UNIVERSITY OF NIŠ
The scientific journal **FACTA UNIVERSITATIS**
Series: **Mechanics, Automatic Control and Robotics** Vol.2, No 7/2, 1997 pp. 471 - 489
Editor of series: Katica (Stevanovi}) Hedrih, e-mail: katica@masfak.masfak.ni.ac.yu
Address: Univerzitetski trg 2, 18000 Niš, YU, Tel: (018) 547-095, Fax: (018)-547-950
http:// ni.ac.yu/Facta

COMMENTS ON DICHOTOMY IN ENGINEERING MECHANICS

UDC: 532.12: .001.4: 371.380: 612.084: 612.085

Jerzy Pindera

Department of Civil Engineering, University of Waterloo
Waterloo, Ontario, Canada N2L 3G1

Abstract. *The increasing demands of modern societies regarding technology, and the explosion of knowledge in all fields during the last several decades, are enforcing a more rigorous approach to development of engineering theories, experiments, design procedures and technological procedures. Of particular importance are new societal and economic criteria for optimization of machines and structures, which encompass the notion of a total cost to the society, which represents not only the traditional cost of manufacturing and servicing the product, but also health issues, use of natural resources, interaction with environment, and disposal of used materials and products. Demands of such a framework exposed strong dichotomy existing in engineering mechanics between the traditional phenomenological approach in development of formulas used in general engineering practice, and the physical approach common in natural sciences and accepted in more demanding aerospace and defence industries. That dichotomy, already reflected in majority of the textbooks on engineering mechanics, is not necessary and results in costly structural failures. Paper outlines patterns of new, physical trends in applied mechanics, and presents typical examples of unnecessary simplifications in mathematical modeling of materials responses, structural behaviour, and experimental procedures.*

1. INTRODUCTION. FRAMEWORK

All human activities develop within a specific framework. This is particularly true regarding engineering mechanics which is understood here as synergy of applied mechanics and applied mathematics, numerical mechanics and mathematics, experimental mechanics and physics, computational mechanics, materials science with physics and chemistry, and computational materials science. The essential components of that framework, as the financial support of research which usually determines the research directions, and the imposed constraints and conditions are recognized but not

---

Received September 16, 1997

discussed here. Briefly characterized below are the components related to societal pressure, to the level and depth of relevant research and development in natural sciences and advanced technology, and to the requirements of the related technologies. It should be noted that the common notion of the *state-of-the-art* could be misleading if the necessary data on the chosen *bench mark*, or *a criterion of assessment*, is not given. The same pertains to the notion of a *small error*.

1.1. Societal requirements

For the first time in recorded history the rapidly developing technologies influence profoundly all aspects of societal life almost everywhere on our planet. Products of our technologies influence significantly all life on our planet, including practically all ecological parameters. In a form of feedback, the new technologies influence the level and rate of development of new knowledge and practice, including university curricula. As a result, the socioeconomic ethical issues become an integral part of practice of a modern engineer. It is evident that the modern societies believe that the objective of engineering is to produce reliable, economical, safe, and environmentally friendly structures, machines, instruments and processes, and to render technological services within the conditions and constraints imposed by far-reaching societal interest. The societal perceptions of the technological hazard and risk allow to quantify the acceptable level of the risk; the related societal demands are influencing profoundly criteria of design optimization. Nevertheless, there still exists a strange belief in general engineering that the engineering research and development activities are essentially intellectual activities not influenced by societal issues. That belief, which is not shared by engineers involved in high level research, is evidently wrong.

1.2. Progres in measurement science and information theory

Measurements of mechanical displacements and motions, and the following evaluation of the derived quantities such as strain, stress, and their time derivatives, used to be the major field of engineering *experimental mechanics*. Thus, traditionally, the term experimental mechanics has been mostly used to denote development of various experimental techniques whose results could be translated into strains and stresses by using elementary relations of applied mechanics, and elementary phenomenological relations describing involved physical phenomena. The term *theory of experiment* denoted mostly the mathematical statistical methods of evaluation of stochastic results. The more theoretical treatment of the theory of experiments, such as that presented by Doeblin [5], has been outside the main stream of engineering experimental mechanics. Lack of such a theory leads to unnecessary errors and faulty evaluation [4]. The main problem was accuracy of measurement and of evaluation of final results; however, the notion of error was often vague. Very often the accepted value of an error was in the range of 5 to 10 percent, or more, and the error itself were determined with respect to prediction of a plane stress solution of analytical mechanics. Physical aspects of information theory, such as those discussed by Brillouin [2], were outside of interest of engineers in experimental mechanics.

The incredible progress in theory and techniques of measurements during the last several decades practically eliminated the problem of accuracy of engineering measurements. Research teams consisting of physicists, mathematicians, optical and electronic engineers, materials scientists, and research engineers, developed methods and instruments, which allow to measure physical quantities with accuracy much higher than the accuracy required by engineers. Instruments, whose resolution was considered theoretically impossible a few decades or only a few years ago, are commercially available. For example, the typical resolutions of modern measurement instruments are:

- Spatial resolution: about 1 angstrom (10^{-10} m).
- Temporal resolution: a few femtoseconds (10^{-15} s).
- Force resolution: picoNewton range (10^{-12} N).
- Typical measurement errors: one part in a million, or even one part in a billion if advanced theories and techniques of measurement are used.

Thus, the load-induced deformation of a single-stranded DNA molecule, having the diameter of about 1 nanometer, can be reliably determined in the force range from 0.01 to 10 pN which produce deformations in the namometer range. Atoms at the surface can be easily observed and their position accurately measured, so the development of physical and mathematical models of various kinds of deformation can be based on sound physical evidence, and hypothetical guessing could be constrained. In summary, the problems of accuracy of measurements and of evaluated results should not exist any longer in experimental mechanics. However, they still exist because of inadequate theoretical bases commonly accepted by experimenters.

A problem of economical collecting, recording, and processing of experimental data was essentially solved with introduction of electronic computer techniques. However, computer collecting of experimental data could result in collection of unreliable experimental data when the theory of experiment is defective; computer evaluation of reliable experimental data may yield unreliable results when evaluation is based on defective or faulty physical and mathematical models which comply with the phenomenological approach of the traditional applied mechanics, but which are at a variance with physical reality. That issue is illustrated by the examples presented in the next chapter.

1.3 Requirements of modern technology

Modern technology could be characterized in many ways, depending on the purpose of characterization. Some of the major traits of the products are: low overall cost, safe operation, user friendliness, predictable failures, assembly line design, easy inspection, environmental and ecological friendliness, use of new advanced materials. Related optimization of strength and deformation requires reliable, advanced relations of analytical mechanics, and advanced knowledge of the actual, coupled responses of structural materials.

