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Perspectives in experimental solid mechanics

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Abstract

The role of experiments in the interaction with theory is reviewed in the context of developing improved procedures in the evolutionary process of establishing engineering principles and design tools. The exceptional benefits derived from the increasing computational capabilities of the past decades are examined, as well as associated impediments to advancing mechanics objectives. Significant needs derive from these observations which command continuing or even increased commitments to supporting experimental efforts in mechanics. A summary of the salient methods in experimental research currently available is supplemented by perceived additional instrumentation needs and related tools that are required to address problems associated with emerging technologies. © 1999 Published by Elsevier Science Ltd. All rights reserved.

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> 'The scholar who does not know mathematics does not know any science' (but) '..without experiment nothing can be adequately known.'

Roger Bacon, 1276

1. Introduction

The above observations by Roger Bacon represent an often recurring theme in his writings (Bacon, 1912, 1928), namely that the evolution of understanding in any field of science is predicated on the

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proper interaction between experiment and analysis/theory. This is also true with respect to mechanics, a sub-field of physics. Although physics has established early on certain principles that define 'proper interaction', their consistent application is today often misunderstood at best, or at worst, ignored. It thus appears prudent in the context of a sizeable sequence of presentations devoted to the exposition of trends in solid mechanics, and in view of the considerable topical breadth offered by the formidable array of contributors, to reiterate these fundamental principles instead of resorting to a further enumeration of topics specifically geared to experimentation. This is done with the motivation or hope in mind that this may improve the reliability of mechanics investigations and ultimately, their applications to quantitative engineering. A portion of this paper is therefore devoted to considering the 'proper interaction' between experimental and analytical[1] work from a philosophical viewpoint that covers broad areas of experimental endeavors and its relation to analysis. While this initial part appears to be somewhat critical or pessimistic, it is the intention here to point out that the current state of experimental mechanics offers a large range of opportunities for interaction of experimental work with practitioners in analytical solid mechanics. The remainder of the presentation endeavors to (a) summarize the current state of experimental capabilities in terms of experimental methods available today to address a large variety of solid mechanics problems, and (b) to assess the needs and directions through which experimental solid mechanics is expected to make significant contributions to ultimately improving the reliability of engineering designs in a quantitative manner.

The umbrella-term 'experimental work' is often used to connote a large array of laboratory (and field) related activity, not all of which is, however, synonymous with executing experiments: A large component of this function is devoted to the development of experimental methods for observing and documenting physical features in an experiment, which have in their wake the design of specialized equipment. An operator of a test machine is not necessarily an experimentalist. Equipment purchased 'off the shelf' is used to make measurements, and experiments represented by a sequence of measurements, tend to be limited in producing new concepts. Another component in the charter of the experimentalist is the 'straight-forward' measurement of more or less well defined quantities (*e.g.* modulus of elasticity, rupture stress, a fracture energy or a frequency of vibration), possibly under variations of a parameter (*e.g.* temperature, or other environmental changes). In the spirit of the classical experimentalists one should, however, distinguish between 'experiments' and 'measurements', even though the two are, today, all too often confused by a surprisingly large number of researchers in the mechanics arena. Thus the determination of such distinct and pre-identified (material) parameters or properties does not occur through an experiment, it merely invokes a suitably careful (laboratory) measurement on a real configuration with a suitable set of instruments or tools.

An experiment[2] is born of a broader question, the answer to which is sought through suitably chosen conditions in the laboratory or 'in the field' so as to inquire into, or to establish a relationship(s) among several physically conceived (causal and/or responsive) parameters. Thus an experiment may need to be designed, for example, to answer the simple question as to whether the deformation mode in the dynamic buckling of a shallow arch is symmetric, antisymmetric or a (complicated) sequence of both; alternately, the question may need to be addressed whether in the determination of nonlinear

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[1] While it is still customary today to distinguish between analytical and numerical methods, with the former denoting 'closed form' representations, that distinction is used here in a more diffuse sense. The term analysis (analytical) is treated here as the scientific complement to experimental observations, whether it is accomplished via closed form or numerical methods.

[2] In this paper the term 'experiment' refers exclusively to the process of extraction of information from physical situations. It specifically excludes the increasing misuse of the word in the computational context, when an examination of variation parameters or changes in a model are classified as 'experiments'. In the latter sense any inquisitive investigation, whether purely analytical or experimental, would qualify as 'an experiment'. For semantic purposes at least, the word 'experiment' should remain reserved for the physical context.

constitutive response a seemingly uniaxially stressed specimen sustains truly homogenous deformations; or the reason needs to be illuminated why dynamic crack propagation occurs more slowly than current (elastocynamic) theory holds. An experiment typically comprises thus a sequence of measurements, which establish or clarify a new concept, but a sum of measurements does not necessarily constitute an experiment. Experiments may be born from an inquisitive mind without recourse to a preconceived theory, or may be the result of analytical developments that are seemingly in contradiction with our usual understanding. If an analytical treatment contains assumptions, only experimental means will determine their veracity in the corresponding physical context, but in no way does an experiment make a model or theory valid unless the specific component of the analysis is scrutinized specifically and successfully by experimental means. Analyses and experiments are jointly the building blocks on which our understanding of the physical world is built, and the loss of one or the other, or the lack of their appropriate interaction, ultimately leads to a hollow support system unsuitable for modern engineering endeavors.

2. An abbreviated historical view of experimental mechanics

In an ideal world the progression of (engineering) science occurs through a process identified in the 17th century as ‘The Scientific Method’ widely ascribed to Galileo, the 13th century ideas of Roger Bacon notwithstanding. While the sequence of experimental/theoretical activity is not necessarily always clear *a priori*, the essence of the ‘method’ consists in observing physical fact(s) and formulating an analytical framework for them to produce a scheme or theory by which other physical results can be predicted.

Important in the qualification for ‘theory’ under this concept is that ‘predicted’ facts must arise under circumstances separate from those which produced the original data and parameters; they must thus be in addition to those used to formulate the theory. Stated in a more graphic manner, a model first requires data to determine the physical parameters derived from a sufficiently broadly construed experiment or measurements, but does not become a theory until its predictive power is tested on data which are not part of the measurements that determined the original parameters of the proposed theory. The theory gains in respect and (quantitative) applicability as the number of situations, on which it is successfully tested, increases. Without this additional experimental examination an analytical framework does not become a theory but represents merely a data-fit. In this sense experimental data do not verify a theory, they simply add more credence to a reasonable construct of an analytical framework, if they transcend the establishment of the necessary parameters characterizing the model.

