Continuous Damage Mechanics - Critical States

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1. PROJECT DESCRIPTION

INTRODUCTION

The ultimate objective of mechanical design is to provide for a structure or device which can be reliably operated under a given set of circumstances for a desired period of time. The question of how long will a structure last and will the failure be catastrophic must be addressed both comprehensively and authoritatively in order to avoid undesirable consequences. These fundamental questions are addressed in engineering through analytical, experimental and computational modeling to attain the economy of experience in replicating and predicting considered processes.

Accelerated development of conventional methods of continuum mechanics in conjunction with the advent of ever more powerful computers gave rise to opinions that "all major problems of theoretical mechanics can now (or soon will) be solved on the computer" (Oden and Bathe 1978). Yet, this until recently considered infallible combination of wisdom and power has been lately undergoing careful scrutiny. Instead of being fine tuned some of these conventional methods are being summarily overhauled. The partial reconstruction of the framework of continuum mechanics has been initiated not only by the availability of new computing devices but even more so as a consequence of a closer collaboration of mechanicians, physicists, material scientists and mathematicians. In particular, the recently reached consensus that the macroscopic behavior can be deduced on the basis of the respective processes on the microscale provided a major impetus for the development of micromechanics.

On their microscale most engineering materials are to a certain degree disordered. Despite existence of short range order (individual crystals, segments of polymer chains, etc.) the long range order is either totally absent (amorphous solids) or disrupted by energy barriers (grain boundaries, second phase particles and layers, etc.) and/or microdefects (voids, microcracks, reaction layers, etc.). Random geometry and hierarchy of strengths on the microscale to a large degree determine not only the mechanical response but, most importantly, the circumstances under which a specimen fails and the mode in which the failure takes place. However, casting random microscale processes into macroscale failure processes, preferably deterministic, proved to be a

daunting task. In general, it was observed (Rice, 1991) that traditional continuum models cannot in a generic sense reproduce the experimentally observed spatial-temporal complexity (microstructural disorder) of the considered phenomena as they approach critical state. The semblance of the disorder is revealed only if special constitutive relations are introduced into these models.

Failure can occur in many distinctly different ways depending on the material, stress and strain fields, temperature field, environmental effects, strain rate, etc.. The proposed research program will focus on a single well defined class of failure modes common to many structures and machine elements. This class of problems is characterized by a gradually evolving microscale process which at a certain point triggers a discontinuous or singular (qualitative) change of macroscale response. Consideration of critical states of cooperative processes requires radical departure from the well travelled paths. Recently developing methods of statistical physics seem to be applicable to the class of problems under consideration. These models are generally formulated as discrete enabling consideration of spatial-temporal complexities as they arise from the microstructural disorder. However, in many cases these models in the limit do not converge to the traditional continuum theories.

MEAN - FIELD MODELS

A great majority of the existing micromechanical models, in slip theory (Budiansky and Wu 1962) and damage mechanics (M. Kachanov 1982, Horii and Nemat-Nasser 1983, Krajcinovic and Sumarac 1989, Krajcinovic 1989, Nemat-Nasser and Hori 1990, etc.) alike, are based on the mean field models (Mura 1982, Kunin 1983, etc.). The mean field, or first order effective continua, models are, in general, based on the following assumptions:

- (a) the external stress field of each defect is approximately equal to the far field or average stress field,
- (b) each microdefect is influenced by the adjacent microdefect only through their contribution to the elastic parameters of the effective continuum, and
- (c) the volume averaging is justified by the defect and specimen geometry.

Subject to these simplifications the ensuing micromechanical models are rendered local and analyses computationally efficient. However, introduction of these assumptions has a limiting effect on the application of mean field theories (MFT) which is not always acknowledged or even clearly understood. The second of two assumptions eliminates from consideration the direct interaction between the adjacent microdefects by disregarding their actual location. Consequently, the application of the mean field models to problems inherently depending on the direct interaction of

defects, for example clustering of defects into a narrow defect band (localization), presents an enterprise of dubious merit.