A particular category of modern technology is the rapidly growing system of theories, processes, new materials, and new technologies at the macro and nanoscale, which is often denoted by the term *high technology*. That kind of technology requires advanced analytical, numerical, and experimental procedures, and also requires use of advanced materials including the functionally graded materials, smart materials and smart sensors. Development and testing of the underlying theories and procedures require a more rigorous and comprehensive theoretical bases than those presently accepted in traditional engineering and considered satisfactory, including various analytical solutions of phenomenological applied mechanics. Revolutionary development of such an advanced sector of modern technology, has been made possible by acceptance of the incredible progress in related fields of science. Particularly fruitful is the acceptance of the physical approach to the analysis of real responses of materials, structures, and systems, instead of the traditional phenomenological one. Electronic computer techniques are playing a major role in this development. Patterns of high technology development accelerated development of the physical trend in engineering mechanics, already indicated or outlined by Valanis [48] and Pindera [25]. It could be noted that one of the major problems of high technology is the lack of sufficiently reliable analytical solutions for the particular tasks of the designing engineer.

2. TRADITIONAL PHENOMENOLOGICAL AND NEW PHYSICAL APPROACHES IN APPLIED MECHANICS

Two intertwined major issues deserve special attention: the reliability of the theoretical foundations of that branches of applied and analytical mechanics which are meant to simulate the actual responses of materials and structures, and the reliability of the theoretical foundations of mathematical modeling in engineering materials science. Presentation of the third major issue, namely of the coupled responses of the structural, measurement, or testing systems, which pertain to energy flow through the system, and of the materials coupled responses which depend on the form of information -detecting energy, depends on the format of presentation of the first two issues.

Format of presentation of responses of materials and structures depends on the chosen approach, phenomenological or physical. Differences between both approaches are profound. A not critical choice of phenomenological approach may result in significant evaluation errors, both in the magnitude and in sign of the evaluated quantity.

2.1. Notions of Model in Engineering Mechanics

No notion or definition is written in stone. This is particularly true during a period of rapid, revolutionary changes, such as those presently occurring in societies, science, engineering and technology. Newly expanded horizons, increased understanding of mechanisms of deformations of materials and structures, and demands for consistency of concepts and notions in engineering, sciences, and mathematics, rendered some traditional notions of mechanics obsolete. For example it was customary in engineering to distinguish a mathematical theory from a physical one. This is not tenable any longer. Mathematics is a language of a book and by itself, without additional information, it does not convey any message about its intended contents and the level of treatment of the subject. It is said that mathematics is about mathematical objects, and mathematical theories are satisfied in mathematical abstract models. It is also said that the book of nature is written in the language of mathematics. It is common to find contradictory concepts of, for example, natural processes related to mechanical and thermal responses of a structure loaded by wind and sun irradiation. Those concepts are presented in the form of mathematical relationships, so, they are mathematical theories but some of them are using obsolete language. Thus, the real difference between the various engineering theories used to describe responses of materials, structures, and machines is the level of treatment of the subject, phenomenological or physical. The resulting theories or relations are phenomenological theories or physical theories, both categories presented in mathematical form.

All theories in sciences and engineering are based on the concept of models of perceived, or speculatively guessed, reality [2, 7, 14, 25]. Basic models are physical models, or conceptual models, which represent major features of the object under consideration, selected according to accepted criteria of modeling. Selected physical models are presented in form of simplified analytical expressions known as particular mathematical models. Further simplification of the system of the basic physical and mathematical models, and introduction of a unifying relationship, results in formulation of an overall mathematical model of the considered object or process. In engineering a mathematical model can be very often treated as a transfer function which relates output signals to input signals. In the phenomenological approach, the basic physical and mathematical models are treated as so-called black boxes developed mostly in a noncritical, speculative manner; responses of those boxes do not necessarily comply with known laws of physics, and are allowed tho violate some assumptions. In physical approach, the basic physical and mathematical models and their speculative features must be noncontradictory with the known relation of physics, and with the underlying assumptions. A certain amount of speculation is accepted by both methodologies, but at different levels. Thus, analytical and experimental mechanics are inherently intertwined at advanced level as stated by Leipholz [18], and indicated by Feynman [7].

The patterns of development of the phenomenological and physical models in engineering are outlined in Figure 1 [13, 25, 28, 29, 33]. It presents, in a very condensed manner, the major features of development of both, the phenomenological and physical, categories of the fundamental, conceptual models, and the necessary testing procedures. Analytical relations used by traditional engineering are based on phenomenological, very simplified approach to model development. Such relations are often not reliable. For example, a particular phenomenological relation of the theory of plasticity, pertaining to deformation of a beam under three point loads, yields data at a variance with observation [34]. However, the phenomenological analytical relations which are developed according to the requirements of scientific methodology, such as those presented by Ramachandran and Ramaseshan [42], are very useful and provide a rational framework for further physical development. The analytical relations used in science, and in high technology research and designing, are based on physical approach, compatible with contemporary knowledge, so, such discrepancies are not allowed.

The experimental models made of matter and energy could be constructed as physical or phenomenological experimental models. Many major failures of engineering structures are caused by the fact that the phenomenological experimental models were used as a basis for assessment of reliability of design. The known examples are failures of the Tacoma Narrows Bridge in 1940, of the first passenger jet plane Comet in 1950's, or of the Hancock buildings in Boston in 1977.

2.2. New trends in applied mechanics

Classical theories of deformation of elastic, plastic, and time-dependent bodies induced by mechanical loads are phenomenological theories, based on an assumed and not tested model of reality. Existence of a material continuum is assumed, which is characterized by some isothermal, single deformation responses to mechanical and thermal loads. This leads to a notion of stress at a point which may be arbitrarily high, and to a notion of a generalized plane stress state which results in an underestimation of maximal local stresses up to 30%. It is already known that the stress state in plates and