James Bell has made the observation (Bell, 1989) that advances in the sciences move in spurts, and that the interaction between theory and experiment is not always in phase. Following the highly successful though largely empirical (trial and error) evolution of magnificent edifice construction from the Egyptian through the Gothic and Renaissance periods, attempts at an analytical formulation of failure (stress) analysis were initiated, as illustrated, for example, by Galileo, even if this first attempt was ultimately not correct in detail. To deal with the emerging problem formulations, roughly, the next phase comprised the evolution of describing the constitutive behavior for (isotropic) solids under the ‘guidance’ of the one-constant theory during the early 19th century. This phase was simultaneously and consecutively enlarged by studies of nonlinear and inelastic material responses. However, it was not until the linearly elastic stress-strain behavior (approximation) was firmed up that the analytical development of the (mathematical) theory of elasticity could develop and burgeon, a process which has then dominated roughly half of the first of the 20th century. Although the time scale of such phases shortens in the same exponential manner as developments in science and engineering do in general, experimentation and analytical developments have interacted more closely for various reasons during the middle of this century in mechanics, being driven largely by the new developments in fracture, in structural instability and in high rate deformation response of solids.

Discussions on the mutually interactive roles of experiment and theory in modern mechanics have been offered repeatedly during the last decades, *e.g.*, by Hetenyi (1950), Drucker (1962) and Bell (1973). Because the holy grail(s) of mechanics seems to be the proclamation of a new theory, these writers also uniformly sense the low esteem often accorded the experimentalist's contribution to mechanics and misconceptions regarding the proper interaction between experiment and theory. For example, in identifying the primary aim of mechanics (stress analysis) as the improved understanding and determination of strength, Hetenyi states in the preface to his volume on Experimental Stress Analysis that:

> 'Experimental stress analysis strives to achieve these aims by experimental means. In doing so, it does not remain, however, a mere counterpart of theoretical methods of stress analysis but encompasses those, utilizing all the conclusions reached by theoretical considerations, and goes far beyond them in maintaining direct contact with the true physical characteristics of the problem under consideration.'

In a similar vein, Drucker (1967) reminds us in the 1960's of the basic function of experiment in that

> '...all too often, experimental work in applied mechanics is thought of only as a check on existing theory or as a convenient substitute for analysis. This is a valid but rather inferior function of experiment. The greater and essential contribution is to guide the development of theory, by providing the fundamental basis for an understanding of the real world.'

This is followed in 1973 by Bell's even more differentiating remarks, presented in the context of an enlightening review of the role of experimental mechanics since the beginning of the 19th century, that

> 'It is essential to view the role of the experimentist as somewhat different from the currently accepted image... Since within some degree of precision several theories based upon different assumptions, may square with the same experiment; and, since in any given situation only one such theory may be currently available, with adjacent theory or theories yet to be produced; it is obvious that an experimentist does not "verify" theories. Moreover, inasmuch as adjacent theories are based upon different sets of initial assumptions, it is fallacious to presume that a correlation between data and prediction implies the validity of any one set of such assumptions.'

It is thus surprising how attitudes have remained constant over the past quarter century. The issues seem to have remained the same in spite of the tremendous changes that have occurred in the details which mechanics has developed for addressing experimental and analytical problems in engineering.

3. Interaction between experiment and theory

It is well to bear in mind that theoretical developments constitute approximations to the real world, and that a successful theory is one that describes the widest range of diverse conditions that may be encountered in (engineering) applications. Today, mechanics researchers tend to use the terms 'theory' and 'model' interchangeably, with 'model' connoting a less comprehensive proposition. Theories or analytical models of physical processes usually contain several components or building blocks, with the final result (prediction?) depending to varying degrees on the details of each of these. Implicit in the term 'model' is often the recognition that some (or all) of the building blocks are less than optimally defined in physical terms. In case one or more of such components are not experimentally supported, the analytical model is only a hypothesis that does not become an acceptable model or theory until the component in question is experimentally evaluated for correctness or replaced. At best, such a theory is not useful until the bounds of applicability are explored experimentally. In today's fast moving and powerful computation world one often encounters that the lack of detailed information is supplanted by 'making reasonable assumptions'. Typically, a 'model' is then supported by a single set of measurements to determine its unknown parameters. If a model that has been constituted with such assumptions correlates one set of data well, then it may be useful for interpolation over the range of test data that have been incorporated to define the model parameters, but is not necessarily useful outside of this range. Certainly, the more general applicability of the model (or the theory) has to be examined further in order to assess whether the 'assumed building block(s)' is (are) valid under physical situations other than those used for the parameter determination.

I draw here on a particularly perspicuous illustration from my own research interests. Following on the heels of a simple (discrete-continuum) mechanics based model for crack propagation in viscoelastic materials (Williams, 1963), a separate but 'molecular theory' was proposed in the early 1960s which contained the idea that the time- or rate-dependent fracture behavior is governed by the deformation rates at the tip of a moving crack. The assumptions were thus made that: (a) individual molecule chains span the crack tip and (b) that they respond to tension as a (linearly) viscoelastic string that snaps upon achieving a critical extension. The resulting 'theory' was then fitted 'reasonably well' to data derived in a particular load history, but did not explore the prediction under a different set of circumstances. In principle these two assumptions need to be subjected to (difficult) physical scrutiny. However, even without such examination these two features were, at best, questionable. First, when stretched molecules act in isolation as postulated, they do not exhibit macroscopically observed viscoelastic behavior. Second, if the molecule chains are considered to be substitutes for polymer strands containing many molecules for a much larger size scale so that viscoelastic behavior results, then the fixed extensibility argument for strand fracture/rupture is untenable on the basis of previously available experimental data. Neither were these details subjected to experimental examination, nor was the 'resultant theory' subjected to experimental evaluation under conditions other than those which produced the original data that determined the model parameters. Such a modeling process, which is not extinct today, is clearly not in the interest of advancing the understanding of engineering principles.