The last of the three assumptions, often implied and seldom questioned, provides for a mapping of average properties of a representative volume element (RVE) of the actual disordered, piecewise discontinuous material on the effective properties in a material point of the effective continuum. A RVE must, by definition, be statistically representative of the actual material. Linear dimension L_r of the RVE must be smaller than the smallest linear dimension of the specimen L_s (to eliminate the conventional size effect) and much larger than the size ξ of the largest defect within the RVE. Thus, the mapping between the actual and effective solid is, within the spirit of the mean field models, possible only when the local properties are influenced by the microdefects (or other inhomogeneities) primarily through their volume averages. In other words, the local field fluctuations attributed to microdefects must have a decay length smaller than the distance separating adjacent microdefects. Simply stated the microdefects must be small compared with L_r and their concentration must be dilute for a mean field theory to apply (see, also, M. Kachanov 1991).

From a purely practical point of view an additional problem associated with the mean field theories is "that little can be done to improve them substantially without solving the problem exactly" (Ma, 1976). Rigorous determination of stress and strain fields within the RVE with disordered microstructure is a process the futility of which is matched only by its lack of feasibility. A further attempt to extend the range of the validity of the MFT to the case of strong defect interaction involves two different strategies involving different simplifying assumptions. A somewhat more conventional strategy is based on the so called cell method (Nemat-Nasser, et al. 1982, etc.) assuming regular, en echelon, patterns of microdefects which persists throughout the deformation process. In this case, using conventional elasticity a rigorous, albeit numerical, determination of stress and stress fields is possible allowing for the determination of overall transport properties incorporating influence of the direct defect interaction. However, as demonstrated by Bazant and Cedolin (1991) a self similar evolution of damage constitutes a thermodynamically unstable path which significantly overestimates the energy dissipated during the process. Even the protagonists of this method ruefully conceded that "in reality inclusions and voids are essentially randomly distributed and may, in fact, form clusters and other anomalous structures" (Nemat-Nasser, et al. 1982). Hence, it is difficult to argue with a somewhat prophetic statement by Cleary, et al (1980) that "until some tractable probabilistic description has been achieved, it seems that a single isolated site model of heterogeneities will have to suffice".

A second class of models is based on the M. Kachanov's (1987) approximate and surprisingly accurate model of the direct slit interaction. Second order effective continua models for solids containing rectilinear slits and penny shaped cracks were suggested by Kachanov and Laures (1989), Montagut and Kachanov (1988) and Ju and Chen (t.a.) present valuable extensions of the MFT beyond their original limits. However, these models are, at least in their present state, limited to cracks of simple geometries which are not allowed to intersect, branch, fork and/or coalesce into defect clusters. Hence, these methods, having as objective extension of mean field models, do not focus on the response near the critical state.

Limitations of these and other models clearly indicate that traditional deterministic methods of elasticity and fracture mechanics are not very well suited for dealing with the disordered media in the vicinity of critical states. As suggested by Cleary, et al. (1980) an entirely different strategy might, indeed, be necessary to gain further insight into the problem in a manner which is not obfuscated by mathematical complexities associated with formulation of higher order MFT.

MODELS OF RESPONSE NEAR THE CRITICAL STATE

Most if not all engineering materials are heterogeneous, or disordered, on the microscale. Its properties are, thus, random functions of spatial coordinates. For computational efficiency these disordered materials are typically modeled as statically macrohomogeneous continua. As already stated the homogenization (averaging) process is justified as long as the three conditions listed in the preceding Section are justified. Homogenization ceases to provide for a reasonable analytical description of the deformation process at a point when the defects organize themselves into a large cluster (localization) spanning the specimen ($\xi \geq L_r$) or when a single defect of preferential geometry becomes critical causing brittle failure. This proposal deals almost entirely with the former case characterized by the existence of a critical state in a cooperative evolution of defects. Recent developments in the field of statistical physics indicate that a valuable insight into the behavior of systems in the vicinity of the critical state is provided by methods of percolation theory, theories of self-organized critical states and renormalization theory. Fundamental argument of this proposal is that the examination of these methods and their modification and extension to the problem of damage mechanics and plasticity theory is a worthwhile venture leading to a better understanding of the considered processes. This argument is further corroborated by the exploratory work reported in Krajcinovic, et al. (1991).

