EFFECTS OF COMPUTATIONAL TECHNOLOGY ON COMPOSITE MATERIALS RESEARCH: THE CASE OF DISSIPATED ENERGY DENSITY

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1. SUMMARY

In most fields of applied science and technology, advances in computational technology have changed the ways of research as well as the roles of researchers. NRL's Mechanics of Materials Branch has adopted a paradigm of “industrialized research” to develop a composite materials characterization technology using a concept of Dissipated Energy Density (DED). Research is industrialized via application of powerful computational technologies and robotic, multiple degree of freedom mechanical testing machinery. Both the computational and physical testing tools are organized in such a way as to allow the scientist-craftsman control at the least tedious (most abstract) level. This approach has accelerated the rate of performing experiments to hundreds of tests per hour while expanding the amount of information collected during each individual test. This in turn has lead to inexpensive (in time and money) determination of bulk composite material nonlinear constitutive behavior, allowing researchers to abstract from many physical tests a concise data driven analytical representation of the material response. In the other direction, application of this local material constitutive relationship to complex structures en-

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ables the user to predict responses under any load combination of interest, making possible inexpensive and fast characterization of any proposed complex structure. This paper discusses these developments and outlines lessons learned in applying the technology to real world problems.

How this computational technology can be used in design and to provide service life predictions for complex composite structures is illustrated by the automated Embedded Sensors for Smart Structures Simulation (ES^3) facility. How this technology is used to create conceptual models for describing and predicting composite material performance is illustrated further for the case of burst pressure prediction of composite pressure vessels.

Finally, the case of interactive simulation of material and structural behavior for realistically sized problems is discussed. Using the rapidly evolving tools of the World Wide Web (VRML 2.0, Java, etc.), it is expected that remotely located analysts will have from their desktop PC's full and simultaneous access to High Performance Computing (HPC) resources of large supercomputer networks. Examples will be presented for simulations of coupled fluid-structure mechanical problems solved in a parallel distributed fashion across heterogeneous supercomputing resource boundaries located throughout the United States.

2. INTRODUCTION

2.1 The Computational Technology Opportunity

2.1.1 *Hardware*

It appears that by some standards the raw computational capability of technology far exceeds that of the human brain. The functional similarity between a human neuron and a transistor forms the basis of the present discussion. Both are switching devices that can alter between two states (the bit states) at certain rates. Disregard of the particular function implemented on a network of such devices (like the human brain or a microprocessor), allows the use of bit-state-changes-per-second as a fundamental raw power metric for implementing the rational and computational process.

Based on the current estimates of neuron density in the brain (10~100 billion neurons) and of typical neural firing rates (~10 Hz), it has been estimated that the human brain is a device of about 10^{11} - 10^{12} bit state changes per second at the axons (neuronal outputs). On the other hand, based on microprocessor chip evolution [1,2] in both transistor density and speed, the evolution of microprocessors from 1971 to 1995 can be plotted as shown in Fig.1. This evolution has consistently followed M*oore's Law* since Intel introduced the first microprocessor (4004) on 1971 [1]. A closer look on the numbers indicates that computational technology has surpassed human brain performance in terms of bit state changes per second since 1974, the era of the Intel 8080 microprocessor, and is currently approximately 1-2 million times higher. The rate of improvement is a doubling of performance every 20 to 30 months. The history of technological evolution suggests that this will not continue forever. In fact, even with the use of X-ray and electron beam lithography technology for masking, integrated circuitry on reasonable size and depth microprocessor dies has limits just a few orders of magnitude beyond current practice. These limits, which will be reached asymptotically, can be computed to be of the order of 10^{18} bit state changes per second for a single chip. This plateau value corresponds to an increase in performance 10^8 times higher than that of the human brain. The opportunity presented, is enormous, and clearly extends beyond number crunching to provide services never before possible.