A well formulated theory cannot reject a (properly executed) experiment, but an experiment is well posed to reject a theory. It is interesting to note that Koiter, well respected for his primarily analytical contributions in mechanics, twice pointed out succinct failures of theories: One dealt with the usefulness of couple stresses, which were being touted in the 1960s as the answer to the proper treatment of (fracture related) high stress/strain gradients; he showed (Koiter, 1964) that if they were indeed important as claimed on the basis of fatigue experiments, then plate bending experiments of the first half of the 20th century should have deviated by 30 or as much as 70% from the results derived from linear elasticity. That finding obviously conflicted with years of experimental results rather well predicted by the classical, linearized theory of elasticity. In the second instance, he called attention to the fact (Koiter, 1985) that a whole class of instability problems as delineated in numerous published investigations, have simply not been observed in practice, nor had they been successfully reproduced in the laboratory. This example is then a demonstration of how experiment interacts with theory, which Drucker (1968) had expressed in the form:

> 'Theory awaits experiment and experiment awaits theory in a wide variety of fields. Often the two must go hand in hand if significant progress is to be made.'

4. Experimental mechanics in a changing computational environment

The arrival of computational mechanics has had an incisive but somewhat divergent influence on advances in mechanics, and on experimental work in particular: The results of that influence are truly revolutionary when seen against the background of the first half of the 20th century. Not only have the pure sciences benefited greatly from the appearance of the computer, but all phases of the engineering profession have achieved large quantum leaps in addressing research as well as applied problems. In mechanics, the computer has freed the analyst from the restrictive boundary conditions and constitutive descriptions which limited the closed form solutions so important prior to the last quarter of this century. As a consequence of this broadly evolving freedom in modeling experimental arrangements, the interpretation of experimental results through more detailed analyses has been enlarged tremendously when compared to the time before (multiple) computers found a place on every desk top or laboratory bench. On the other hand, apart from this analytical aspect influencing experimental work, the computerization of experiments proper has greatly expanded the scope of the process of conducting experiments, because it has now become possible to extract physical information from more involved experiments than was previously possible. Thus computers allow the automation of measurement sequences so that many more measurements can be made — 50 or 100 instead of 3 or 5 — to improve their precision. Similarly, computers make use of sensors on specimens for automatic feedback, thus providing very special control capability to the conduct of an experiment; these controls can be as simple as strain gage input to produce a true strain rate history or as complicated as image acquisition and computational feedback based on features developing in the real-time image sequence (Pulos and Knauss, 1999). Finally, the evaluation of measurements either in the form of image de-convolution or in the extraction of specific material parameters on an analytical basis has increased tremendously over the times when closed form analytical solutions were the norm.

On the other hand, expanded numerical capability is poised to obscure the need for fundamental experiments. The invention of a 'theory' is the apparently ultimate goal of most present-day (and past) mechanicians in the engineering sciences. Some highly innovative contributions to the engineering literature notwithstanding, one thus observes a proliferation of numerically based publications offered as 'theories' or 'models' that are ultimately no more than a demonstration of computational feasibility, without adding any really new understanding of the underlying science. Bell deplores this situation (Bell, 1989) in comparing the present status to the apparent separation between theory and experiment in the 18th century, characterizing it as a

> '...trend to neglect theory-related experiment, and instead, to maximize the influence of, and preference for, abstract theory, analytical model making, and now, computer conjecture that is sometimes even labeled as "experiment".'

Because our computational capability and usage has, to a large extent by sheer volume of effort, outpaced the current capacity or simply the numbers of experimentally functioning investigators to supply correspondingly numerous and **new** scientific information or phenomena, most of these computations contain components of assumptions that may appear (superficially) plausible, though their breadth or implications are rarely explored, if questioned at all. As a consequence, many of today's detailed computations are constructs that contain building blocks like houses of cards. The results of these computations thus add marginally realistic engineering information unless the associated assumptions are explored experimentally in an appropriate manner for their independent quantification: the computations have no real predictive power for future engineering designs, regardless of how 'reasonable' the multicolored presentation of the results depict 'what one would have expected' (anyway). This situation bears resemblance to aspects of the scholasticism during the 13th century, which fathered the far reaching philosophical innovations by Roger Bacon.

This perception of theory/experiment interaction is quite representative of many (though not all) publications in mechanics today. While half a century ago the corroboration of a mechanics model by experimental data could be celebrated as a 'success' because of the extraordinarily high analytical barriers, one was rather forgiving in allowing a limited number of reasonably appearing assumptions that constitute one or more of the building blocks for the model, so that one was sometimes satisfied with even qualitative results. Today, that excuse no longer exists, inasmuch as numerical computations allow such wide freedom of dealing with details of a model. In order to make a model or even a theory more widely acceptable and powerfully reliable for engineering predictions, it becomes increasingly necessary to examine the assumptions experimentally. Thus the need for experimental work increases more than proportionately to our analytical/numerical capabilities.

5. Consequences for the educational process

Another corollary of the relative ease with which numerical computations yield problem answers ('results' and publications) has been an excessive exercise of the computer as documented in the printed literature. While many desirable advances have been made in how to deal with the implementation of problem solutions on a complex scale, no doubt many efforts are motivated by a false belief that computational answers supplant the determination of physical facts. This uncontrolled increase in the number of computationally oriented investigators has often occurred at the expense of any experimental programs: besides making the return on intellectual investment more tangible in terms of publications, this situation often presents Engineering Deans additionally with the option of lower financial outlays than a proper experimentalist appointment would require. The net result of these various reasons is a gradual disappearance of the experimental component in engineering education so that one can no longer be surprised if one finds analytically oriented investigators, who do not even have the ability anymore to evaluate the quality of an experimental effort. A possible reason for this trend is that instruction in science and engineering courses follows heavily along analytical paths, so that students absorb the analytical methods more naturally. As a consequence, *any* 'experimental result' associated with laboratory hardware becomes accepted as physical (experimental) fact worthy of modeling and forging into a 'theory'. Just as experimentally oriented students need to be well versed in mathematics and the foundations of solid mechanics, so must the analytically oriented student be educated in the proper conduct of experimental work.