1. Percolation Models

Within the framework of the percolation theory a deformation process emphasizing damage evolution is modeled by gradual dilution of a homogeneous continuum through a sequential introduction of microdefects (microcracks and/or microvoids). Percolation theory is generally found to be applicable to the considerations of universal trends in the neighborhood of the critical state of a phase transition type. Critical state, i.e. elastic percolation threshold, emerges at microdefect density f_{ce} at which a defect cluster spanning the specimen is formed. At this point one or more components of the macro-stiffness tensor of the specimen vanishes. The described type of systems constitutes a universal class. Systems belonging to the same universal class have identical asymptotic behavior as the microdefect density approaches the percolation threshold $f \rightarrow f_{ce}$. The percolation threshold f_c itself and the scaling law for transport properties near the percolation threshold are same for all materials and processes belonging to the same universal class. Thus, once the percolation threshold and the scaling law are determined for a given universal class either experimentally or by numerical simulation the behavior of all systems within this class is defined in the neighborhood of the critical state.

The universal class depends (Sengers 1985) on the dimensionality, number of the components of the order parameter exhibiting singular behavior and the connectedness range. As a result the universal parameters obtained for the conductivity processes are different from universal parameters for elastic (stiffness) percolation problems. This is especially true for three dimensional problems since the defect density $f = f_c$ needed to form a cluster traversing the specimen is much smaller than the defect density $f = f_{ce}$ required to form a cluster transecting the specimen into two or more fragments.

Elastic percolation problems are further complicated by the tensorial character of stress and strain fields. Additionally, in case of cracks a distinction must be emphasized between tensile and compressive fields. For example, cracks subjected to compressive normal stresses will not contribute to the increase in compliance. Consequently, instead of conventional models it will be necessary to modify, extend and apply models such as directed percolation (Kienzel 1983, Grimmitt 1989, etc.), invasion percolation (deGennes and Guyon 1978) and anisotropic percolation (Aizenman, et al. 1987, Grimmitt 1989, etc.). In all of these cases numerical simulations for the determination of universal parameters were almost exclusively developed for the conductivity problems.

Another heretofore totally ignored problem is related to the determination of the behavior of considered systems in the crossover regime. A similar problem related to the determination of the viscosity near critical temperatures was addressed comprehensively by Bhattacharjee, et al. (1981) and Sengers (1985). At the same time analogous effort needed to determine the elastic moduli within the transition regime separating mean field and percolation phases of the deformation process has yet to be made. This is by no means an accident since the response in the crossover phase is characterized by strong interaction of defects none of which has a dominant role similar to one attributed to the spanning cluster in the percolation regime. The hydrodynamic behavior of the fluid is described by three parameters: thermal conductivity, bulk and shear viscosity only two of which exhibit singular behavior at critical temperature (Stanley 1971). In the case of solid containing microdefects any number of the components of the stiffness tensor may become singular depending on the dominant stress field (see, Krajcinovic, et al. t.a.).

