and without residual stresses ($P_{res}=0$).

Other applications of the PCE have been summarized in [1, 2, 12], such as the superposition of mechanical and electrical effects, the superposition of the mechanical loads and magnetic field by shells/buckling, the superposition of effects in thermoelectromagnetism, etc.

4.3. Applications in the field of multiple pollution

The natural environment can be polluted chemically, electromagnetically, thermally, nuclearly, etc. To date, the individual maximum/allowable concentrations of various pollutants affecting the environment and the living organisms have been identified [25–36]. The crucial issue lies in determining when the critical state is reached in case two or several pollutants act simultaneously and/or successively.

Actually, one has to deal with the superposition of pollutant action, or the cumulation of their action and sometimes with the superposition and cumulation of their action. The problem is solved relatively simply by using PCE, according to which the total participation of pollutant action is equal to the sum of their individual participations. By analogy with Eq. (4) we may write:

$$P_T(t) = \sum_i P_i \left[\left(c_{p,i} \right) ; t_i \right],$$ (35)

where $c_{p,i}$ is the pollutant concentration i acting over time t_i.

For the sake of generality, one allows that the relation between the pollutant and its effect is a power law, similar to law (6), namely:

$$c_{p,i}(t) = M_{c_{p,i}} \cdot e_{p,i}^{k_{p,i}}(t)$$ (36)

where $M_{c_{p,i}}$ și $k_{p,i}$ are constants while $e_{p,i}(t)$ is the effect of the pollutant upon the natural environment, living organisms, plants, etc.

By analogy with the general relation (12) one gets the total participation caused by pollutant action:

$$P_T(c_p) = \sum \left[\frac{c_{p,i}(t)}{\left(c_{p,i} \right)_{cr}} \right]^{\alpha_{p,i}+1}$$ (37)

where $\left(c_{p,i} \right)_{cr}$ is the critical concentration of the pollutant i, while $\alpha_{p,i} = 1/k_{p,i}$. The critical or allowable value of the concentration is specific to the biophysical factor that is being calculated (water, air, earth, some plant, some living organism...), as shown in the examples listed in Tables 2 and 3.

Physical or chemical agent pollutant	UM	Maximum allowable concentration (MCA)			The limit value for protection of ecosystems			Limit value for protection of human health		
		The period of mediation								
		1 h	24 h	1 year	1 h	24 h	1 year	1 h	24 h	1 year
Benzene	$\mu g/m^3$	-	-	5	-	-	-	-	-	5
Carbon monoxide	mg/m^3	-	10	-	-	-	-	-	-	-
Lead	$\mu g/m^3$	-	-	0.5	-	-	-	-	-	-
Arsenic	ng/m^3	-	-	6	-	3.6	-	-	3.6	-
Cadmium	ng/m^3	-	-	5	-	3	-	-	3	-
Nickel	ng/m^3	-	-	20	-	14	-	-	14	-
Benzo (a) pyrene	ng/m^3	-	-	1	-	0.6	-	-	0.6	-

Table 2. Maximum allowable concentration for environment factors in air (extracted with permission from [27])

Global indicators	UM	Waste water discharges in sewer networks	Waste water discharges into natural receivers
A. Physical and chemical indicators			
Maximum temperature of discharge	^0C	40	35
pH of wastewater discharge	pH units	6.5–8.5	6.5–8.5
B. Pollutants discharged maximum allowable concentration (MCA)			
Suspensions	mg/dm^3	350	35.0
Ammonia nitrogen (NH_4^+)	mg/dm^3	30	2.0
Sulphur and hydrogen sulphide(S_2^-)	mg/dm^3	1.0	0.5
Sulphites (SO_3^{2-})	mg/dm^3	2	11.0
Total phosphorus(P)	mg/dm^3	5.0	1.0
Total cyanide(CN)	mg/dm^3	1.0	0.1
Free residual chlorine(Cl_2)	mg/dm^3	0.5	0.2
Lead (Pb^{2+})	mg/dm^3	0.5	0.2
Cadmium(Cd^{2+})	mg/dm^3	0.3	0.2
Hexavalent chromium(Cr^{6+})	mg/dm^3	0.2	0.1
Copper (Cu^{2+})	mg/dm^3	0.2	0.1
Nickel (Ni^{2+})	mg/dm^3	1.0	0.5
Zinc (Zn^{2+})	mg/dm^3	1.0	0.5
Total manganese (Mn)	mg/dm^3	2.0	1.0

Table 3. Maximum allowable concentration for environment factors in water (extracted with permission from [29])

The total participation thus calculated is compared to the critical participation,

$$P_{cr}(t) = 1 - D_T(-t)$$ (38)

where $D_T(-t)$ previously produced deterioration $(-t)$ upon the biophysical factor.

If $P_T(c_p) < P_{cr}(t)$ the status of the biophysical factor is subcritical, while if $P_T(c_p) \geq P_{cr}(t)$ — the state is critical or supercritical.

