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Scalability and homogenization of transitional functions: Effects of non-equilibrium and non-homogeneity

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ABSTRACT

Mono-scale functions refer to the individual scale range of the SI system of measurement. Coarseness of the segmented scale was dictated by state-of-the-art of technology at that time. By to-day's standard, non-equilibrium and non-homogeneity (NENH) are first order considerations whereby scales must be refined to include micro, nano and pico effects. The conventional technology applies to monoscaling, confined to equilibrium and homogeneity (E&M). Their conversion to multiscaling requires the use of transitional functions. The ultra high strength and light weight structural materials rely on the absorption of energy at more than one scale. For considerations are effects at microscopic, nanoscopic and picoscopic scales.

The irony is that NENH are subject to eventual homogenization for otherwise the multiscale effects could not be transferred to improve and modify the monoscale rules in practices. To this end, additional Postulate and Corollary are needed to account for scale directionality of energy transfer, prevalent to NENH. Direction-dependency differentiates the transition of macro → micro and micro → macro. Transitional functions are not the same when they traverse up and down the scale. Homogenization averages out NENH effects such that corrections may be applied to monoscaling.

Transitional functions can lock-in the load, material and geometry effects of the macro–micro test data to produce the nano-pico data. This is related to the obtainment of small crack data from large crack test data. To this end, the volume energy density factor (VEDF) or the volume energy density (VED) can be used as the transitional functions as a form-invariant criterion such that multiscale effects can be used to correct and modify monoscale results. *When NENH effects are highly localized and cannot be averaged out, the time rate of VEDF and VED or the equivalent of the power energy density must be used.*

The *scalar* correction for NENH is derived for the macro–micro cracking of a line crack subject to the combined effects of loading, material and geometry. Two correction factors Λ and Ω are used, one for macro → micro and another for micro → macro. The outcome can be checked by results for crack length and/or crack growth rate.

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1. Introduction

The technology of the 21st century invokes multiscaling, to which non-equilibrium and non-homogeneity (NENH) are the rules rather than the exception. The current design know-how and manufacturing practice are locked-in by the rules of equilibrium and homogeneity. These inconsistencies can through off the design requirements. The additional costs of refitting and late delivery have resulted multi-billion dollars of rivalry between the Boeing 787 and Airbus A350. Regulatory agencies [1] are no replacement for learning the potential danger of highly localized power energy density. Structural designers are not accustomed to local energy releases as high as 10–100 times larger than that encountered in fracture by cracking. A localized miniaturized explosion has the potential to trigger disaster in a large structure. The manufacturers of wide body aircrafts may be experiencing the transition of conventional technology (CVT) of monoscaling to multiscaling technology (MST).

In a nut shell, ultra high power in a micro or nano unit volume results in energy localization. It is equivalent to a "hotspot" in an otherwise homogeneous medium. These hotspots, can trigger sudden release of energy. The situation is analogous to localized energy concentration at the singular crack tip encountered during the earlier days of designing pressurized jet transport cabins. Pressurized cabins exploded in mid air for no apparent reason, not until

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the cause of disaster was known such that the excessive energy could be contained locally. The discipline that made this possible was known as "fracture mechanics". MST presents a new challenge, beyond the know-how of CVT. The issues at stake are the hotspots in contrast to the crack tips, except the power density of the hotspots are several orders of magnitude more intense.The ineptness of the current situation can be summarized:

- Containment of hotspots with CVT.
- Remove hotspots and use CVT.

The alternative choice to determine the cause of failure caused by the hotspots is the long term solution. The CVT has to be replaced by MST for the design of wide body jet transports. There is always a price to be paid for the advancement of science and technology. In the meantime, the correction of CVT by homogenization can serve as a short term remedy but not the cure. Conditions of severe localized NENH must be properly accounted for.

MST calls for the use of transitional functions [2,3] that enable the simultaneous treatment of NENH according to scale segmentation [4,5]. Monoscaling defies scale shifting [6,7] and scale segmentation, which is the basis of multiscaling. *The incompatibility between monoscaling and mulltiscaling is a fundamental issue that is not likely to be resolved in this century. On the other hand, application calls for the use of monoscale results in the presence of mutiscaling, even though apparent incompatibility stands in the way. Corrective measures are thought only as a refuge*. The impasse of the uniaxial stress and strain data from one scale to another stems from the inability to relate the macrostress and macrostrain to microstress and microstrain. No theories to-day are able to treat dual scaling. Macro–micro effects are implicated only superficially by assumed and invalidated criteria. There are no acceptable relations established for stress and strain at the macrosocpic and microscopic scale [8]. In other words, empirical data for large and small specimens remain as separate entities. Existing scaling laws apply to rigid bodies and not to deformable bodies where NENH are involved. The 21st century can no longer rely on the testing know-how of the 18th century.