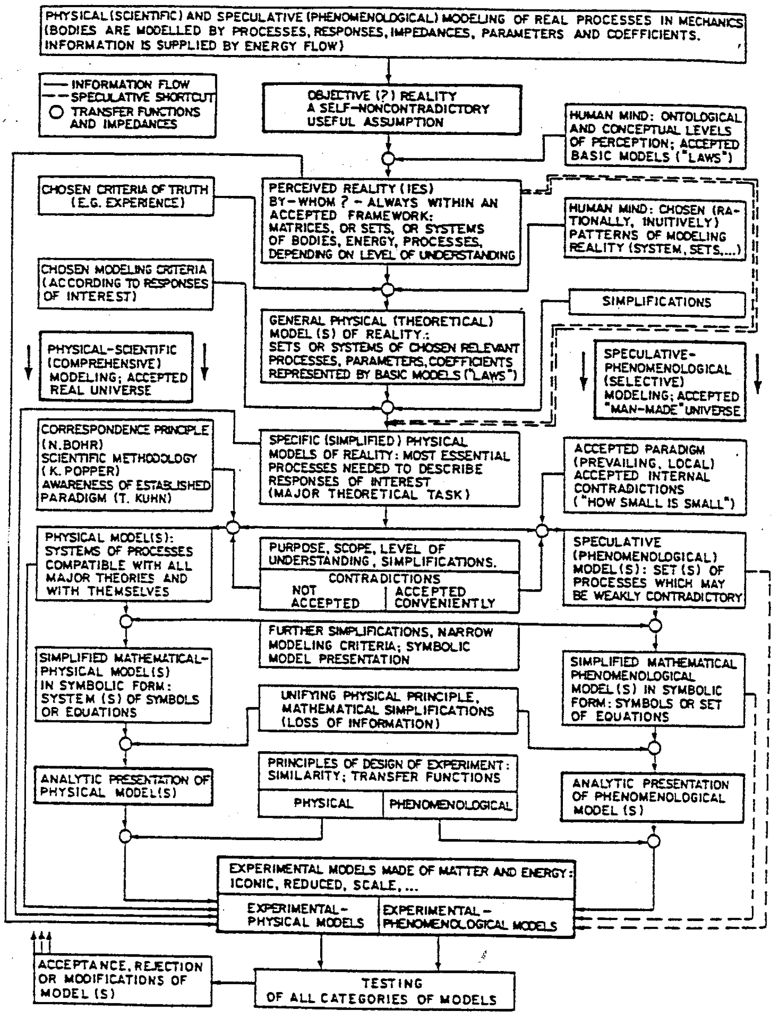

Fig. 1. The origin of a dichotomy in mechanics. A schematic presentation of two incompatible methodologies and resulting approaches, phenomenological and physical, used to model real bodies and events in engineering. Both methodologies result in mathematical relations. [25, 28, 29].

beams is not plane, but depends on the in-plane stress gradients [31, 32, 33] So-called singular solutions of mathematical elasticity theory, which accept violation of some geometric assumptions, may allow predictions which do not comply with the force equilibrium principle. Within such a framework the external work is equal to the produced strain energy, because the partly reversible coupled effects, as the thermoelastic effect (heat production resulting in temperature alteration), or energy of the produced electric and magnetic fields, are neglected. The relatively huge heat production during local plastic deformation, which results in a related temperature increase up to several hundred degrees of Celsius, and in resulting huge local thermal strains and thermal stresses, is completely neglected in the theories of the inelastic deformation. Shortcomings of such models are apparent when the responses of real bodies are considered from an engineering point of view. For example such models do not allow to rationally optimize strength or service life of structures and machines.

Recognition of the facts that the continuum mechanics reaches its level of flexibility at the macro level, that the classical continuum theories fail to predict certain phenomena exhibited by real materials, and consideration of the requirements of modern technology, leads to development of various new approaches. The aim is to develop analytical relation which reliably simulates actual responses of real materials and engineering products. One of the approaches is to include the effect of the microstructure within the continuum framework. As result a new field of continuum micro mechanics is developing. The non-local mechanics and its concepts regain strong interest. Computational materials science already contributes to a better understanding of the mechanism of fracture at the atomic level. Recognition is growing that, actually, all kinds of deformation processes are inherently coupled with thermodynamic processes. Thus, an elastic deformation state in a body always produces a corresponding temperature alteration [23, 33], and inelastic (plastic) deformation always generates heat. Evidence is accepted that the time-dependent deformations are often caused, at least, by two different mechanisms [19, 20, 22, 33, 45]. It is also accepted that the fracture processes are dynamic processes resulting in secondary interference fractures, and that the temperature at the crack tip may reach several degrees Celsius [49]. In effect, it can be said that a strong trend is developing in applied mechanics, including materials science, to comply with the principles of scientific methodology as formulated by Brillouin [2], Popper [41], Bohr [14], Feynman [7], et al., and discussed by Pindera [25, 28, 29, 33] using practical engineering examples. In particular, significant effort is made to include thermodynamic phenomena in analysis of viscoelastic and plastic deformations, and to develop analytical solutions which could simulate actual three-dimensional stress states in plates, beams, or shells. Local effects attract increasing attention [17, 32].

Those new physical trends in applied mechanics exposed strongly dichotomies in applied mechanics between phenomenological and physical approach to modeling or real responses of materials and structures, illustrated by Fig. 1, and rooted in psychological and other factors, discussed by Kuhn [16]. This dichotomy leads to an unnecessary confusion between capacities of both approaches and their applicability in engineering designing, because both approaches are used simultaneously at the present time. Thus, it seems useful to illustrate that dichotomy by examples, to contribute to reduction of this costly confusion. Selected illustrative examples are given in the next chapter. The limited volume of this paper allows presentation of only few examples.

3. TYPICAL DICHOTOMIES AND THEIR RESULTS

3.1. Theories behind evaluation of results of a tensile test for steel

It is usually assumed that the tensile test procedure for determination of mechanical responses of low carbon steel is one of the straightforward tests, so the force-deformation diagram plotted by the testing machine is a single-valued stress-strain diagram for steel.

Using terminology of the theory of measurement, such an assumption is tantamount to the statement that the testing and recording systems are zero-order instruments. Such an assumption is wrong. Components of the real testing machine are characterized by inertial masses and by stiffness, so their responses must be presented in a form of a transfer function, Fig. 2 [25], and the corresponding, simplified analytical presentation of the machine responses should have a form of a second order ordinary differential equation. The mechanical response of the system consisting of the testing machine and specimen could be quite complicated, so the mathematical model of such a system presented in an analytical form should be, at least, represented by a system of second order differential equations. It is known that the mechanical responses of a system machine-specimen contain dynamic terms, when the system is loaded by a unit step loador by a ramp load. This occurs when the tested specimen exhibits instability caused by necking. The actual responses of the measurement and recording systems can be only roughly approximated by the first order ordinary equations. Thus, a response of the testing machine with a specimen is a response of a dynamic system, including the experimenter, Fig. 3 [25]. As the thermal expansion coefficient of steel is positive, a tensile stress in a tensile test specimen always produces a lowering of the temperature of material, Fig. 4 [23, 25, 28]. To assure that the positive or negative heat produced in a test specimen has enough time to dissipate in the surroundings, mostly by radiation, majority of testing standards in Europe and in the USA require that the strain rate is limited, when the purpose of testing is to determine the Young elastic modulus. When the stress rate is higher than the corresponding value of a maximal stress rate of 10 N mm^{-2} s^{-1}, or 100,000 psi per min, the evaluated quantity is larger that the Young modulus.

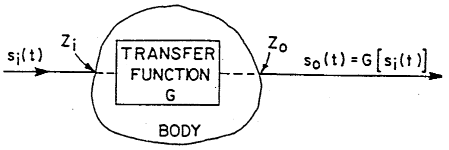

Fig. 2. The notion of transfer function which presents patterns of energy flow through a real body [25].

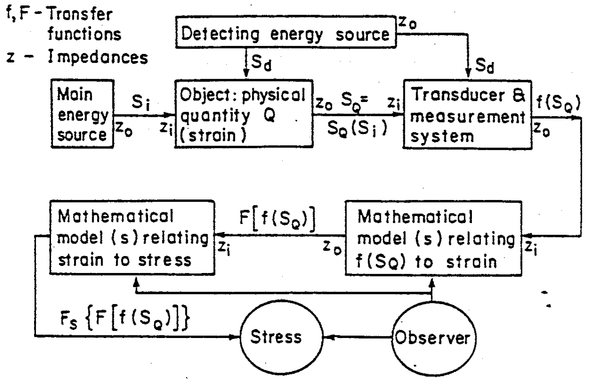

Fig. 3. Illustration of the notion of a system. All components of a system interact. Measures of interaction are impedances and transfer functions, which influence flow of energy and information. An experimenter is an integral part of a system [25].