Sometimes the interaction of pollutants from a mixture produces a change in their behaviour, as they mutually enhance their obnoxious effects. One can get a positive synergistic effect, meaning that the effect of the mixture is greater than the sum of the individual effects of the pollutants [14]. Positive synergism does not mean that one can get more out of 'something plus something else', but it means that the behaviour of that 'something' changes in the presence of the 'something else' which makes the whole effect be greater than the sum of the composing effects!

4.4. Application in the medical field

A body or an organism can be subjected to the action of several harmful external factors, such as: radiation flow (ultraviolet, thermal, neutrons, X-ray, etc.), viruses, stresses, etc. The total effects of the cumulative action of a viruses, a radiation, stress and a pollutant upon an organism, or upon a particular cell, may be obtained by calculating the total participation of the specific energies,

$$P_t(t) = \left(\frac{m_v}{m_{v,cr}}\right)^{\alpha_v + 1} + \left(\frac{\Phi}{\Phi_{cr}}\right)^{\alpha_\Phi + 1} + \left(\frac{S}{S_{cr}}\right)^{\alpha_S + 1} + \left(\frac{c}{c_{cr}}\right)^{\alpha_c + 1}$$ (39)

where m_v and $m_{v,cr}$ is the 'quantity' of a certain virus and its critical values; Φ and Φ_{cr} is the certain radiation flow and its critical value; S and S_{cr} is the stress produced upon the organism and its critical value; c and c_{cr} is the concentration and its critical value of a certain pollutant. The exponents α_v, α_Φ, α_S and α_c have the meaning of α_i from Eq. (12). That means the virus behaviour, the radiation flow behaviour, the stress behaviour and the pollutant behaviour are nonlinear and are described by general law (6).

If they are more external action for each category the total participation is:

$$P_T(t) = \sum_i \left(\frac{m_{v,i}}{(m_{v,i})_{cr}}\right)^{\alpha_{v_i} + 1} + \sum_j \left(\frac{\Phi_j}{\Phi_{j,cr}}\right)^{\alpha_{\Phi_j} + 1} + \sum_k \left(\frac{S_k}{S_{k,cr}}\right)^{\alpha_{S_k} + 1} + \sum_l \left(\frac{c_l}{c_{l,cr}}\right)^{\alpha_{c_l} + 1}$$ (40)

If $P_t(t)<1$ or $P_T(t)<1$ the critical state is not attained, whereas if $P_t \geq 1$ of $P_T(t) \geq 1$ the critical state is reached or exceeded (the organism dies).

The critical participation contains deterioration of the living body and the weakness due to lack of vitamins, oligoelements, etc. W_n, such as:

$$P_{cr}(t) = 1 - D(t) - \sum_n W_n \qquad (41)$$

If $P_T(t)<P_{cr}(t)$, the critical state is not attained.

In order to help the organism to survive, or to get beyond the state of temporary illness, one administrates a quantity of medication m, whose critical value is m_{cr}. The medication partici-pations opposes the weakness, such as,

$$P_{cr}(t) = 1 - D(t) - \sum_n W_n + \left(\frac{m}{m_{cr}}\right)^{\alpha_m + 1} \qquad (42)$$

can be higher the unity.

If more useful medication will be administered,

$$P_{cr}(t) = 1 - D(t) - \sum_n W_n + \sum_p \left(\frac{m_p}{m_{p,cr}}\right)^{\alpha_{m,p} + 1} \qquad (43)$$

4.5. Viscoelastic and elastoviscos behaviours

The unitary properties of matter at the microscopic scale are viscosity (μ) and elasticity (E). Viscosity as a property is associated to purely viscous fluids, while the elastic property is associated with purely elastic bodies.

Actually, matter is viscoelastic if viscosity prevails and it is elastoviscos if elasticity prevails. For a real physical body, which features the two properties in different ratios, based on PCE one can write that the total participation of specific energies is:

$$P(\mu) + P(E) = 1 \qquad (44)$$

where $P(\mu)$ is the contribution of the viscous component, whereas $P(E)$ is the contribution of the elastic component.

If $P(\mu)=0$, the body is perfectly elastic ($P_T=P(E)$), whereas if $P(E)=0$, the body is perfectly viscous ($P_T=P(\mu)$).

If: $P(\mu)<P(E)$ —the body is elastoviscos;

$P(\mu)>P(E)$ —the body is viscoelastic.

The *purely elastic nonlinear* behaviour is mapped on the form of the general law (6),

$$\sigma = M_\sigma \cdot \varepsilon^k \tag{45}$$

where σ is the normal stress, ε —strain, while M_σ and k —constants of the elastic solid.

The *purely viscous nonlinear* behaviour is given by Oswald—de Waele's law

$$\tau = K \cdot \dot{\gamma}^v \tag{46}$$

where τ is the shear stress, $\dot{\gamma}$ is the shear strain, K and v are the constants of the viscous fluid.