2. Self Organized Critical States Model

Percolation models discussed above represent, in effect, an attempt to solve the governing equation on the disordered geometry. This approach leads to valuable results that cannot be obtained by application of conventional methods. However, another method became recently available for studies of critical states resulting from localization of microdefects during their evolution into thin bands. Currently, localization problems are in applied mechanics considered on a purely phenomenological level as a case of Hadamard bifurcation instability (Rice 1977, Rudnicki and Rice 1975, Needleman 1988, etc.). Without dwelling on the physics of the microstructural processes leading to an abrupt change in the nature of the macro-response, this class of models examines conditions under which in addition to a homogeneous deformation field a nonuniform deformation (emphasizing narrow planar shear bands) becomes possible. A variety of conceptual and/or computational problems (Bazant and Belytschko 1985, Needleman 1988, etc.) related to a local loss of ellipticity of the momentum balance equation (surface wave trapping - Kitagawa 1987), localization bands of zero thickness and spurious mesh dependency of the results spurred emergence of a host of seemingly disparate remedies. However, as shown by Simo (1989) methods such as: mesh dependent moduli method (Pietruszczak and Mroz 1981), non-local models (Bazant and Pijaudier-Cabot 1988, etc.), gradient models (Triantafyllidis and Aifantis 1986, etc.) and viscoplastic regularization represent but different algorithmic approaches to non-local regularization of the dissipation function of the continuum model. Moreover, these methods address the microstructure only in a very perfunctory manner.

It seems, therefore, that instead of insistence on exploring different algorithmic approaches to the same conceptual scheme a radical departure from conventional thinking may prove to be more fruitful. The criticality of cooperative phenomena is a result of the direct interaction of defects which cannot be described as a perturbation of a decoupled mean field state (Bak, et al. 1988). A particularly revealing insight into dissipative dynamical systems evolving towards a critical state, through a sequence of many metastable states, is provided within the framework of the self organized critical state (SOCS) concepts. Using simple cellular automaton it becomes possible to study the effects of small perturbations (associated, in the considered case, with energy released during forming of new internal surfaces - microcracking) on the stability of the macro-state. While not universal (Jaeger, et al. 1989) this method, profitably applied in providing physical basis for the Gutenberg - Richter law predicting the probability of an earthquake of a given size (Bak and Tang 1989, Goss Levi 1990, Davy, et al. 1990, Sornette, et al. 1990, etc.), introduces the elusive length dimension in a completely natural manner. This length dimension, not merely *a priori* postulated as in other models, associated with the cluster (slide or avalanche) size distribution is directly related to the total energy dissipated on the local disturbances on the microscale and is again a universal parameter. Some caution must be exercised since the SOC models in their present form do not in the limit reduce to the partial differential equation governing analogous processes in continua (Rice, 1991).

Spatial self-similarity at the transition point (at which avalanches of *all* sizes occur), robustness of the results with regard to the local details of the system (i.e. its microstructure), power (fractal) laws valid over several decades, provide ample assurance of the "universality" of the SOCS methods. The SOCS results should also be compared with the results obtained analyzing block-spring (slip-stick) models considered by Rice and Ruina (1983), Dmowska and Rice (1986), etc.. In formulation of these models it became obvious that the frictional forces must depend on the past history. In this sense the SOCS models are very similar since the critical state depends on all local instabilities recorded in the past. Nevertheless, the constitutive dependence of shear resistance on the slip velocity and state (including fading memory of preceding slips) are different in discretized and continuum models. Thus, a formulation of a micro-to-macro transition between the two classes of models seems to be needed as well.

3. Softening Regime Models

Analytical modeling of the material response within the softening regime was, until recently, studied entirely within the framework of deterministic methods (for example, see papers in Mazars and Bazant, 1989). Conventional percolation studies of regular lattices (Beale and Srolovitz, 1988)

proved to be, at best, a partial success. Further advance in studies of the softening phase of the deformation of real material (with a wider dispersion of toughnesses on the microscale) must involve polychromatic lattices with quenched disorder (Hansen, et al. 1989, Herrmann, et al. 1989, Krajcinovic and Basista 1991). Main advantage of these studies is that they enable consideration of a wide spectrum of rupture strengths of individual elements which is a much more accurate approximation of physical reality than one provided by conventional percolation models. Analyses of an ensemble of different realizations of the same statistics (same probability density distribution of link strengths) indicate that (Krajcinovic and Basista 1991):