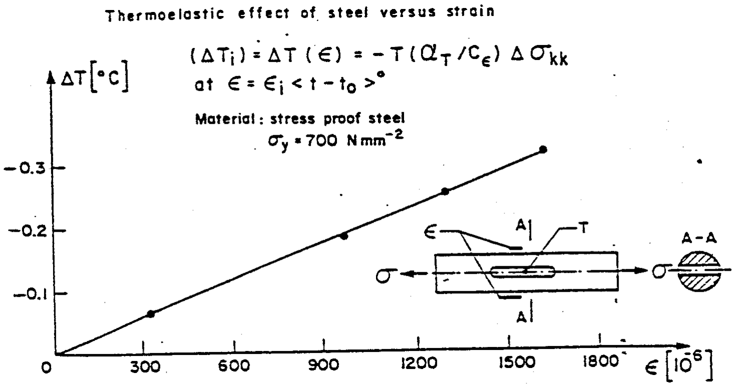

Fig. 4. An example of thermoelastic response of a steel bar in tension, in adiabatic conditions. The measured signals are modulated by impedances and transfer functions of sensor, system components, and by environmental parameters [25].

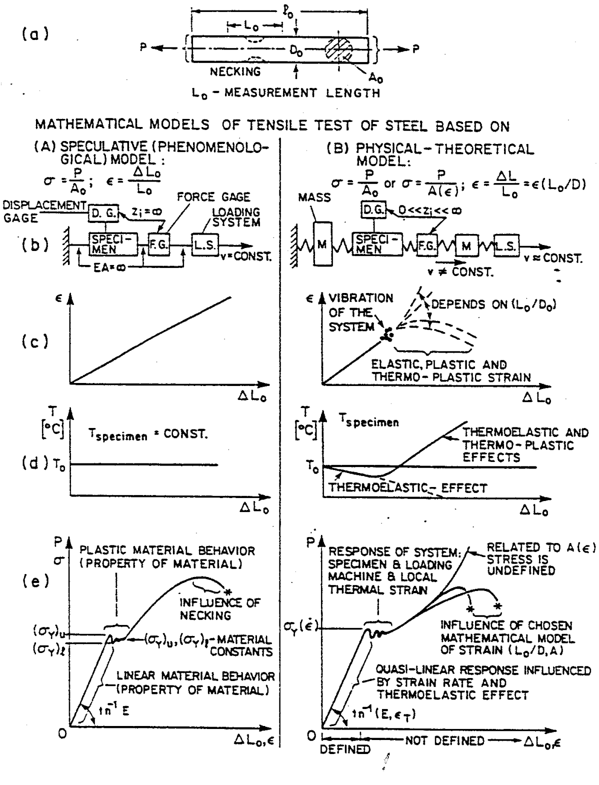

Fig. 5. An example of two incompatible evaluations of results of a simple tensile test of a low carbon steel. The incompatibility is caused by accepting two incompatible systems of models of experiment [25, 28].

Fig. 5 [25, 28] illustrates the issue. The same tensile test graph is differently understood, depending on the accepted physical and mathematical models of the theory of testing, sketch (Ab) and (Bb). The left column (A) presents a phenomenological conceptual model of the test, including elementary basic definitions, typical models accepted in traditional engineering mechanics, and components of assumed physical model. The testing system presented in the column (A) is rigid (Ab), so no vibrations occur (Ac); all measurement instruments are zero-order instruments so there is no influence of the transfer functions; the deformation of material is obviously isothermal (Ad), so no thermal strain exists; and the observed strain is elastic or plastic strain caused by loads only; the magnitude of the cross-section of the specimen changes negligibly, so the tensile diagram represents the stress-strain diagram (Ad). Such models lead to the statements that the slope of the stress-strain diagram represents truly the Young modulus; that two yield stresses exist, upper and lower; and that force equilibrium is possible at two strain values (Ad).

The right, physical column (B) presents the same components as the phenomenological column (A), but on an advanced, physical level. It presents advanced basic definitions, advanced conceptual models introduced by advanced experimental mechanics, and actual components of a comprehensive physical model. The testing system is elastic (Bb); this allows vibrations of the system caused by load instability induced by sudden necking of the specimen (Bc); the responses of measurement and recording instruments are approximated by higher order ordinary differential equations; the temperature of the specimen evidently decreases with increasing strain within the linear range of deformation; with the onset of necking the temperature of the plastically deformed part of a specimen suddenly increases up to several hundred degrees of Celsius, which produces large thermal strain contributing to load instability (Bd). Such a physical approach to modeling allows to get insight into the mechanism of a deformation-tensile load diagram. Within such a theoretical framework the apparent values of the Young modulus depend on the thermal parameters of specimen material and surroundings; the upper and lower yield stresses do not exist because they are artifacts of the assumed phenomenological model; the strain above the yield point is not defined because it depends on values of the unknown thermoelastic and thermoplastic strains, which - in the case of steel - have opposite signs. In addition, the portion of the stress-strain diagram above the yield point has no physical meaning because it depends on the value of the measurement length of the deformation gage l_0 expressed in terms of the specimen diameter D_0.

It is very interesting to note that all discussed parameters of the real physical conceptual models have been known for a long time. Nevertheless, it is still common to understand the results of a tensile test within the framework of a primitive, phenomenological physical model, which leads to a misunderstanding of the material response. The influence of Kuhn s paradigm [16], which is prevailing in engineering textbooks, is very strong.

3.2. Characterization of responses of time-dependent materials

Many important engineering materials exhibit dependence on the loading time. A convenient, general analytical framework for time-dependent responses of a number of materials is given by known relations of the phenomenological viscoelasticity [9, 43]. It is convenient to use the notion of a creep at constant stress, and the related creep recovery, and the notion of relaxation at constant deformation, and the related relaxation recovery. It was proven in the analytical mechanics that the common relations of stress analysis could be applied for the time-dependent materials if their responses to stress are within linear viscoelastic range, when the deformations are small. Thus, the analytical stress analysis requires that the stress-strain relations for the time-dependent materials are linear when presented as isochronous relations. In addition, the iso-chronous presentation gives the apparent values of elastic modulus as a function of time, and allows to determine the range of the linear elastic material response. Such information is needed to better understand the mechanical deformation responses, and the coupled optical birefringence responses.

