Finite Causal Processes in Engineering

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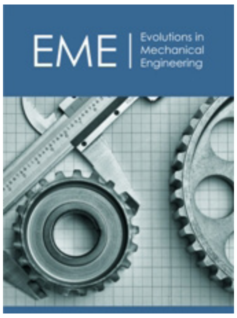

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Introduction

The review summarizes the properties of finite causal processes until a cause can produce the effect. Next, it presents the material yielding as a finite cause (stress) and effect (strain) interaction instead of curve fitting.

The Finite Cause and Effect Interaction

An ideal Cause and Effect (CE) relation expresses the direct proportionality $C \Rightarrow E(C)$ between the driving cause C and the ensuing effect $E(C)$ with progression rate p representing the initial propensity to interaction:

$$E(C) = p \cdot C \qquad (1)$$

The causal process theory affirms the causation in terms of interactions $I(E,C)$ between $E(C)$ and C [1]. Studies of $C \Leftrightarrow E(C)$ Finite Cause and Effect Interactions (FCEI) limited by finite ultimate cause CU are earlier applied on practical problems how things worsen [2], material plasticity [3] and fatigue life predictions [4]. The FCEI concept implies that the perpetuating total effect $E(C, I)$ is decomposable into a primary linear relation $E(C)$ as in (1) and into a quantifiable interaction $I(E,C)$ between cause C and effect $E(C)$ induced by the effect of feedback $F[E(C)]$ of the effect $E(C)$ to the primary cause C, as presented below (Figure 1):

$$E(C,I) = E(C) + I(E,C) \qquad (2)$$

The FCEI relation in dimensionless format is presented by a dimensionless variable $c=C/C_U$ in the range 0-1.

The prescribed property of FCEI imposes that the interaction $I(C,E)$ is the effect of the feedback $E\{F[E(C)]\}$ of effect $E(C)$, due to the ultimate capacity C_U. The rate of change of interaction $I(E,C)$ depends not only upon the effect $E(C)$ (1) but also in the counter proportion to the remaining causal capacity (C_U-C) (Figure 1), as follows:

$$\frac{dI(E,C)}{dC} = i \cdot \frac{E(C)}{C_U - C} = i \cdot \frac{C}{C_U - C} = i \cdot \frac{c}{1-c} \qquad (3)$$

The constant i in (3) is the interaction intensity parameter.

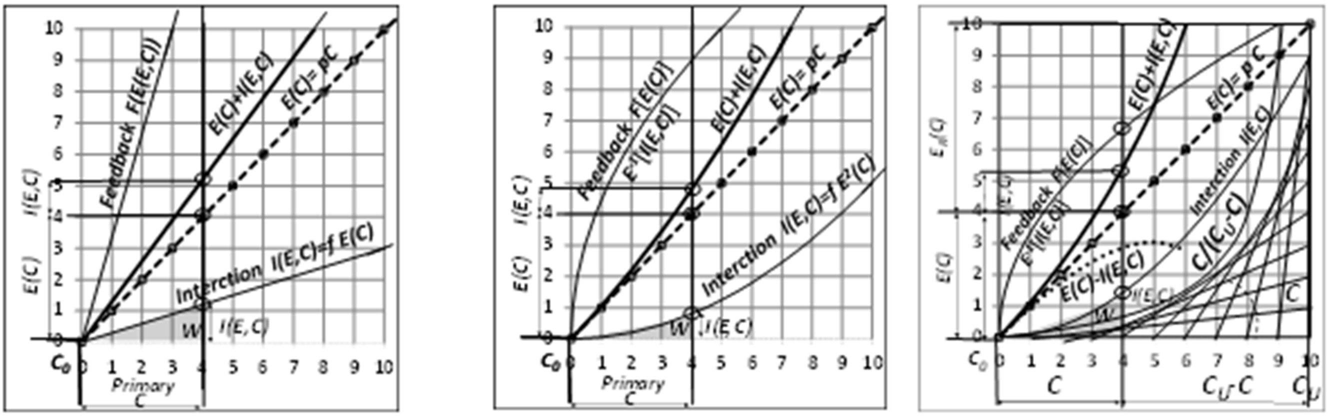
The interaction $I(C,E)$ is the integral of (3) as show:

$$I(C,E) = \int_0^C \frac{dI(E,C)}{dC} = i \cdot C_U \cdot \left[-c - \ln(1-c)\right] \qquad (4)$$

The term (3) represents the asymptotic growth of the slope of the FCEI curve (4) (Figure 1).