It is probably too severe a proposition to blame the rise of the computer for this development exclusively. Before computers dominated every-day life as much as science/engineering, Drucker warned (Drucker, 1968) about a '... strong steady drift of far too large a fraction of the best students' towards analytical work, and opined that:

> 'Unless appreciable numbers of the most qualified students aim at combined experimental and theoretical research, the storehouse of physical information will be depleted by the tremendous emphasis on analysis and theory, and the theorist will be reduced to playing useless games.... Over the years, experiment alone provides the basis for the refinement and extension of existing theory and the development of new theory.'

This observation is as true today as it was when Drucker made it.

Singer, Weller and Arbocz raise another issue in the introduction to their recent first volume on Buckling Experiments....(Singer et al., 1998), namely, that the student of today and of the future will suffer a (probable) disconnect from the historical perspective of mechanics. This is the result of computerizing literature searches, which operates with an influence coefficient limited to more recent times. He/She will thus tend to ignore the fundamental studies, with a proclivity to 'rediscover America', if not the wheel. It would indeed be deplorable, if the investigator of the future were to be separated from his/her heritage any further than is true already at this time.

6. Experimental methods and opportunities

The evolution of experimental tools has been a fundamentally enabling aspect for mechanics. Although we tend to think today that modern technology provides the mainstay for refined experimental procedures, it is quite enlightening that our forebears were able to make highly accurate measurements more than a century and a half ago. Thus interferometry allowed strains of 10^{-6} to be measured in the first half of the 19th century, and Grüneisen was able to improve those measurements to strains as small as 10^{-8} around the end of that century. Nevertheless, the advances in technology have made measurement methods much more convenient, and have fostered a tremendous proliferation of tools offering a large range of precision. Although it is beyond the scope of this presentation to address and analyze even the major methods in use today, it is appropriate to at least list them and refer the reader to more detailed documentation in the open literature (Dally and Riley, 1991; Cloud, 1995; Epstein, 1993; Kobayashi, 1987).

One can separate methods roughly into two types, namely those that generate primarily information at a point on a solid, and those which produce field information. Amongst the former we find principally the (wire, foil and semiconductor) **strain gages** in unidirectional and rosette form; **accelerometers** as used in structural vibration (modal analysis) problems; and **acoustic emitters/sensors** which can also be arranged to function in a scanning mode to render field information. A particularly refined form of these is the **acoustic microscope**, which allows field examination inside a solid, but only in domains the depth of which are measured in millimeters or microns from the surface, depending on the frequency used: the high sound wave attenuation in virtually all materials at the high frequencies used (gigahertz) forces a trade-off between resolution and depth of observation. Finally, the optical shadow method or method of **caustics** also falls into this category, although it samples field information but delivers a single value (possibly as a function of time).

Most of the methods producing field information are optical in nature and are thus, practically speaking, limited in resolution by the wavelength of the light used, although many of them cannot approach that limit for other reasons. They comprise **photoelasticity**, **moiré** and **shadow moiré**, **holography** and **speckle interferometry**, **heterodyning**, **gradient sensing**, [Twyman–Green] **interferometry**, **moiré interferometry**, and **thermography**. The information is obtained typically in the form of fringe fields that have yielded historically spatial resolutions on the order of a millimeter(s). This spatial resolution can be improved with the aid of computer processing, once improved reliable codes for representing fringes numerically have been established.

Perhaps the interferometric and moiré interferometric methods deserve special attention because of their power to resolve displacements measured in terms of the wavelength of light (∼ one micron) and because of their potential (when used carefully) for high spatial resolution of the displacement field. These two methods also illustrate the evolution of experimental methods over the last 100 years and thus demonstrate how the need in a certain science field (solid mechanics) culls a new method (moiré interferometry) from a well established physical principle for a special application. An illustration of the precision which interferometry and moiré interferometry can deliver (simultaneously) is illustrated in Fig. 1: This figure depicts measured and computed displacements at the tip of a crack in a 4340 steel plate of finite thickness which resulted from a study that examined the precision of current