Research at NRL has been designed with the growth of computing power, both for pure computation and for automation of the tedious physical tasks of ac-

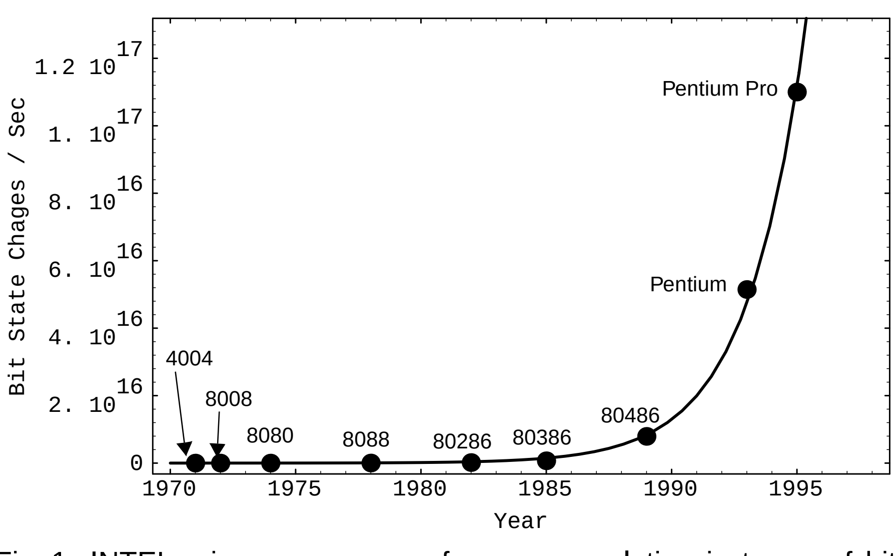

Fig. 1. INTEL microprocessor performance evolution in terms of bit-state-changes per second.

quiring experimental data, constantly in mind. Samples of the payoff from this approach will be presented here.

2.1.2 *Software*

As computational technology evolved, more and more tasks that had always required the human brain, were implemented in computer hardware. Sequences of instructions, or programs, which caused the machine hardware to perform the intended actions are called software.

Although it appears that software evolution has always lagged behind and been pulled on by hardware evolution, the history of various quantitative indices for software evolution indicate dramatic progress in software technologies. Considering "time needed to acquire skills to develop a new application using off the shelf software", we have transitioned [3] from the period of the 1950's through the 1970's where the average time to acquire skills was about 10 years, to the period after 1985 where it takes only about a month to acquire the skills to develop an application. As a consequence of this change, the number of people involved with software development has increased from a population of 50 thousand people to that of 50 million. New software technologies like declarative programming, object oriented programming, computer aided software engineering, visual programming, and automated program synthesis have been some of the major contributing technologies for these trends.

This trend appears to correspond to the change in the role of researchers in their effort to generate new tools and to abstract and capture models of the physical world in computer applications.

2.1.3 *Wetware*

Once computers enabled people to solve problems more quickly than had been possible by hand more time was left available for other tasks. People started realizing that their new role was to make use of computed answers. This new role of people as consumers rather than producers may be the next level of utilizing computational technology.

Both the rational process and its implementation on the human neuronal machine have been captured under the term "wetware". The high rates of evolution of hardware and software have not only been affected by wetware, but have had an effect on it as well. Some goals that motivated the growth of computational technology have been the automation of information handling such as the paperless office and the integrated laboratory. Although the degree to which these goals has been a controversial subject, the fact is that their implementation has put a very high demand on the human ability to absorb and use information. In the pre-computer era of the 1800's the amount of information available for consumption worldwide was doubling every 50 years with annual percentage increase of the order of 5 to 10% [4]. Today we are in a track of worldwide information doubling every 3 years with an annual percentage increase of the order of 35% [4]. It appears that we are faced with the irony of success in using computational technology to generate information without a corresponding increase in human ability to assimilate it.

This experience has pushed for the creation of alternative information representation technologies that utilize the visual, aural and tactile avenues in an attempt to enhance the bandwidth of information conveyed to the human brain. The products of these technologies can be found today in the advanced physical reality simulation tools.

Examples of the various effects computational technology can have on human behavior during the process of research will be presented below.