2. Scale shifting necessitated by segmentation: Violation of the first principles

When models and theories violate the first principles, they can be ambiguous. One of the tests for this violation is the positive definiteness of the surface energy density of VEDF [9] and/or the volume energy density (VED) as they are connected [10]. Negative VEDF or VED can occur when multiscale data are used to fit monoscale parameters. The negative portions of the results are often disregarded or unreported. Open literature examples can be found in [9] and the references therein.

2.1. Negative monoscale energy release rate (EER)

The EER and path independent integrals are based on the a priori assumption of monoscaling. They yield negative results when using multiscale data, theoretically or experimentally. That is they contradict their initial direction of energy flow. Under dual scaling, ERR has been known to yield negative results [9] when both macro and micro effects are present. Multiscaling can benefit the durability of materials and structures. The following monoscale criteria when applied to dual scale data can yield contradictory results:

- ERR assumes the release of a unit macrocrack surface, a monoscale proposition.
- Path independent integrals invoke monoscale energy conservation.

Traditional fracture mechanics has also relied on the equivalency of EER and path independent integrals to justify their use in situations other than monoscaling. They entail non-elasticity, non-local, damage mechanics theories and others, all of which invoke *superficially created* length or damage parameters that do not address scale transition. Simply put, scale crossing, say from macro → micro or micro → macro, is not addressed with the effects of NENH. Models with empirically fitted length or damage parameters are basically monoscale that assumes equilibrium and homogeneity (E&M). They are vulnerable to contradictions when using multiscale data. Among the more serious violations of the first principles are those empirical models developed from path independent integrals, often used for creep and fatigue. Negative results for creep and fatigue imply that the physical process is highly path dependent and can no way be assumed as path independent.

2.2. Relaxing the monoscale restriction of EER

Non-violation of the first principles should be observed as a rule such that contradictions and ambiguities can be minimized. This should apply to the use and definition of strength and toughness which are based on the notion of stress and EER under the conditions of equilibrium and homogeneity (E&H). However, strength toughness test data are inherently NENH. The inconsistency has been hush-hushed into material testing by the professional societies. *Multiscaling and NENH, however, are case specific that defies standardization.* It is not surprising that empirical models and theories based on monoscaling can only add to the further wide spread of ambiguities, especially when multiscaling becomes more pronounced.

The rules of monoscaling of the conventional definition of strength and toughness have to be relaxed so as not to violate the first principles. The relaxation involves defining a pseudo transitional energy release rate G^* [11] to allow the transition of macro to micro. The traditional EER is limited to monoscale and macro effects. This is the basic idea of scale shifting that was thought in the early 1974 [12] in relation to examining micro–macro interactive effects of geometry and material property. The form-invariant relation of the VEDF or VED was used. The VEDF was referred to in fracture mechanics as the specific surface energy or the energy release rate (ERR). The difference is that VEDF applies to multiscaling while EER is restricted to monoscaling. The seemingly similar appearance of VEDF and EER is deceiving because of the adverse difference of their physical interpretations. *The monoscale EER refers to the creation of a unit of macro surface as an a priori while SED refers to the energy stored in a unit area that can be macro or micro. VEDF can be interpreted as the released energy only at the onset of instability.* It is not necessary to specify the direction of the surface created as an a priori. The monoscle ERR can be negative [9] when both macro and micro effects are present. Both *VEDF and VED remain positive definite under multiscaling.*

2.3. Transitional functions and scale directionality

Scale directionality of transitional functions was recognized from the homogenization of multiscale functions. Segmentation of the SI system of measurement was decided on a consensus basis for the expediency of assigning units to stress and energy density like quantities. In retrospect, the persistent use of monoscale theories has stymied the progress of multiscaling. Transitional functions [2,3] were necessary to deal with the effects of NENH. Scale segmentation gave rise to directionality preference. Defined in Table 1 is the difference between the ascending and descending direction of scaling [14], an irreversible property of the physical

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