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Irreconcilability of uniaxial test data with irreversibility of loading and unloading

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ABSTRACT

Uniaxial material properties of macroscopic average stress and strain invoke monoscale global equilibrium. The procedure does not hold for microscopic uniaxial stress and strain test specimens. There lacks *direct* connection between the measured stress and strain at the macro and micro scales. Scale transmissibility of stress and strain must be validated by models and/or laws. Material testing philosophy of the 18th century are not valid for the 21st century applications, where microscopic and nanoscopic effects enter into design. Simply put, the dual scaling of distortion (micro) and dilatation (macro) is no longer uncommon.

The use of true versus engineering stress and strain (S&S) can be troublesome as they entail contrasting physical interpretation for the same material, say for the 4130 steel for example. The true S&S curve shows *hardening* while the engineering S&S curves exhibit *softening*. The fictitious concept of elastic and plastic unloading also renders different meanings. Dissipated and available energy density from the uniaxial data can yield positive and negative efficiencies for 4130 steel. The benefit of micro and/or nano effects to macro properties can depend on the sustainable time of the test data. The active holding time of the nano interface reinforcement depends on manufacturing know-how, a highly guided trade secret that cannot be commonly acquired without the analytical skill and knowledge of non-equilibrium mechanics and metallurgy.

The competition of the 21st century rests on energy efficiency for the use of super strength materials and structural systems. The axiomaticism of material testing can no longer walk alone without the emphasis of "identifiability and synchronicity" (I&S) of I-Ching or the Books of Changes. Uncertainties are not likely to be revealed by postulating and testing models without a knowledge of I&S. Physical events are biased by synchronicity, a property that can mitigate uncertainty. As application is extended from the macro to the nano or even smaller scale, multiscaling models will be the rules in material science research rather than the exception.

1. Introduction

Deformation recovery upon removing the load was the motivation of Galileo Galilei (1564–1642) to test a weighted cantilever beam. This was followed by the postulate of Robert Hooke (1635–1703). Quote: "*Ut tension sic vis*" or "*as is the extension, so is the force*". This was about the time when Issac Newton postulated his laws of motion related to "force". The concept of stress, strain or the modulus of elasticity was not introduced until the time of Augustin-Luis Cauchy (1789–1857). Stress and strain were convenient for constructing the mathematical theory of elasticity for a smooth medium without size effect. The stress was conceived as a measure of the average force per unit area of a surface within the body on which internal forces act. These internal forces arise as a reaction to external forces applied to the body. Because the loaded deformable body is assumed to behave as a continuum, these internal forces are distributed continuously within the volume of the material body, and result in deformation of the body's shape. These remarks are pertinent to the applicability of elasticity that has lasted for centuries to situations even when the initial assumptions were violated.

Two fundamental issues, with reference to force and stress, deserve attention. The size effect of the test specimen emerged when the elastic modulus was introduced to associate the stress with the strain. The elastic modulus should be distinguished from the proportionality constant in Hooke's law. *The elastic modulus depends on the length and cross-sectional area of the specimen*; it is not a "material constant". The justification for using the uniaxial test data in the multiaxial theory of elasticity relied on adopting the

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ASTM E8/E8M-11 Standard Test Methods for Tension Testing of Metallic Materials. The ad hoc procedure is used until this day. *Different standards were used for different loadings, different materials and different specimen types*. The procedure is now known as the field of "Strength of Material". Material strength became loading specific, an ambiguity, if not a violation of the axiom of "*Constitutive Relation*" that is postulated to be independent of loading and geometry. The separate use of tensile strength, compressive strength, shear strength, etc. persisted up to the good part of the 19th century, when failure were regarded as a *permanent change of shape change*, or failure by yielding.

Failure by fracture or breaking was considered at the time of uniaxial testing but it was mentioned in the Books of Mojing of the 5th century around 221 BC. Breaking by tension was thought as a disruption of material continuity. The experiment was referred to a hair separated locally because of inhomogeneity [1]. Quoting from Mojing [1], "*Let a small weight hang on a hair. Even if is very light, the hair will break. This is because the hair is not truly even, or continuous. If it were, it would not break*". Mojing further argued that the reason why a fiber breaks under tension is that it is formed of elements unequally strong or unequally cohesive. That is a breaking-plane must occur somewhere. This was the Mohist early concept of the geometrical points (particulates) and *the indivisible instance of time*. The dualism of the particulate and wave related to light arose from tests and models based the axioms that incidentally may not be the reality via "identifiability and synchronicity" (I&S) of I-Ching or Books of Changes [2]. Uncertainties in modern physics are the creation of axiomatic models rather than the changes of nature. The basic difference between axiomaticism and I&S may be stated. To reiterate, *I&S observes and records the evolutionary changes of nature while axiomaticism advocates tests designed from postulates.* The emphasis is to *learn from nature and its changes, instead of learning by trail-and-error.* Axiomatic approach has quick assessment of the behavior of large bodies. It becomes less certain for smaller bodies atomic and sub-atomic in size. The I&S approach has recorded changes of nature by means of binary progression, following the rule 2^n, to construct a biased arrangement of the hexagrams. Data were collected for thousands of years for $n = 3$ and $n = 6$. A mathematized version of I-Ching was made available recently by CTM (Crack Tip Mechanics) [3] and IDM (Ideomechanics) [4]. The ideons [4] are the counterparts of the hexagons in I-Ching [2] except that n values other than 3 and 6 can be explored mathematically by the electronic computer. Thousands of years can be reduced to a few months or years. Already many of the non-equilibrium and non-homogeneous laws have been deduced from $n = 2$ using four ideons, while $n = 4$ and 5 can also be explored.