The overall effect of interaction (4) is logarithmic and amounts to:

$$E(C,I) = E(C) + I(E,C) = C_U \cdot \left\{pc + i \cdot \left[-c - \ln(1-C)\right]\right\} \qquad (5)$$



Linear feedback Quadratic feedback FCEI

Figure 1:

The potential of a FCEI process represents its capability for interaction is the integral of (5) as follows:

$$W\left[I(E,C)\right]=\int_0^C I(E,C)dC=i\cdot C_U^2\cdot\left\{-c^2/2+\left[c+(1-c)\cdot\ln(1-c)\right]\right\} \quad (6)$$

Empirical Presentation of Non-Linear Material Strains

In the widest practical use in material testing is the mathematical approximation for non-linear stress (σ) and strain (ε) curves proposed in 1943 by Ramberg and Osgood (RO) [5], as it is shown below:

$$\varepsilon=\int_0^\sigma \frac{d\varepsilon}{d\sigma}d\sigma=\frac{\sigma}{E}+K\cdot\left(\frac{\sigma}{E}\right)^n \quad (7)$$

K and n are two constant parameters of the power rule (7) normally obtainable by tensile testing.

Stress-Strain Interaction Model of Material Yielding

The analytic formulation for material Stress and Strain Interaction (SSI) $\varepsilon \Leftrightarrow \sigma$ on the macroscopic level is reconsidered in terms of the FCEI concept as the interaction between the progressing internal bond breakings C and the enduring resistance of remaining unbroken bonds (C_U-C) at the material micro-structural level [3]. The Hook's elastic Stress σ (the cause C) and Strain ε (the effect E) (SS) relation is a typical example of an ideal CE relation $\varepsilon \Leftarrow \sigma$ as in (1), normally known from the initial material properties (Figure 2-4):

$$\varepsilon(\sigma)=p\cdot\sigma \quad (8)$$

Values $s=\sigma/\sigma_R$ and $e=\varepsilon/\varepsilon_R$ represent the normalized CE relation (8) where the appropriate reference stress σ_R and the reference strain ε_R are the material properties (Figure 2-4). Following the FCEI concept (2-6) the SSI thesis is that the overall strain is decomposable into primary linear strain $\varepsilon=\varepsilon(\sigma)$ and into accumulation of secondary strains $\varepsilon=\varepsilon(\sigma_I)$ due to interactions of strains and stresses, as in (5):

$$\varepsilon(\sigma,\sigma_I)=\varepsilon(\sigma)+\varepsilon(\sigma_I) \quad (9)$$