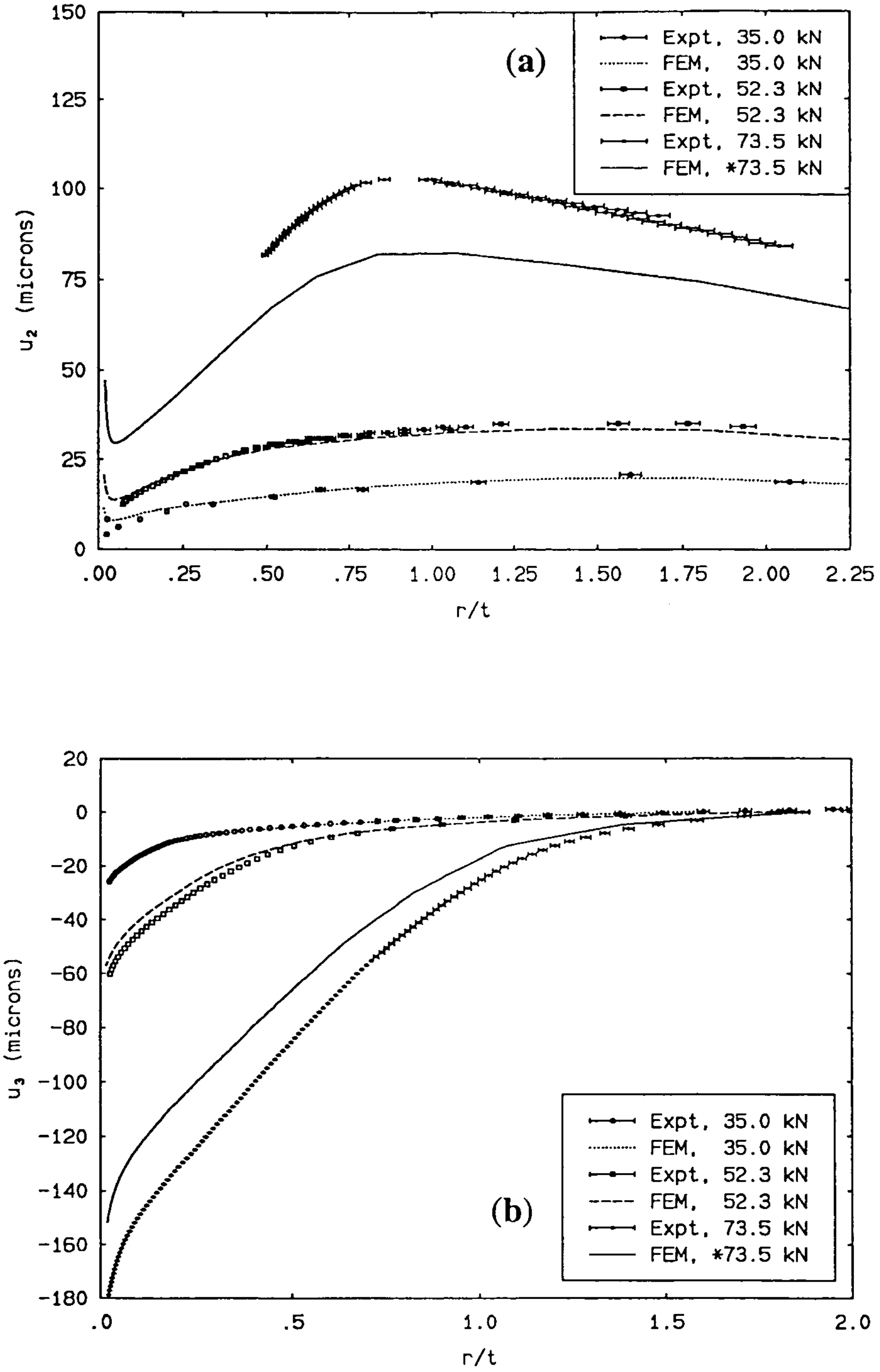

Fig. 1. Comparison of measured and computed surface displacements near the crack tip for three load levels in a plastically deforming 4340-steel plate of finite thickness (10 mm); unstable crack propagation commenced at 73.5 kiloNewtons. Note that the small error bars indicate uncertainty in the locality of the point, the displacement uncertainty cannot be indicated on the scale of the plot. (a) In-plane surface displacement u_2 normal to the crack along a line making an angle of ±60° with the line of crack extension. (b) Surface-normal displacement u_3 along the same line.

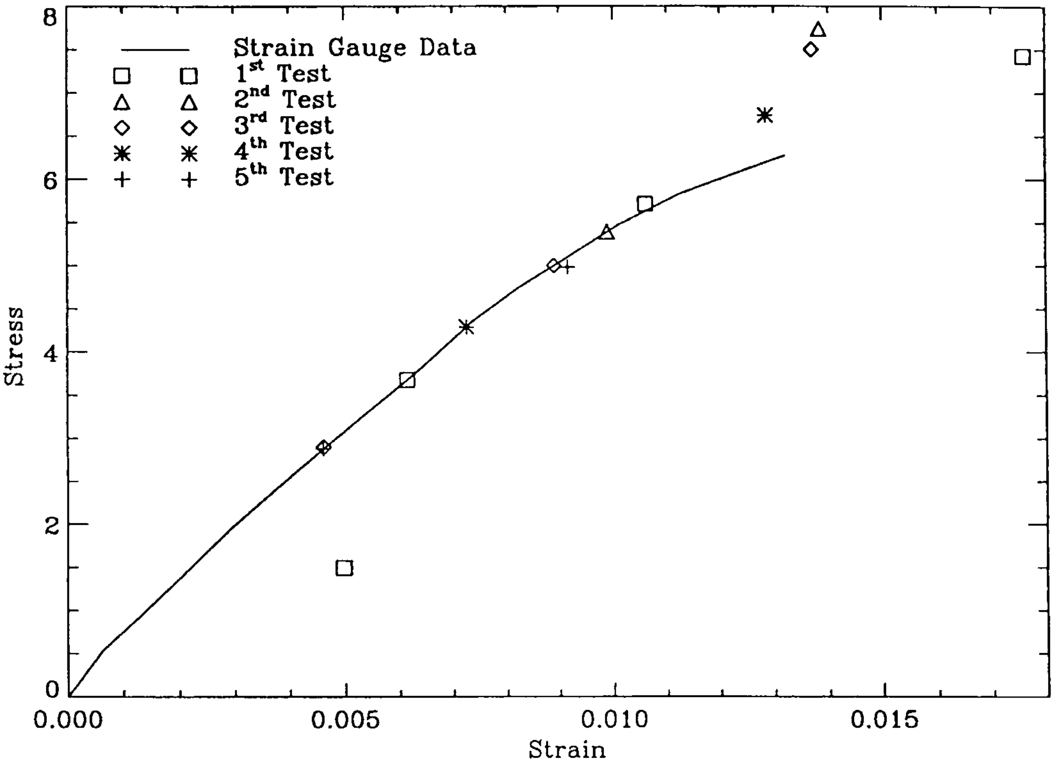

Fig. 2. Measurement of strain in a uniaxial PVC tension specimen as determined via strain gage and Digital Image Correlation. The latter method allowed strain determination over a domain of about 200 nanometers. At smaller domain sizes inhomogeneous deformations could be observed.

computational capabilities in nonlinear fracture mechanics *vis-à-vis* physical reality (Schultheisz et al., 1999). As long as the surface normal remains so within 2° a spatial resolution of 5–10 microns is readily achievable by moiré interferometry for in-plane displacements. Out-of-plane deformations of a micron or two are standard with [Twyman–Green] interferometry. Because of this high resolution power of moiré interferometry, it has been an important addition to the repertoire of tools for experiments and became thus a favorite tool for refined deformation measurements on electronic micro chips; in this connection this method has served virtually the same purpose for these small devices as photoelasticity has for the larger engineering structures during the middle of this century; the major difference being that photoelasticity addresses the stress state more directly than moiré interferometry, which renders displacements.

Thermography is feasible for point as well as field measurements. In the first mode it is often used for high speed events (Zehnder and Rosakis, 1991) because full field representation is too slow or too expensive with available technology. However, at 30 to 50 frames per second, full field thermal images can be captured today with commercially available 'Thermal Camera' equipment.