Typical time-dependent, coupled mechanical and optical, responses to limited unit step loads of several polymers used in structures and machines are given in Fig. 6 [20, 22, 33]. The character of the mechanical creep and creep recovery responses does not depend on the stress level. The character of the optical creep and creep recovery responses depends on the stress level (below or above linear limit stress), and depends on the spectral band of detecting radiation. Set of diagrams such as that presented in the top sketch allows to evaluate isochronous mechanical and optical responses presented in the bottom part. A less expensive and faster procedure is presented by Pindera in 1959 [20], and by Pindera and Pindera in 1989 [33]. Results presented in an isochronous coordinate system, do not allow development of a typical confusion which is related to the testing at a constant strain rate. A typical example of such confusion is introduction of the notion of different values of Young modulus depending on the manner of loading, by tension, by bending, or by torsion. Evidently, such a dependence is not acceptable in applied mechanics. Fig. 6 conveys information that the simple mechanism of coupling between the mechanical strain and the optical birefringence accepted in the text books on photoelasticity is incorrect and misleading. Evidently, the actual mecha-

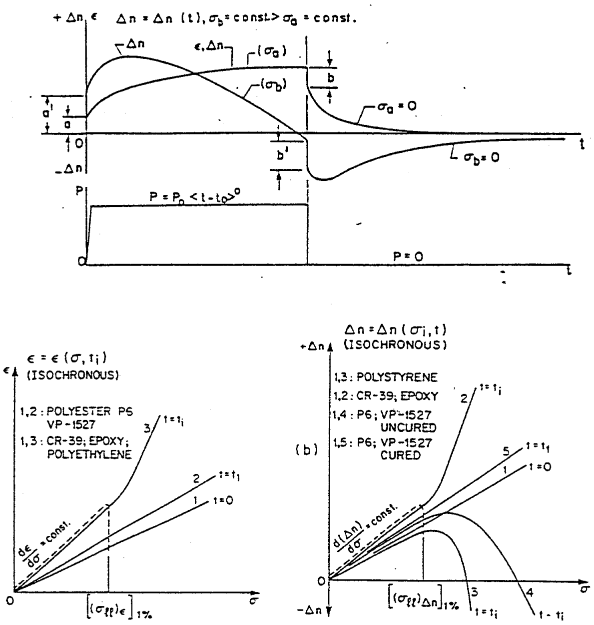

Fig 6. An example of an isochronous presentation of mechanical and optical responses of some polymeric materials. Top: coupled active creep and creep-recovery diagrams for strain, and for birefringence at constant temperature. Bottom: Typical isochronous stress-strain and stress-birefringence relations in an isochronous coordinate system [20, 22, 33].

nism of coupling is much more complicated, and is related to the mechanism of viscoelastic deformation. Isochronous presentation shows directly whether and in which range industrial polymer could be considered linearly viscoelastic, and what is the value of the linear limit stress [22]. One of the major parameters of coupled responses is the dependence on the spectral band of the detecting radiation [8, 21]. This dependence is often neglected.

3.3 Theories behind determination of stresses in local effects

Local effects are of a great importance in engineering, but their analytical treatment is not satisfactory [17, 32]. It is common to invoke the notion of generalized plane stress state to justify the drastic simplification of equations representing three-dimensional stress state in local effects (notches, cracks, local loads), and to believe that an assumed plane stress state represents satisfa-ctorily the actual stresses. Consequently, such important in engineering notions as the stress concentration factor, or the stress intensity factor, are based on the assumption of the existence of a plane stress state in regions characterized by very high stress and strain gradients [44, 47].

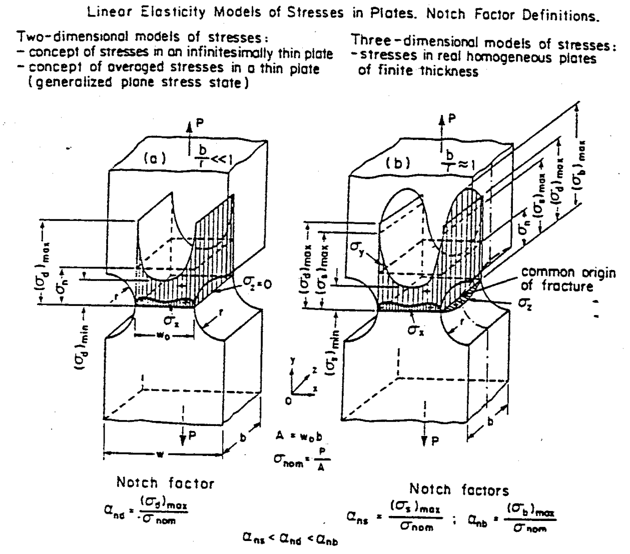

Fig. 7. An example of two incompatible models of stress states in plates with notches, which are concurrently used in analytical, numerical, and experimental procedures of stress analysis. Both models lead to different notions of stress concentration factors, stress intensity factors, and yield different values of maximal boundary stresses [25].

Such a belief is at a variance with the experimental evidence accumulated during the last half of century. As a result, at the present two incompatible physical and mathematical models of stresses in regions of notches in plates exist in engineering mechanics, Fig. 7 [25]. Practical differences are significant. It was shown that the actual maximal stress component in a notch occurs at the middle plane of the plate, and the difference in stress values between the maximal surface stress and maximal middle plane stress is 30%, or more; the neglected thickness stress is between 10 and 20% of the surface stress [37]. Such errors, on the unsafe sides, are not acceptable in modern designing. An illustrating example, pertaining to stresses at the crack tip is given in Fig. 8 [26]. The fact that the stresses in a notch region are three-dimensional is known for more than 50 years [46].

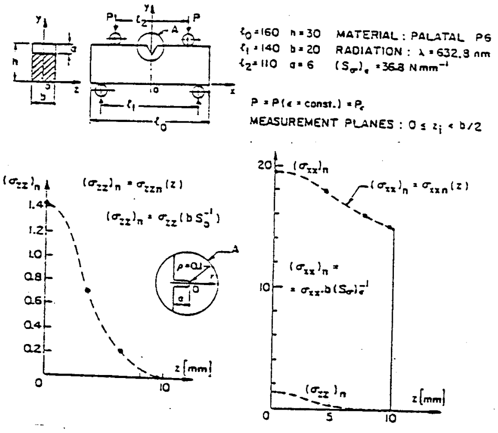

Fig. 8. Actual distribution and values of two normal stress components at the bottom of a crack in a prismatic beam in pure bending. Data obtained using optical isodyne technique [26].

3.4 On the validity of singular solutions of applied mechanics

Singular solutions are used to analytically determine stresses due to concentrated loads, or occurring at sharp edges such as a crack tip. They are usually simple and elegant, but often not reliable within smaller or larger regions. For example, it is said that the common concept of the concentrated load is a mathematical abstraction resulting from specific assumptions, and that developed singular solutions depend on the chosen limiting processes [44]. Attempts to bypass the problem of infinite stress and strain values by applying the renormalization mathematical techniques only shift the problem. Fig. 9 illustrates the issue. It presents distributions of the principal stresses normal to the loaded diameter of a circular disk. Stresses were obtained analytically, by means of strain gages, and by using optical isodynes. Strain gages yield data on the surface stresses, and optical isodynes yield differential principal stresses in the disk middle plane [25, 33]. Comparison of results shows that the analytical evaluation of stresses, which is extensively applied in engineering, is wrong. It violates equilibrium conditions, and yield erroneous results, in a magnitude and in sign, within about 20% of the disk area. However, some general solutions yield predictions which are com-

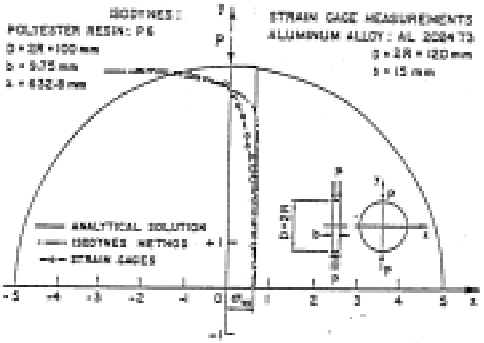

Fig. 9. An example of ranges of reliability of a singular solution of analytical mechanics. Circular disk loaded diametrically. Evaluation of principal stresses normal to the loaded diameter using analytical singular solution, strain gages, and optical isodynes. Analytical solution is incorrect in large regions [33].

patible with the experimental data, with the exception of the thickness stresses [3, 12].