- (a) The force - displacement relationship along the ascending (hardening) segment of the curve is robust with respect to the details of the initial (quenched) disorder, i.e. the macro-response depends primarily on the volume averages of the defects (probable events).
- (b) The mechanical response in the softening (post critical) regime is strongly dependent on the size effect (discretization or mesh dependence) and higher statistical momenta of the initial disorder (unlikely events - Hansen, et al. 1989).

Experimental corroboration of these conclusions, heretofore almost totally ignored, becomes evident through inspection of experimental results for concrete specimens collected in Hegemier and Reed (1985).

One of the most hopeful aspects of the behavior of disordered lattices (inferred in Krajcinovic and Basista 1991) is related to the existence of "universal" parameters. The magnitude of a properly defined damage parameter and the secant modulus at the critical state are shown to be independent of lattice size, details of the initial damage distribution and dilution process. These universal parameters depend only on the dimensionality and statistical distribution of link strengths (microstructure).

Further development and extensions of this model to ductile/brittle processes (Krajcinovic and Silva, 1982), fatigue and irregular lattices should lead to a more balanced insight into the behavior of real materials in the post-critical regime. At the present time it appears reasonably sure that the response in the post critical regime is nondeterministic. This conclusion, consistent with results obtained by Duxbury (1990), is in direct contradistinction to the prevalent modeling strategies in applied mechanics. Thus, it seems reasonable to conclude that modeling of the material response in post critical regime is far from being resolved on the conceptual or any other level.

4. Fatigue Failure Model

Fatigue failure is one of the most important and yet not entirely understood example of critical phenomena. A vast amount of experimental data has been collected, empirical models fitting these data suggested and a host of different micromechanisms responsible for fatigue failure examined in the past. Initial attempts in formulation of analytical models were purely empirical in nature. Miner - Palmgreen linear accumulation rule, Paris' power law, Woehler's curves are some of the most frequently used models belonging to this class. A veritable avalanche of other models (over hundred in number as listed in Kocanda 1978) is a consequence of the complexity of the problem and its importance to science and industry.

One of the major problems in fatigue modeling is related to a misguided and optimistic belief that a universal fatigue model is possible or even desirable. The distinctly disparate shapes of the sigmoidal da/dn vs ΔK fatigue curve is an indication that the fatigue process is dominated by a sequence of different micromechanical mechanisms (Klesnil and Lucas 1980, Suresh 1991) as the damage evolves through nucleation, growth and coalescence of microcracks.

Duration of the initial phase of a fatigue process is strongly influenced by surface treatment of the specimen. It is generally agreed that in many cases microcracks nucleate on the surface by the so-called Cottrell - Hull mechanism responsible for the staircase morphology of surface by producing extrusions and intrusions. These surface effects are free surface terminations of dislocation pile-ups (Hertzberg 1976, etc.). Relative sliding motion of thin plates along the interfacial slip surfaces results initially in regular and smooth waviness of the free surface. As the specimen is cycled the resistance to slip along the slip surfaces decreases (Helgeland 1965, Hertzberg 1976) leading to localization of the surface deformation into sharp peaks and troughs (notches) acting as stress concentrators responsible for crack nucleation. The softened (persistent) shear bands penetrate into the material and once formed cannot be removed by polishing, etching, shot peening or other methods of surface treatment.

Hence, this class of fatigue processes within the incubation regime represents a self-organizing dynamic phenomenon during which a system of distributed slips localizes in one or several sharp slip bands. The results for a specific surface treatment are experimentally reproducible. Thus, the process is robust with respect to the details of the microstructure and represents a type of a problem for which the SOCS methods should be applicable.