A relatively new method for determining displacements and strains has evolved through the significant power of (desk) computers, the **Digital Image Correlation** method (Sutton et al., 1983; Chu et al., 1985; Sutton et al., 1986Sutton et al., 1988). First considered in the context of fluid mechanics investigations, this non-contact method records images of (shadows of) surface irregularities or painted-on spots before and after deformation. By postulating a (large deformation) continuum transformation (Vendroux and

Knauss, 1998b) for image points between these two states, which contain rigid body motions and local strains as parameters, the latter are determined such that a correlation function, connecting the deformed and undeformed states, is minimized. The capability of this method depends somewhat on the gradients of the strain field because a large field of view containing a (nearly) constant strain field provides a larger 'gage length' than a strain field that changes over a short distance. Improvements in the resolution capability are desired, since, typically, current values are limited (with some difficulty) to strains larger than 0.0005.

This new DIC imaging method is a potential boon to investigations at extremely small size scales, namely micro- and nano-mechanics. Along with the means of the Scanning Electron and the Transmission Electron Microscopes (SEMs and TEMs) the more recent arrival of probe microscopy (Scanning Tunneling and Atomic Force microscopes) spatial resolution down to the atomic level is becoming available. These are the size domains that need to be addressed in order to resolve issues in what is often called meso-mechanics which ostensibly covers problem areas where the distinctions between classical continuum mechanics and atomic or discrete molecular formulations are essential. While these tools have a standing history in terms of providing images (rendition of topography), the major means of translating these images into displacement fields was offered through stereoscopic recording (Lindholm, 1990), with strain determinations limited to subsequent numerical differentiation. In contrast, the DIC method allows the simultaneous determination of displacements **and** their gradients. Inasmuch as SEMs, TEMs, STMs and AFMs yield pixelated images, the DIC method is a natural tool to evaluate such data. An illustration of strain measurement at the nano-scale has been given by Vendroux and Knauss (1998c) as illustrated in Fig. 2; attempts at extending that method in combination with the SEM is currently underway at Yale University (Tong, 1998).

7. Opportunities in experimental solid mechanics

In this presentation allusion has been made repeatedly to the idea that the objective of (future) mechanics investigations should be heavily slanted towards improving the **quantitatively** predictive power available to the engineer today through unprecedented computational/analytical capabilities. This process of improving predictive accuracy for engineering designs comes largely from improved physical input, *i.e.* experiment. From an engineering point of view there are several topics that invite extensive experimental involvement. These divide naturally into (a) continuing needs of topics currently under consideration, as well as (b) new areas that are under-represented in mechanics but distinctly in need of resolution. These are discussed in light of:

Constitutive description: Much of the experimental work during the first half of this century was devoted to determining deformation and stress fields in solids, because the mathematical-analytical methods could not cope with many realistic engineering situations. Thus a major interaction between experiment and analysis concerned exploration of the limits of analytical solutions. In addition, a major thrust of experimental mechanics was the determination of physical properties of materials, to which discipline much of the efforts of the last century were devoted, as described above. In fact, if failure and fracture are excluded from consideration, then the primary objective of experimental mechanics would be the determination of the material properties as input into proper stress analyses. Although there exists a plethora of assumed approximations to constitutive behavior (*e.g.* Gurson, 1977), some of it used extensively (Tvergaard, 1990), but rarely submitted to a detailed experimental examination as in (Zavaliangos and Anand, 1993), there appears to be only little urgency today to pursue this aspect of mechanics vigorously. However, it appears clear that with one's ability to formulate the basic equations of mechanics for the computer, whether involving large or small deformations, improved descriptions for constitutive response that matches the (possible) refinement of computational analyses, is certainly in order. It appears that prime among these is the description of large strain plasticity. Although propositions for mathematical formulations of the relevant constitutive descriptions exist, there is, outside of special situations, a dearth of comparative experimental data addressing the generality of such formulations. This area of investigation is clearly in need of future expansion.

Fracture and Fatigue: From a technology point of view this topic is extremely important, especially if one recalls that about 80 to 90% of engineering failures relate to fatigue situations. Much has been accomplished in the last two or three decades regarding the propagation of existing, macroscopic cracks, whereby the safety of certain engineering designs (*e.g.* pressure vessels, piping) has been markedly improved. There is little point arguing the fact, however, that much of what has been learned is in the form of 'understanding' and semi-quantitative formulations rather than reliably predictive analysis. For example, any design of a critical structural aircraft component is submitted to extensive full scale tests, to ascertain that the design analysis is indeed appropriate. There is thus a distinct need for improved precision in failure estimation that hinges on the more detailed physics and analysis of the material deforming in the immediate vicinity of the crack tip. This observation is particularly true when other than monotonic or non-complex loadings arise. Current material models need to be improved beyond the classical plasticity descriptions if progress is to be made in this direction. Moreover, there are many situations involving materials to which metal plasticity does not really apply (*e.g.* polymers) and for which equivalent material descriptions need to be found, often involving large deformations. The discussion as to whether that is to be accomplished through homogenized damage models or through physics-based detailed modeling at the micro-scale is going to be a continuing question in failure mechanics that can be resolved in a rational manner not through computational efforts alone, but only if material response is characterized in sufficient detail through experimental means at the tips of cracks.

It is a fact of life that in a fatigue environment only about 10 to 20% of the life of a structure is covered by the final stages of macroscopically propagating cracks. Fracture mechanics is not suited to deal with the initiation and 'early' evolutionary phase of the fatigue failure process. Although persistent shear bands play a major role in some materials for generating fatigue cracks, such is not the case for all materials, many being subject to the micromechanical deformation mechanisms at the size scale of material grains and smaller.

Materials & Nanomechanics: During the last decade solid mechanics has moved strongly into the interdisciplinary area of the mechanics of materials. This continuing trend has arguably major implications for the experimental sector of mechanics and on its interaction with the analytical efforts. Problems in this domain are characterized by the distinctly small size scale. These are addressed today primarily via analytical modeling by assuming certain aspects of the experimentally inaccessible domain and examining whether the modeling assumptions are contradicted by experiments executed at a (much) larger scale. As alluded to above, such modeling does not, of course, yield unique answers, in that several (or many) assumed small scale details will render (virtually) the same macroscopic response, allowing little differentiation at the micro-scale. One may refer to this behavior as the 'Reverse St. Venant Principle'. Just as St. Venant pronounced that the effect of load distribution detail is lost with increasing distance from the loading domain, so does it become difficult or even impossible to conclude from an integrated macroscopic response what happens in detail at the sub-scale in the interior of a (multi-phase) body. For this reason it is of fundamental importance that research in micromechanics be supported by detailed experimental investigations at the **relevant** size scale. For the present discussion purposes, this field may be distinguished by the following three domains of (a) composites and smart materials, (b) Microelectromechanical Systems (MEMS), and (c) relation to molecular dynamics.