3.5 Deep dichotomy in engineering photomechanics

Experimental methods which use the coupling between the velocity of light propagation and the alteration of various physical parameters of solid and fluid bodies are often denoted by the term photo-mechanics. However, the theoretical foundations of the methods of photo-mechanics accepted in engineering differ drastically from the theoretical foundations accepted in advanced engineering, and in sciences. Fig. 10 presents some examples of two categories of physical models of the same physical phenomena [28, 33]. Left column presents the drastically simplified phenomenological-physical models commonly used in engineering photomechanics. Right column presents elementary scientific-physical models used in natural sciences and in advanced experimental mechanics. The analytical relations for stress birefringence, and the resulting experimental and evaluation procedures are different for different categories of the underlying models. This results in unnecessary errors.

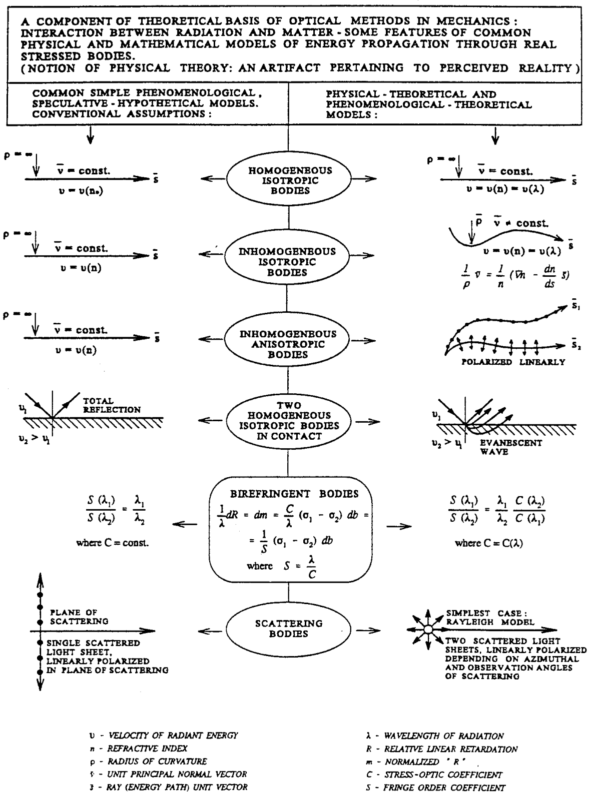

Fig. 10. An example of a typical dichotomy in contemporary engineering photomechanics. Two incompatible sets of basic physical and mathematical models of patterns of interaction between flow of radiant energy and matter lead to incompatible engineering formulas, and result in unnecessary errors [28, 33].

3.6 New experimental methods based on scientific physical models

Two new groups of methods are mentioned below: the three-dimensional stress analysis isodyne methods [24, 27, 31, 33, 35, 38, 39], and the strain-gradient stress analysis methods [1, 10, 11, 30]. Fig. 11 illustrates the differences between the common transmission photo-elasticity and the optical isodynes [24]. The trans-mission photoelasticity reco-rdings carry information on the differences of principal stresses, averaged through the thickness of the specimen. The isodyne recordings carry info-rmation on the normal force intensities in selected planes within a specimen, which are related to the direction of measurement; corresponding differentiations yield normal and shear stress components. Economic factors require intro-duction of electronic techni-ques to isodyne stress analysis as illustrated by Fig. 12 [40]. Fig. 13 presents the theoretical basis of the strain gradient light bending [30]. Fig. 14 illustrates the capacity of the strain-gradient method to testing the reliability of singular solutions and of experimental method of caustics, by using, as an example, the dependence of the light deflection on the immersion conditions [36]. One of the next steps is introduction of the optical tomography [6]. It was demonstrated that the techniques based on scattered radiation are very promising, provided that a rational theoretical background is chosen [15, 33].

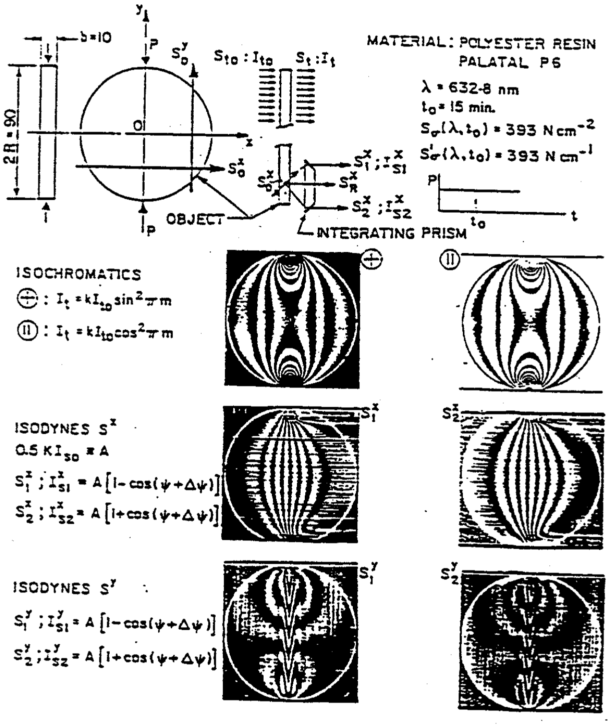

Fig. 11. An example of one of the new methods developed on the basis of the theoretically correct models of interaction between radiation and stressed matter. Definitions, and examples of the averaged transmission photoelasticity recordings, and of the recordings of two families of optical isodynes [24].

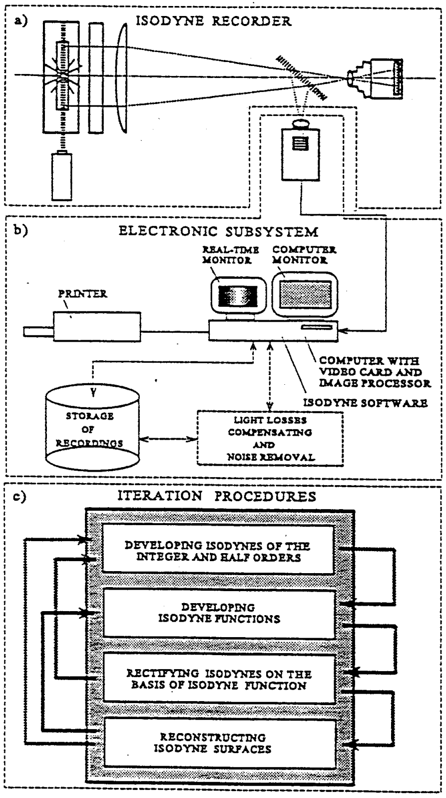

Fig. 12. A schematic presentation of electronic techniques in three-dimensional isodyne stress analysis [40].