The participation of the specific energy corresponding to the elastic component is:

$$P(E) = \left(\frac{\sigma}{\sigma_{cr}}\right)^{\alpha+1} \tag{47}$$

where $\alpha=1/k$.

The participation of the specific energy corresponding to the viscous component is:

$$P(\mu) = \left(\frac{\tau}{\tau_{cr}}\right)^{\beta+1}, \tag{48}$$

where $\beta=1/v$.

Out of relations (43), (46) and (47), one gets:

$$\left(\frac{\sigma}{\sigma_{cr}}\right)^{\alpha+1} + \left(\frac{\tau}{\tau_{cr}}\right)^{\beta+1} = 1 \tag{49}$$

The graphical representation of the relationship (48) in Figure 5 separates the zone of elasto-viscos bodies from the zone of viscoelastic bodies.
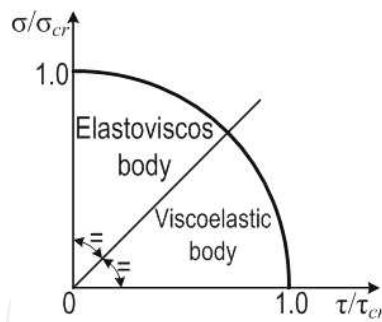
Figure 5. Graphic representation of relation (48).

4.6. The principle of critical energy, synergy and catastrophe theory

The principle of critical energy combines the essentials of synergetics and catastrophe theory. This statement is easy to account for:

- The total effect, P_T, according to PCE is obtained as the sum of the partial effects P_i, produced by the actions of Y_i. Thus, the total effect results from the *cooperation* of several actions that are external and/or internal to the body analysed. But one of the basic principles of synergetics[1]

- According to the principle of critical energy, a phenomenon is triggered when the accumulated specific energy likely to jumpstart it reaches its critical value. This cumulation can be slow, fast or sudden. On the other hand, the transformation achieved by reaching the critical specific energy is often sudden, it is a leap. Such a leap can be catastrophic or dramatic.

Such a sudden transformation has been called catastrophe [38]. It underlies the theory of catastrophe [39]. Here are some examples of leap-type transformations which are the object of the theory of catastrophes and also lie at the core of some particular cases of PCE application: buckling bars, ice melting, water boiling, earthquakes, the camel back likely to withstand n loadings, but fails—as well known—under load $n + 1$, a cell that suddenly changes its reproduction rate, doubles and redoubles, etc. Some phenomena are triggered when the friction forces are overcome, like the rustling of a plant, or the noise of an earthquake.

The cumulation of the state of stress (frustration, desolation), coupled with alienation (alienation, lack of communication) may lead at a certain moment, in prisons, to rebellion. There is a sudden violent switch from quiet to disturbance, to disorder.

Bar buckling, for example, was first analysed by Euler [40] that is so long before the emergence of the catastrophe theory, a theory capable to bring some clarity on structural instability,

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1 Synergetics studies: the common actions of the micro-components of an open system meant to attain a certain goal. With this aim in view, the system may exchange energy and mass; the macroscopic structures that appear in the sudden transition between the two states of the system, due to their cooperation.

For instance, when a **critical value** of a physcial parametre has been exceeded, the microscopic components of the system may suddenly start working in the same direction. The effect obtained at a macroscoppic level is a state of the system that is qualitatively different from the previous state. [37] is precisely the cooperation principle (the principle of effects superposition through self-organizing at a microscopic scale).

characterized by abrupt changes when the critical value of loading is reached. The problem of structural stability (including bar buckling) was extensively analysed on the basis of the principle of critical energy in [41].

5. Conclusions

The critical energy principle, a principle of Energonics, turned out to have a high degree of generality and it is—in essence—transdisciplinary. Its application in a number of tangible cases of superposition and/or cumulation of actions upon a physical body, assigns it to the inter-disciplinary area.

The reason why PCE can be used in all cases of actions upon physical or biophysical bodies comes from its being based on the concept of specific energy and the fact that it introduced the sign of external action in relation to a process or some phenomenon.

Nevertheless, the essential element that makes PCE likely to be used in the superposition or cumulation of actions of various types, but mostly, of different nature comes from the fact that PCE introduced the concept of specific energy participation, a dimensionless value dependent on material behaviour.

On the other hand, the definition of the concept of critical participation in connection with the structural deterioration caused by cracks, aging, overload, etc., allowed the calculation of their strength or the computation of their lifetime without resorting to the concepts of fracture mechanics.

The few practical examples of solving problems of action superposition, both in physical bodies as well as in living organisms, subjected to various external actions (mechanical, chemical and electromagnetic loading, some pollutant actions, of some medicine, etc.) confirms the trans-disciplinary of the principle of critical energy, its great degree of generality.

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