Despite the fact that the fatigue process in an essential manner depends on the surface treatment and microstructure (Ritchie 1977), including the initial (quenched) disorder, almost entire effort in the development of analytical models of fatigue was directed towards deterministic models. Most of the success was, not surprisingly, achieved in replicating the experimental data within the region of stable crack growth (Region II). During this phase a typical crack is in size larger than a grain and as such less influenced by local disorder (grain boundaries, dislocation bands, etc.) near its tip. At the same time cracks are far apart rendering their interaction a second order effect. This is in sharp contrast to the Region I growth of "short" cracks which are smaller than inhomogeneities and are therefore influenced by the disorder of the material on micro scale.

Within the Region III, preceding the fatigue failure, crack (defect) interaction becomes a significant aspect in determination of the crack growth rendering conventional fracture mechanics estimates of stresses to which a single crack is exposed unreliable. In order to assess the influence of interaction of many randomly distributed cracks of random geometry it will be necessary to study disordered lattices similar to those considered in percolation analyses. In view of the importance of the small scale yielding on the fatigue crack growth these studies must involve polychromatic lattices, i.e. each link can be elastic, can yield and/or rupture. The yield and rupture stresses of individual links will be considered as random parameters distributed in a manner consistent with the microstructure of the material.

Until recently, such a study would have been purely numerical and probably difficult to justify in view of many parameters and variables. However, these studies can be greatly facilitated through the application of the mathematical models of hysteresis. In a recently published seminal study on this problem Mayergoyz (1991) established a firm mathematical foundation for the further developments of algorithms as yet not used in mechanics (Sumarac, et al. t.a.). In its classical form the Preisach model (Mayergoyz 1991) belongs to the class of mean field theories. It ignores spatial location and shape of the slip band. Fortunately, as the studies of disordered lattices (Krajcinovic and Basista 1991) suggest, the mean field models appear to be surprisingly adequate for the entire ascending part of the force - displacement curve including the assessment of the onset of critical state. Hence, it will not be entirely unreasonable to expect that the lattice model in conjunction with Preisach model becomes capable of supplying a reasonable accurate assessment of the fatigue life in the case of load controlled processes. However, the proposed effort will require modifications of the Preisach model in order to consider translation and possible distortions of major loops in the course of strain and/or stress softening fatigue processes.

The great advantage of the Preisach model (Mayergoyz, 1991) is directly related to spectral decomposition of a complicated hysteresis operator with nonlocal memory into simple hysteresis operators with local memories. This decomposition allows for simpler and less ambiguous material identification and is entirely compatible with rheological modeling of complex materials by systems consisting of simple rheological mechanisms connected in series or in parallel. The properties of each subelement, defining a Preisach (weight) function can be directly related to a specific experimentally identifiable irreversible microstructural rearrangement (Asaro 1975, Krajcinovic, et al. 1987). The macro properties of the specimen can, subsequently, be determined by experimental identification on the macro scale (Mayergoyz 1991) or through a homogenization of micro properties. Coupling of these two identification processes will lead to coherent and systematic algorithms for analyses of cycled structures endowed with a well defined physical meaning.

One of the major problems in fatigue modeling is related to so called "cycle counting" in case of random load histories. Random succession of "small" and "large" load cycles requires careful characterization since the contributions of individual cycles depend on the order of succession. In the past several competing empirical cycle counting methods were suggested creating a fair deal of controversy related to their relative merits. It is interesting that the Preisach model provides a resolution of this controversy. The wipe-out property of the Preisach model (i.e. its nonlocal memory) can be shown as being closely related to the rainflow cycle counting method (Collins 1981) which is widely considered in the industry as being "the best representation" (Broek 1989) of a random load cycling program. This fact lends further credence to the Preisach model and its application to mechanical fatigue failure since it is, at least in one of its main aspects, in agreement with empirical rule supported by a majority of experimental data.