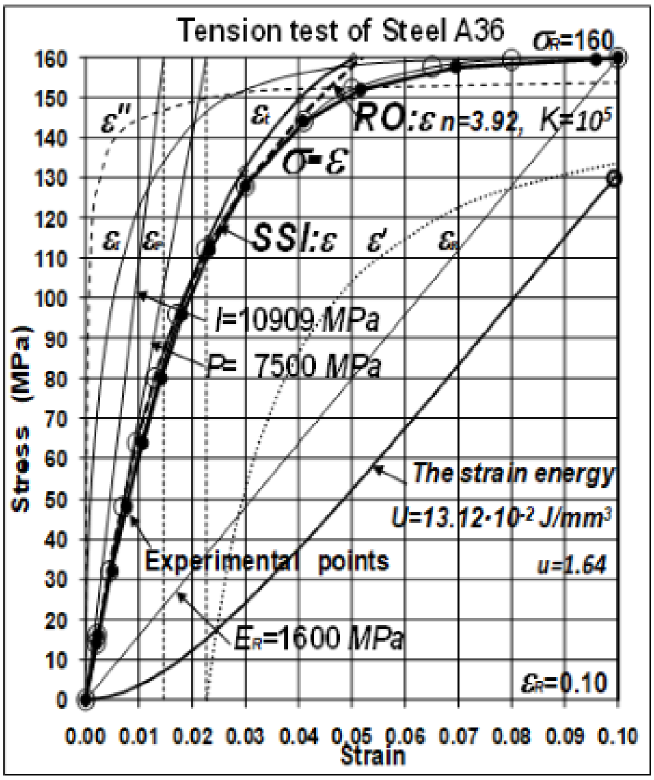


Figure 2: The SSI and RO yielding parameters of steel A36 [6] in $\sigma-\varepsilon$ diagrams.

The basic FCEI assumption is that the progression of strains $\varepsilon(\sigma_I)=i\cdot\sigma_I$ at rate i due to interaction is induced by the changes of stresses σ_I affected by the remaining endurance $\sigma_R-\sigma$ is as in (3):

$$\frac{d\varepsilon(\sigma_I)}{d\sigma}=i\cdot\frac{d\sigma_I}{d\sigma}=i\cdot\frac{s}{1-s} \quad (10)$$

The strain accumulation ε_I due to the SSI is derived as the integral of the interaction rate (10) as shown:

$$\varepsilon(\sigma_I)=i\cdot\sigma_R\cdot\left(-s-\ln(1-s)\right) \quad (11)$$

The parameter i in (10) and (11) is appropriate to the yielding intensity.

The term (10) represents the slope of the SSI curve (11).

The resulting overall strain ε superimposes the primary elastic strain $\varepsilon(\sigma)$ as in (1) and of the strains $\varepsilon_I(\sigma,\varepsilon)$ induced by interaction (5) as follows (Figure 2):

$$\varepsilon(\sigma,\sigma_I)=\varepsilon(\sigma)+\varepsilon(\sigma_I)=\int_0^{\sigma}\frac{d\varepsilon(\sigma,\sigma_I)}{d\sigma}d\sigma=\sigma_R\cdot\left[p\cdot s+i\cdot(-s-\ln(1-s))\right] \quad (12)$$

The potential of a FCEI process represents its capability for interaction is the integral of (5) as follows:

$$U\left[\varepsilon(\sigma_i)\right]=i\cdot\sigma_R^2\cdot\left\{-s^2/2+\left[s+(1-s)\cdot\ln(1-s)\right]\right\} \quad (13)$$

The yielding intensity follows from the potential (13) for s=1, based on reported stress-strain data:

$$i=2\cdot U\left[\varepsilon(\sigma_i)\right]/\sigma_R^2 \quad (14)$$

The second derivative of (10) represents the sensitivity of the strain rate as follows:

$$\frac{d^2\varepsilon}{d\sigma^2}=\frac{1}{I}\left(\frac{\sigma_R}{\sigma_R-\sigma}\right)^2=i\cdot\frac{1}{(1-s)^2} \quad (15)$$

The above reasoning (8-15) for yielding can be adapted to necking of materials (Figure 3,4).