The definition of non-dissipated elastic and dissipative plastic effects cannot be extended to multiaxial stress states. Monoscale models can violate the first principle when applied arbitrarily to multiscale [5,6] physical systems. It took nearly 60 years to realize that the internal structures of nanomaterials can be unstable and lose their superiority. Codes and standard cannot be developed fast enough for application. In other words, nanomaterials can change their properties. The unstable behavior can be shown mathematically by non-equilibrium mechanics and metallurgy. Failure to hold the correct manufacturing to tolerance can result. These are new experiences for the air transport industries [7,8]. The behavior of ultra strength materials should be understood before application. The is also reflected by the amendment of codes and standards for the nuclear reactor power plants [9,10].

Monoscale technology is not appropriate for nanomaterials. Multiscaling based on surface energy density (SED) is suggested for non-equilibrium physical systems. The shape change effect at Galileo's time and the hair breaking thought of Mozi are integral parts of the volume energy density (VED), a nonlinear function of dilatation and distortion. They are mutually dependent and cannot be separated linearly as in elasticity [11].

2. Distortion and dilatation to account for shape change and fracture

Force, extension and energy do not address shape change and breaking of solids. Stress, strain and energy density were defined to set limits for the distortion and dilatation of solid elements at the different space–time scales. Shape change has been observed at the macroscopic scale. The effect, when extended to yielding, implicates microscopic entities. While elastoplasticity were intended to address deformation beyond the elastic range via the yield criterion, it remains as a monoscale model. No reference has been made to associate yielding with microscale effects. In addition, dilatation and fracture are separated from the yield criterion. Shape and volume change occur simultaneously. Their presence should be accounted for accordingly. *There are no theoretical and physical justifications to apply the a priori assumption that distortional and dilatational effects are separable at any space–time scales.* Uniaxial tests of metals and non-metals show that the specimen distorts and dilates for each load increment, however, small. The effects are accumulated in steps from the initial to the final loading state. *Distortional and dilatational effects* cannot be added linearly as in elasticity, by separating the respective strain energy density components [11]. Elasticity assumes reversibility at the macro scale. Linear stress–strain curves do not guarantee reversibility at the microscale. *Since irreversibility may prevail simultaneously at both the macro and micro scale, the extent of distortion and dilatation should be weighed simultaneously. This can be done by invoking the stationary values (maxima and minima) of the energy density function* [12]. Moreover, the same argument can be shown to hold for nanomaterials whose distortional and dilatational effects are not negligible at the nanoscale. The scale shifting scheme [5,6], based on the invariant character of the *surface energy density* (SED), accounts for space–time scale effects, where codes and standards are non-existent.

2.1. Macroscopic versus microscopic considerations: codes and standards

Handbook value material properties refer to specific loading rate, specimen geometry and dimension, in addition to material type. The combinations of the three choices *need to be assumed* to be sufficiently stable such that the data can hold for the operational time of the structures and their components. This applies to the design of buildings, bridges, and transport systems of the 19–20th century, where considerations were primarily macroscopic. Microscopic effects emerged into the design of modern air transports [7,8] and nuclear power generation plants [9,10] that may fall outside the limits of the codes and standards. As mentioned earlier, microscopic entities do not have sufficient sustaining time for setting up codes and standards. The life time estimates of structures and their components are based on invalidated presumptions, where safety has relied on inspection and maintenance. It is only prudent that the basic philosophy and wisdom of codes and standards should be scrutinized in light of modern technology and the operational specificity of modern structural systems.

2.2. Ad-hoc character of loading and unloading: available and unavailable energy

Loading rate of uniaxial specimens determines the amount of dissipated and stored energy and they cannot be arbitrarily assumed to be equal to those in an element under multiaxial stress.