Composite and smart material: Although we commonly identify 'composite materials' and 'smart materials' as materials, they are, more appropriately, multiphase structures, the response of which to load is dictated by the interaction of the components and their interfaces and interphases. Typical issues revolve around the global stress-deformation description and the evolution of failure/fracture.

Disregarding concretes for the present, the dimensions of the phases are typically measured in terms of millimeters and microns, a size scale that is characteristically difficult to deal with by classical experimental tools. Since scaling requires that stress and deformation gradients be resolved at a size scale considerably smaller than the largest structural dimension, one is faced with the need to resolve deformation features below the resolution of optical methods (˜ micron). These problems draw upon the use of powerful (electron, transmission) microscopes and on probe microscopy (scanning tunneling and atomic force microscopes.)

MicroElectroMechanical Systems (MEMS) are poised for a major impact on future engineering designs. The mainstay of commercial ink-jet printing as well as automotive airbag technology (accelerometers), they are being explored in other transportation related designs for gyroscopic and other control purposes, which will make control of space hardware at the very small size scale possible. Similarly, micro-mirror arrays are being explored for high resolution in video displays and constitute a large economic potential. MEMS based valves have a huge potential as medical implant devices for medicinal dosage, which can be controlled by remote control exterior to the body. Chemical sensing devices offer a vast potential of low cost disposable medical sensors (NRC, 1997).

The main issues of durability of these devices are the same as those of larger engineering designs. However, the actual physics of the failure process occurs at a much smaller scale and while the transplantation of the governing principles of solid mechanics is not in question, the transference of physical understanding and material response to this small scale is not clear at all and thus demands detailed attention, certainly an evolution of appropriate test methods that go far beyond the needs in packaging of microelectronic devices (chips). There is thus a need to repeat a large number of the physical examinations of failure and properties accessible today at the macro-scale, but now for the submicron domain.

Today, properties of MEMS are determined through miniaturization processes of methods applied for what one used to refer to as strength of materials: In the simplest forms, these employ typically tensile, bending and vibration methods applied to sub-millimeter sized specimens (Sharpe et al., 1998). On the other hand, the STM and AFM method combined with DIC (Vendroux and Knauss, 1998a) offer the means of resolution at a considerably smaller size scale. The beautiful experiments by Kim (Choi et al., 1992; Kim et al., 1999; Kim and Picu, 1999) resolving the deformation field around single dislocations and allowing conclusions regarding the interatomic force field are very hopeful signs that experimentation at the nano scale is possible and very rewarding.

Molecular dynamics: The emerging discipline of (computational) molecular dynamics raises issues for support by the experimentalist. There has been a continuing disconnect between the usual (say millimeter) size scale of mechanics (as governed by experience and limitation in experimental observation tools) and the molecular understanding from ‘first principles’. For example, chemists have desired for years to predict in some detail the physical properties of polymers from the known molecular structure without need to resort to laboratory measurements. That feasibility is becoming more real with respect to properties of pure substances and multiphase materials at the nano scale. However, in the drive to construct larger and larger domains from molecules with even the largest computers envisioned for the next decades, there will be a continuing need to simulate such large molecular structures through assumptions that need physical examination, *i.e.* experimentation at the nano scale. This statement is particularly true with respect to the response of physical systems approaching or reaching failure/fracture.

8. Additional problem areas

Extensive evaluation of fringe field data was an extremely time consuming process for photoelasticity investigations and presented thus a major obstacle in its application. Today, virtually all optical methods suffer from the same predicament. It would therefore seem desirable to evolve a (computer based) method to **digitally fit and evaluate fringe data** so reliably that even differentiation of the field data has meaning. Although several individuals have made efforts in that direction, there is, apparently, no such code available today to the serious investigator.

A recurring problem in experimental mechanics is that observations on opaque solids is restricted to the body's surface when the real interest is on processes occurring in the interior. This is particularly true in fracture related situations. Today's answer to this puzzle is the computational link between surface deformations and the state of stress/strain in the interior, provided the constitutive behavior of the material is indubitably well established. When the latter condition is in doubt, only direct experimental observations are productive. Following **tomographic methods** widely used in medicine, it will be necessary to extend these methods to the investigation of solids.

In the domain of high speed phenomena of fracture and flow a major impediment to physical definition is the current trade-off between spatial and temporal resolution of today's frame recording devices: **High speed field data acquisition** is feasible at the expense of reduced spatial resolution, and *vice versa*. However, the need exists to improve the spatial resolution at high recording rates in order to refine the determination of the detailed, physical processes that control the deformation and fracture/failure of solids.

9. Summary

The need for rational interaction between experimental and analytical efforts in solid mechanics has been reviewed. It is perceived that the strongly evolving computational capabilities to attack solid mechanics problems raise the specter of fostering analyses in increasing detail without the requisite hard physical data to support such detail. This need is construed as an opportunity for experimental mechanics that should be supported at the university and at the funding agency levels in order to make engineering in the new century more reliable and predictive. The opinion is offered that these needs are particularly strong in the emerging mechanics at the micro- and nano-scales, where great needs exist and continue to arise.

The need for renewed and closer interaction between theory and experiment is stressed, based on the classical way in which the two domains of mechanics have interacted and need to continue to do so. A solidly constructed theory intended for use in general engineering applications should contain only building blocks that are physically well established. However, often the detailed information required is not readily available, and as a result, the required information is supplanted by assumptions. What should happen in a normal interaction between experimental and analytical efforts is that the *validity of the assumptions* be then subject to experimental scrutiny. However, the lack of experimentally cooperating researchers is simply too small today to cope with satisfying this need relative to the frequent occurrence in the computationally oriented sector of solid mechanics. As a result, there are many published theoretical treatments that are physically plausible, as demonstrated in superb color images or movies, but which lack specification of the range of applicability as needed for engineering application purposes. The computer has given us the ability to model complicated physical processes which, as long as all building blocks of the model are 'reasonable', render the qualitative results one has experienced before and which one has come to expect. What is needed today is the insertion of experimental data into such computational constructs which then assure the engineer of the future that when he has need to use these theoretical developments, the resulting numbers are physically reliable. This need for detailed experiments presents one of the challenges in the future of engineering research, education and the profession.