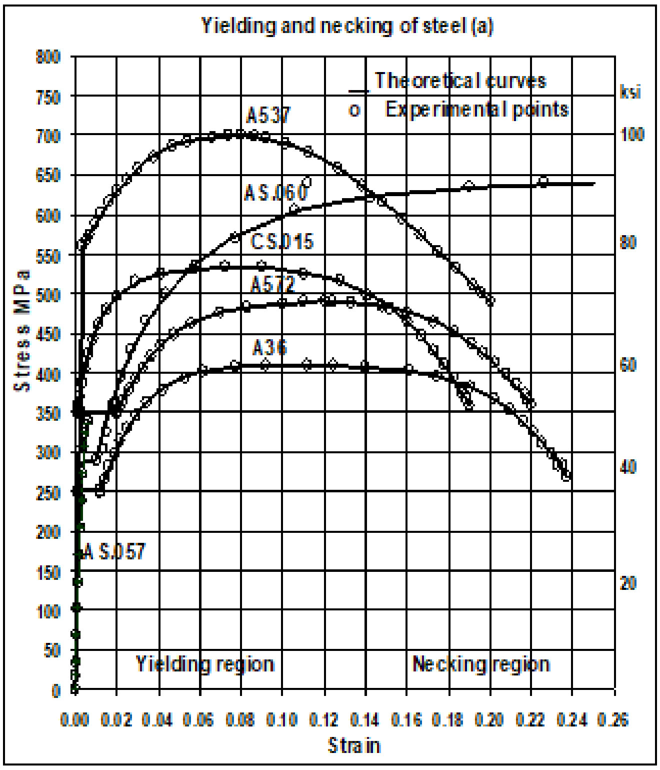


Figure 3: The SSI and RO yielding parameters of four types of steels [6] in $\sigma-\varepsilon$ diagrams.

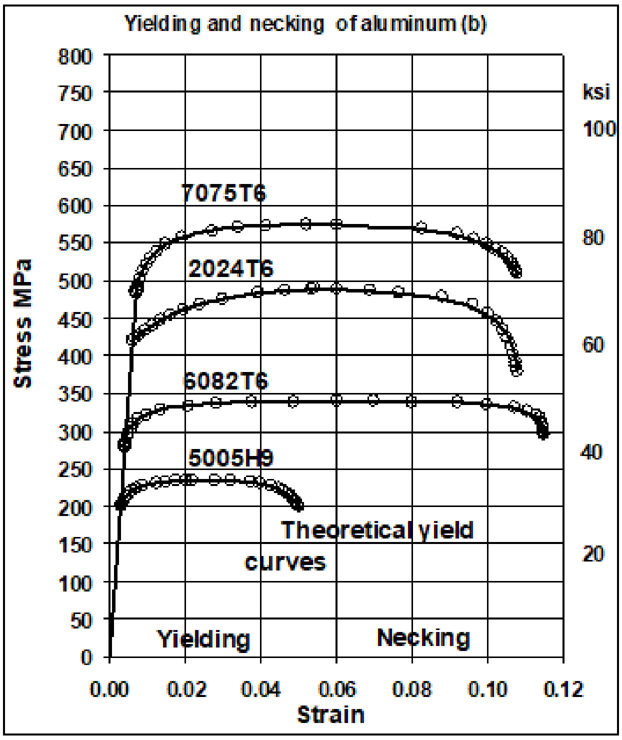


Figure 4: The SSI and RO yielding parameters of four types of aluminum [6] in $\sigma-\varepsilon$ diagrams.

Examples

The goal of the following examples is to compare the SSI parameters based on the FCEI concept with reported parameters of realistic materials with crystalline structures, metals and alloys. The reference values σ_R and ε_R, as well as the initial modulus P are known from material testing. The FCEI is defined by the interaction propensity p=1/P and the interaction intensity parameter i=1/I. The yielding modulus I is calculated from strain energy (13) normally derivable by integration of the $\sigma-\varepsilon$ curves. The first numerical example elaborates the tension test results for Steel A36 [6] (Figure 2) in FCEI terms. The second and third examples elaborate the four types of steels and aluminums (Figure 3,4). The examples show that the SSI model aptly describes the reported engineering stress-strain curves.

Conclusion

The FCEI concept suggests that cause-stress and effect-strain mutually interact under external loading. The examples uphold that micro-structural propagations of dislocations triggered by progressing bond breakings and by observable macroscopic material strains can be theoretically related and practically evaluated by using the FCEI concept to define the SSI model. The initial propensity represents the starting micro-structural internal constellation of constituent material particles and their bonds that are normally evident based on initial conditions. The interaction intensity may be viewed as the averaging of massive progression of dislocations, including the material imperfections and shape irregularities, by a single parameter which is obtainable from the overall causal potential and evident from the experiments.

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