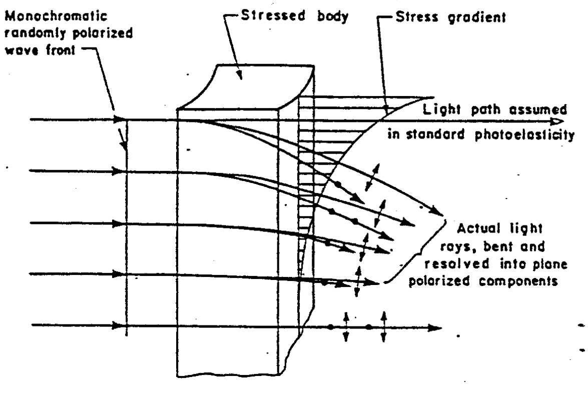

Fig. 13. Light propagation in a stressed plate. Differences between the phenomenologically assumed and the theoretically correct physical models of light propagation [30].

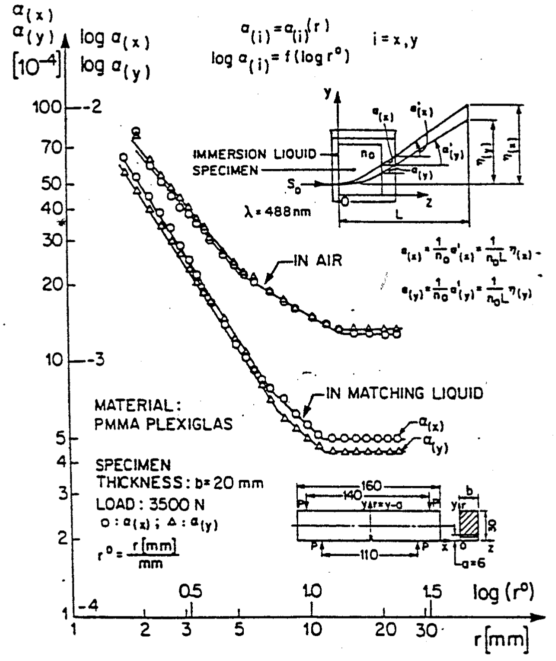

Fig. 14. An example of an error which is caused by phenomenological assumption that light propagates rectilinearly in a strained body. Application of the strain gradient stress analysis to the testing the theory of caustics in fracture mechanics, and to the testing the singular solution for the Standard Bend Specimen in pure bending [36].

4. SUMMARY

The tremendous progresses in many fields such as physics, mathematics, or information theory allow to base relations of the analytical mechanics of interest to engineering on sound theoretical foundations. However, the format and level of the accepted text books and major part of published papers, show that the new physical trends in mechanics are still opposed by a large number of engineering researchers and educators. Thus, the major problem of contemporary engineering mechanics is how to accomplish the necessary paradigm shift from the convenient and easy phenomenological approach to the demanding physical approach.

REFERENCES

1. Acloque, P. (1962) *Methods for local determination of both principal stresses in a plate by using oblique incidence and the index of total reflection*, in G. Haberland (ed.), Proceedings of the International Symposium on Photoelasticity, Berlin, Akademie Verlag, pp. 10-15.
2. Brillouin, L., (1964) *Scientific Uncertainty and Information*, Academic Press, New York.

3. Davidson, T. S., Wadley, N. G. and Pindera, M. J. (1994) Elastic Response of a Layered Cylinder Subjected to Diametral Loading, Composites Engineering 4, 995-1009.
4. Dean, R. C., (1977) Truth in Publication, Trans. of the ASME, Journal of Fluid Engineering 99, 270.
5. Doeblin, E. O., (1983) Measurement Systems. Application and Design, McGraw-Hill Book Co., New York, N. Y.
6. Faris, G. W. and Byer, R. L., (1987) Quantitative Three-dimensional Optical Tomographic Imaging of Supersonic Flow, Science 238, pp 1700-1702.
7. Feynman, R., (1993) The Character of Physical Law, The MIT Press, Cambridge, Massachusetts.
8. Fitting, D. W. and Adler, L. (1981) Ultrasonic Spectral Analysis for Nondestructive Evaluation, Plenum Press, New York.
9. Haddad, Y. M. (1995) Viscoelasticity of Engineering Materials, Chapman & Hall, London.
10. Hecker, F. W., Pindera, J. T. and Wen, B. (1995) Actual Light Deflections in Regions of Crack Tips and Their Influence on Measurements in Photomechanics, Optics and Lasers in Engineering 22, 325-345.
11. Hecker, F. W. and Pindera, J. T. (1996) General relations of strain-gradient stress analysis, Theoretical and Applied Fracture Mechanics 25, 233-261.
12. Hondros, G. (1959) *The Evaluation of Poisson s Ratio and the Modulus of Materials of a Low Tensile Resistance by the Brazilian (Indirect tensile) Test with Particular Reference to Concrete*, Australian J. Applied Sci. 10, 243-268.
13. Kac, M. (1969) *Some Mathematical Models in Science*, Science 166, 695-699.
14. Krajewski, W. (1977) *Correspondence Principle and Growth of Science*, D. Reidel Publishing Company, Dordrecht.
15. Krishnamurthy, A. R. and Pindera, J. T. (1982) *Study of Basis Patterns of Light Scattering in Aqueous Solution of Milling Yellow*, Experimental Mechanics 22, 1-7.
16. Kuhn, T. S. (1985) *The Structure of Scientific Revolution*, University of Chicago Press, Chicago.
17. Ladevèse, P. (ed.), (1985) *Local Effects in the Analysis of Structures*, Elsevier, New York.
18. Leipholz, H. H. E. (1983) *On the Role of Analysis in Mechanics*, Trans. of the CSME 7, 3-7
19. Mohamed, F. A. and Soliman, M. S. (1982) *On the Creep Behavior of Uranium Dioxide*, Materials Science and Engineering 53,185-190.
20. Pindera, J. T. (1966) *Remarks on Properties of Photoviscoelastic Model Materials*, Experimental Mechanics 7, 375-380.
21. Pindera, J. T. and Cloud, G. L. (1966) *On Dispersion of Birefringence of Photoelastic Materials*, Experimental Mechanics 7, 470-480.
22. Pindera, J. T. and Straka, P. (1974) *On physical measures of rheological responses of some materials in wide ranges of temperature and spectral frequencies*, Rheological Acta 13, 338-351.
23. Pindera, J. T. Straka, P. and Tchinke, M. F. (1978) *Actual Thermoelastic Response of Some Engineering Materials and its Applicability in Investigations of Dynamic Responses of Structures*, VDI-Berichte 313, 579-584.
24. Pindera, J. T. and Mazurkiewicz, S. B. (1981) *Studies of Contact Problems Using Photoelastic Isodynes*, Experimental Mechanics 21, 448-455.
25. Pindera, J. T. (1981) *Foundations of Experimental Mechanics: Principles of Modelling, Observation and Experimentation*, in J. T. Pindera (ed.), New Physical Trends in Experimental Mechanics, Intern. Centre for Mech. Sciences, Udine, and Springer-Verlag, Wien, pp. 88-236.
26. Pindera, J. T. and Krasnowski, B. R. (1982) *Determination of Stress Intensity Factors in Thin and Thick Plate Using Isodyne Photoelasticity*, in L. A. Simpson (ed.), Fracture Problems and Solutions in the Energy Industry, Pergamon Press, pp. 147-156.
27. Pindera, J. T., Krasnowski, B. R. and Pindera, M.-J. (1985) *Theory of Elastic and Photoelastic Isodynes. Samples of Applications in Composite Structures*, Exp. Mechanics 25, 272-281.
28. Pindera, J. T. (1987) *Advanced Experimental Mechanics in Modern Engineering Science and Technology*, Transactions of the CSME 11, 125-138.
29. Pindera, J. T. (1987) *Advanced Experimental Mechanics and its Components: Theoretical, Physical, Analytical and Social Aspects*, in A. P. S. Selvadurai (ed.), Developments in Engineering Mechanics, Elsevier, New York, pp 367- 414.
30. Pindera, J. T. and Hecker, F. W. (1987) *Basic Theory and Experimental Techniques of Strain-Gradient Method*, Experimental Mechanics 27, 314-327.
31. Pindera, M.-J., Pindera, J. T. and Ji, X. (1989) *Three-dimensional Effects in Beams - Isodyne Assessment of a Plane Solution*, Experimental Mechanics, 29 (1), pp 23-31.
32. Pindera, J. T. (1989) *Local Effects and Defect Criticality in Homogeneous and Laminated Structures*, Trans. ASME, J. Pressure Vessel Technology, 111, pp. 136-150.
33. Pindera, J. T. and Pindera, M.-J. (1989) *Isodyne Stress Analysis*, Kluwer Academic Publishers,