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References

Bacon, R., 1912. 'Opus Tertius'. In: Little, A.G. (Ed.), Including a fragment.. University Press, Aberdeen.

Bacon, R., 1928. 'Opus Majus', transl. by Burke, R. University of Pennsylvania Press, Philadelphia.

Bell, J.F., 1973. The experimental foundations of solid mechanics. In: Flügge, S. (Ed.), Encyclopedia of Physics, VIa/1. Mechanics of Solids, Springer Verlag.

Bell, J.F., 1989. Experimental mechanics in the 19th century. Experimental Mechanics June, 157–165.

Choi, H.C., Schwartzman, A.F., Kim, K.-S., 1992. Experimental deformation mechanics of materials from their near-atomic-resolution defect images. Mat. Res. Soc. Symp. Proc. 239, 419–424.

Chu, T.C., Ranson, W.F., Sutton, M.A., Peters, W.H., 1985. Applications of digital image correlation techniques to experimental mechanics. Experimental Mechanics 25 (3), 232–244.

Cloud, G., 1995. Optical methods of engineering analysis. Cambridge University Press.

Dally, J.W., Riley, W.F., 1991. Experimental stress analysis, 3rd. McGraw-Hill, New York.

Drucker, D.C., 1962. On the role of experiment in the development of theory. In: General Lecture, Proceedings of the 4th US National Congress of Applied Mechanics. ASME, pp. 15–33.

Drucker, D.C., 1968. Thoughts on the present and future interrelation of theoretical and experimental mechanics. Experimental Mechanics March, 97–106.

Epstein, J.S. (Ed.), 1993. Experimental techniques in fracture, Society for experimental mechanics, Inc. VCH Publishers, New York.

Gurson, A.L., 1977. Continuum theory of ductile rupture by void nucleation and growth — I. Yield criteria and flow rules for porous ductile media. Journal of Engineering Materials Technology 99, 2–15.

Hetenyi, M., 1950. Preface to the handbook of experimental stress analysis. John Wiley & Sons, New York.

Kim, K.-S., Tsai, K.-H., Choi, H.-C., 1999. Deformation analysis of near atomic resolution images of crystal defects. Phil. Mag. (submitted for publication).

Kim, K.-S., Picu, R.C., 1999. Point field projection method of characterizing crystalline defects near atomic resolution. Journal of Mechanics and Physics of Solids (submitted for publication).

Kobayashi, A.S. (Ed.), 1987. Handbook on Experimental Mechanics, Society For Experimental Mechanics, Inc. Prentice-Hall, New Jersey.

Koiter, W.T., 1964. Couple-Stresses in the Theory of Elasticty. I. Konigl. Nederl. Akad. Wetenshappen-Series B 67(1), Amsterdam.

Koiter, W.T., 1985. Elastic Stability. Zeitschr. für Flugwissenschaften und Weltraumforschung 9 (4), 205–210.

Lindholm, U.S., 1990. Experimental mechanics: New challenges in micromechanics. Mechanics of Materials 10, 31–42.

NRC, 1997. Microelectromechanical Systems, Advanced Materials and Fabrication Methods, NMAB-483. National Academy Press, Washington D.C.

Pulos, G.C., Knauss, W.G., 1999. Non-steady crack and craze behavior in PMMA under cyclical loading. III: Effect of load history on cohesive force distribution of the craze. International Journal of Fracture 93, 187–207.

Schultheisz, C., Pfaff, R.D., Knauss, W.G., 1999. An experimental/analytical comparison of three-dimensional deformations at the tip of a crack in a plastically deforming plate, III. Comparison of numerical and experimental results. International Journal of Fracture 90, 47–81.

Sharpe Jr., W.N., Brown, S., Johnson, G.C., Knauss, W., 1998. Round-robin tests of modulus and strength of polysilicon. In: Microelectromechanical structures for materials research. Materials Research Society 518, 57–65.

Singer, J., Weller, T., Arbocz, J., 1998. Introduction to buckling experiments: Experimental methods in buckling of thin-walled structures: basic concepts, columns, beams and plates. John Wiley & Sons.

Sutton, M.A., Wolters, W.J., Peters, W.H., Ranson, W.F., McNeil, S.R., 1983. Determination of displacements using an improved digital correlation method. Image Vision Computing 1 (3), 133–139.

Sutton, M.A., Cheng, M., Peters, W.H., Chao, Y.J., McNeil, S.R., 1986. Application of an optimized digital image correlation method to planar deformation analysis. Image Vision Computing 4 (3), 143–150.

Sutton, M.A., McNeil, S.R., Jang, J., Babai, M., 1988. The effect of subpixel image resaturation on digital image correlation estimates. Optical Engineering 27 (10), 870–877.

Tong, W., 1998. Yale University. Personal communication.

Tvergaard, V., 1990. Material failure by void growth to coalescence. Advances in Applied Mechanics 27, 83–151.

Vendroux, G., Knauss, W.G., 1998a. Submicron deformation field measurements part 1: demonstration of deformation determination. Experimental Mechanics (March) 38 (1), 18–23.

Vendroux, G., Knauss, W.G., 1998b. Submicron deformation field measurements part 2: improved digital image correlation. Experimental Mechanics (June) 38 (2), 86–92.

Vendroux, G., Knauss, W.G., 1998c. Submicron deformation field measurements. Part 3: demonstration of deformation determinations. Experimental Mechanics (Sept.) 38 (3), 154–160.

Williams, M.L., 1963. The fracture of viscoelastic material. In: Drucker, D.C., Gilman, J.J. (Eds.), Fracture of Solids. John Wiley & Sons, pp. 157–188.

Zavaliangos, A., Anand, L., 1993. Thermo-elasto-viscoplacity of isotropic porous metals. Journal of Mechanics and Physics of Solids 41 (6), 1087–1118.

Zehnder, A., Rosakis, A., 1991. On the temperature distribution at the vicinity of dynamically propagating cracks in 4340 steel. Journal of the Mechanics and Physics of Solids 39 (3), 385–415.