In summary, the Preisach model (in Mayergoyz version) is well suited as a mathematical framework for studies of the fatigue of materials. Initial studies on simple series and parallel connection of spring-friction rheological mechanisms (Sumarac, Lubarda and Krajcinovic, 1992) clearly indicate the power of the Preisach model in replicating major trends observed in specimens subjected to cycled loads. However, in their present form these models are unable to predict the fatigue failure since the support of the Preisach function remains constant in the space of material parameters. Since the fatigue failure almost as a rule involves coupling of different microstructural mechanisms (for example, slip and microcracking) and their interaction the load-displacement loops as a rule do not stay within a single (major) loop. Therefore, modifications of the Preisach model are necessary to enable estimates of fatigue failure caused by cycle softening and similar microstructural mechanisms.

SUMMARY OF SPECIFIC TASKS

Primary objective of this proposal is to examine some of the as yet unresolved aspects of the material behavior in the neighborhood of the critical state and within the post critical regime. An argument is made that fine tuning of traditional methods of applied mechanics is unlikely to result in further breakthroughs and that the insight to be gained will not be commensurate to the effort. Starting from this premise it seems both logical and useful to change the strategy and focus on some of the currently developing methods of statistical physics and applied mathematics. Most of these methods are developed for problems of magnetization, electrical networks, fluid mechanics, heat conduction and polymerization problems. Hence a significant effort must be devoted to generalization and modification of these methods and algorithms in order to render them applicable to the problems of mechanical failure resulting from gradual damage evolution. Some of the specific tasks to be addressed in the proposed research program are:

(a) Determination of elastic compliances and stiffnesses of an elastic solid for the entire hardening range including the critical state (apex of the force - displacement curve). This task includes considerations of a host of percolation models including directed, invasion and anisotropic models. Incorporation of these models into micromechanical process theories is one of the major components of proposed studies. A significant effort will be directed towards establishing universal parameters for three-dimensional elastic percolation problems in case of spherical voids and penny shaped cracks. A comprehensive study of interaction models (Kunin 1983, M. Kachanov 1987, etc.) will be conducted in analyses of the crossover regime (transition between the mean field and critical phase of the deformation process).

(b) The problem of localization of microdefects into a narrow band will be considered as an example of a self organized critical state. Owing to universal properties of the SOCSs it should be possible to introduce the length parameter (thickness of the band) as a function of microstructure and recorded history (preceding metastable states). An attempt will be also made to find a common (transition) ground between the SOCS model and the continuum methods.

(c) Study of the material behavior within the softening regime will be conducted using statistical models in order to be able to investigate the dependence of the macro failure in a strain controlled case on the distribution of initial damage (birth defects in composites, surface treatment of metallic specimens, etc.).

(d) Problem of fatigue failure in stress controlled circumstances will be addressed using disordered lattices coupled with extensive modifications of the Preisach model. Identification of material parameters (Preisach function) and their relation to observed trends and microstructure of the material will be considered as one of the major subtasks of the proposed research program.

In summary, the proposed work will address an entire class of seemingly dissimilar problems. A common denominator in these problems is that a gradual change in density of microdefects results, at a well defined threshold level, in a sudden qualitative change in the macro response. This threshold is herein defined as a higher order phase transition or emergence of a self organized critical state. Onset of softening, localization, tertiary regime in fatigue and/or brittle failure are some of the deformation processes belonging to this subset of critical states.

Finally, it is obvious that the proposed research program will not address, let alone resolve, all of the problems belonging to the examined class. The intention is, somewhat more realistically, to provide a different viewpoint and provide several new analytical models linking methods of applied mechanics and statistical physics. It seem, at least to this prospective PI, that such an attempt is not only worthy of effort but overdue as well.