Dordrecht.

34. Pindera, J. T. (1990) *Comments on modeling plastic deformation of low carbon steel*, in A. S. Krausz et al. (edits.) Constitutive Laws of Plastic Deformation and Fracture, Kluwer Academic Publishers, Dordrecht, pp.279-284.
35. Pindera, J. T. and Wen, B. (1991) *Isodyne Evaluation of Three-dimensional Stresses in Fracture Mechanics*, in Proceedings of the 1991 SEM Spring Conference on Experimental Mechanics, The Society for Experimental Mechanics, Inc., Bethel, CT, USA, pp. 895-902.
36. Pindera, J. T., Hecker, F. W. and Wen, B. (1991) *Testing theoretical bases of caustic methods in fracture mechanics and stress analysis*, Theoretical and Applied Fracture Mechanics 15, 11-33.
37. Pindera, J. T. And Liu, X. (1992) *On the Actual Three-dimensional Stresses in Notches and Cracks*, Composites Engineering 1, 281-301.
38. Pindera, J. T. and Wang, G. (1992) *Isodyne Stress Analysis of Adhesively Bonded Symmetric Joints*, Experimental Mechanics 32, 348-356.
39. Pindera, J. T. (1995) *Scattered-light Optical Isodynes-Basis for Three-dimensional Isodyne Stress Analysis*, Optics and Lasers in Engineering 22, 373-425.
40. Pindera, J. T., Josepson, J. and Jovanovi} , D. B. (1997) *Electronic Techniques in Isodyne Stress Analysis. Part 1: Basic Relations. Part 2: Illustrating Studies and Discussion*, Experimental Mechanics 37, 33-38, 110-114.
41. Popper, K. R. (1968) *The Logic of Scientific Discovery*, Harper and Row, New York.
42. Ramachandran, G. N. and Ramaseshan, S. (1961) *Crystal Optics*, in S. Flegge (ed.), Encyclopedia of Physics XXXV/1, Springer-Verlag, Berlin, pp. 1-217.
43. Reiner, M. (1958) *Rheology*, in S. Flegge (ed.), Encyclopedia of Physics VI, Springer- Verlag, Berlin, pp. 434-520.
44. Sokolnikoff, I. S. (1956) *Mathematical Theory of Elasticity*, McGraw-Hill, New York.
45. Stuart, H. A. (ed.), (1952-1956) *Die Physik der Hochpolymeren I-IV*, Springer-Verlag, Berlin.
46. Thum, A. et all. (1960) Verformung, Spannung und Kerbwirkung (Deformation, Stress and Notch Action), VDI- Verlag, Diesseldorf.
47. Timoshenko, S. P. and Goodier, J. N. (1970) *Theory of Elasticity*, McGraw-Hill Book Co., N.Y.
48. Valanis, K. C. (Ed) (1976) *Constitutive Equations in Viscoplasticity: Phenomenological and Physical Aspects*, The American Society of Mechanical Engineers, United Engineering Center, New York, N. Y.
49. Zehnder, A. T. (1991) *On the temperature distribution at the vicinity of dynamically propagating cracks in 4340 Steel*, J. Mech. Phys. Solids 39, 385-415.

KOMENTARI NA PODELU U INŽENJERSKOJ MEHANICI

Jerzy Pindera

Rastući zahtevi modernih zajednica s obzirom na tehnologiju i eksplozija znanja u svim poljima u toku poslednjih nekoliko dekada, prisiljavaju na rigorozniji pristup razvoju inženjerskih teorija, eksperimentima, postupcima konstruisanja i tehnološkim postupcima. Od posebnog su značaja novi društveni i ekonomski kriterijumi za optimizaciju mašina i struktura, koji uključuju pojam ukupnog troška za društvo, koji pretstavlja ne samo tradicionalne troškove proizvodnje i održavanja proizvoda, već takođe pitanja zdravlja, korišćenja prirodnog bogatstva, interakciju sa prirodnom sredinom i odlaganje iskorišćenih materijala i proizvoda. Zahtevi u ovim okvirima su izloženi snažnoj podeli koja postoji u inženjerskoj mehanici između tradicionalnog fenomenološkog pristupa u razvoju formula korišćenih u opštoj inženjerskoj praksi i fizičkog pristupa uobičajenog u prirodnim naukama i prihvaćenog u zahtevnijim vazduhoplovno-svemirskoj i vojnoj industriji. Ta dikotomija, već izražena u većini knjiga inženjerske mehanike, nije neophodna i ima za posledicu skupe strukturne neuspehe. Ovaj rad ocrtava obrasce novog fizičkog trenda u primenjenoj mehanici i prikazuje tipične primere nepotrebnih pojednostavljenja u matematičkom modeliranju ponašanja materijala, strukturnog ponašanja i eksperimentalnih postupaka.