2. BIOGRAPHICAL SKETCHES

Dusan Krajcinovic, Professor in the Department of Mechanical and Aerospace Engineering at Arizona State University, will be the Principal Investigator in charge of the proposed research program. Prof. Krajcinovic was engaged on the research in the field of damage mechanics and micromechanics in the last two decades. He published 80 journal papers on these two topics, edited 4 books, organized a course at the International Center for Mechanics and was asked to be one of the editors of the Int. J. of Damage Mechanics.

Prof. Krajcinovic will be assisted for three months by Dr. Dragoslav Sumarac who collaborated with him on more than 15 papers and a book. The research team will include a graduate student for the entire duration of the research program.

DUSAN KRAJCINOVIC, VITAE

Degrees

Ph.D.	Northwestern University, 1968
M.Sc	University of Belgrade, 1966
B. Sc.	University of Belgrade, 1958

Academic Experience

1961-1966	<i>University of Belgrade</i> , Department of Civil Engineering.
1973-1989	<i>University of Illinois at Chicago</i> , Chicago, IL., Professor
1989-present	<i>Arizona State University</i> , Professor

Industrial Experience

1968-1969	<i>Ingersoll Rand Research, Inc.</i> , Princeton, NJ, Solid Mechanics Group, member technical staff.
1969- 1972	<i>Argonne National Laboratory</i> , Argonne, IL. Theoretical and Applied Mechanics Group, member technical staff.

Consulting Experience

Energoprojekt, Consulting Engineers, Belgrade, Yugoslavia
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US Department of Interior (Office of Coal Research)
US Department of Energy
Procedyne Corp., New Brunswick, NJ
Electric Power Research Institute, Palo Alto, Cal.
Conselho de Gestao, Gabinete da Area de Sines, Lisbon, Portugal
Power Project Ltd, Chicago, IL
Sargent and Lundy Engineers, Chicago, IL
The World Bank, Washington, DC.
Lufthansa, Hamburg, West Germany
Enrico Fermi National Accelerator Laboratory, Batavia IL
Paslode Co., Lincolnshire, IL

The University of Michigan, Ann Arbor, Mich
Wiss, Janney, Elstner Associates, Inc., Northbrook, IL.
Allied Signal Corp., Tempe, AZ

Professional Societies and Activities

- Fellow ASME (rec. secretary of the AMD Executive Committee, member of the AMD Transportation and Energy and Environment Committees, member of the Committee on Constitutive Equations).
- American Academy of Mechanics (Charter member)
- Stability Research Council (member of the committee for shell-like structures, chairman of the committee for dynamic stability)
- International Association for Structural Engineering in Reactor Technology.
- American Society of Civil Engineers (non-member advisor of the Committee for Inelastic Behavior of Materials)
- Visiting Professor at Universite de Paris VI, 1988.
- Visiting Professor University of Belgrade, Yugoslavia, 1990 - present.
- Lecturer at the NATO Advanced Study Institute on Disorder and Fracture, Cargese, Corsica, France, 1989.

Awards, Scholarships and Honor Societies

- Who's Who in Technology Today
- Who's Who in Engineering
- International Who's Who in Engineering
- 1990 October prize for Physical and Mathematical Science, Yugoslavia.
- Directory of World Researchers
- Who's Who in Midwest
- Directory of Forensic Engineers, etc.

Editor of Scientific Journals

Applied Mechanics Reviews
 European Journal of Mechanics
 International Journal of Damage Mechanics

Principal Areas of Interest

Mechanics of Materials, Structures, Damage and Fracture Mechanics

Principal Publications and Papers (last five years)

Books:

Matrix Analysis of Thinwalled Structures (with C. F. Kollbruner and N. Hajdin), Institute for Engineering Research, Zurich, Switzerland, 1969.
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Fundamentals of Fracture Mechanics, (with D. Sumarac), Scientific Books, Belgrade, Yugoslavia, 1991.

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Creep Rupture of Solids - An Analytical Model (with S. Selvaraj), *Journal of Eng. Materials and Technology*, Trans.ASCME, **106**, Oct. 1984.
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