2.2 Composites Research

The development of new materials related technology has been primarily motivated by:

- the need to design structures that can perform under user defined operational envelopes, while at the same time satisfying economic and other constraints, and
- the need to be able to customize manufacturing and tailor materials by controlling material processing/production parameters to achieve predetermined specification of behavior.

Composite materials research has inherited the means of satisfying these needs from successful experience in other fields of physical systems modeling.

The behavior of a material has traditionally been the main ingredient in meeting these needs. Much work has been devoted to developing methods and technologies that capture the material constitutive behavior. Structural integrity requirements add the component of failure behavior analysis. Therefore, emphasis has been placed on developing material constitutive behavior representations useful for satisfying identified needs, including structural integrity.

What has been accomplished up to now by way of capturing the constitutive behavior of composites can be classified in two distinct categories. In the first category, focus has been given to developing a constitutive behavior model/theory from knowledge of the material components. This theory is then verified or calibrated by a limited range of low number of degree of freedom experiments (usually one or two d.o.f.). There is available a host of constitutive theories for composite materials developed in this fashion.

In the second category, focus is given to systematically stimulating test specimens of the material with a wide range of combined load sequences in as many degrees of freedom as possible, while observing the material response in all corresponding degrees of freedom. A suitably general model of the material can then be adjusted so that the behavior of test specimens incorporating this constitutive behavior does not violate the systematically measured behavior of the material. Computational tools for adjusting the model and automated many-d.o.f. test methods are essential to this approach. Only this category is examined here.

3. AUTOMATION OF EXPERIMENTATION

3.1 Physical System Identification

3.1.1 *Scientific Method and Scope of a Theory*

Francis Bacon and Rene Descartes were the founders of the two major schools of thought on the scientific method [5]. Both had as a goal the codification of the rational procedures of science in a way that would free them from arbitrary, unfounded, or superstitious assumptions and ground them in a logically sound manner on the properties of clear and distinct fact.

These schools have been described as:

- The inductivist (empiricist) approach, which states that scientists begin by doing experiments and then derive their theories from the data. This branch was started by the preoccupation of John Locke and Francis Bacon with empirically observed facts.
- The hypothetico-deductive (rationalist) approach, which states that scientists begin with hypothetical theories and then do experiments to test them. This branch was started by Rene Descartes, who believed that all phenomena of physics could be accounted for by a single fully comprehensive mathematical theory, based on Euclidean foundations and conforming to his own deductivist principles. It was Newton, however, who clearly practiced the hypothetico-deductive method for the first time.

The first firm discrete description of what a theory is within the context of the scientific method appeared in the 1920's and 1930's. This was by the *Vienna Circle* of philosophers, who advocated the doctrine of logical positivism or logical empiricism. It combined empiricist epistemology with the techniques of formal logic that had been developed by Frege, Russel, and Whitehead [6]. According to logical positivists, scientific theories are to be understood as sets of axioms in formal deductive systems. Theories are confirmed by deducing their consequences from the axioms, and checking to see whether the predictions (hypotheses) hold. In contrast to earlier empiricist views which carried the Baconian theme, such as those of John Stuart Mill [5], this methodology has been called hypothetico-deductive because it emphasizes the use of hypotheses to make predictions, rather than derivation of laws from observations. The views of Popper evolved around the same time as those of the logical positivists, and were also hypothetico-deductive, but differed primarily in that he saw the main role of prediction to be the attempt to falsify theories, not to confirm them [7]. The general hypothetico-deductive scheme is

- Start with hypothesis H.
- Use logic to deduce predicted observation O.
- If O is observed, then H is confirmed (Hempel [8]), but if not-O is observed H is falsified (Popper).

The dramatic improvement of computational technology in the last 30 years has enabled some researchers to transition from these 18th century approaches which are limited by the performance of the human brain, to that of an industrialized inductivist approach. This approach, which uses the tools of logical positivism within an empirical framework, can be followed because increased computational power allows both automation of experimentation for massive collection of observations and also the assimilation of these observations into a compact and analytically useful form. The general industrialized inductive scheme includes the following activities:

- Identify observables to be measured.
- Collect massive amounts of data spanning the control and observation spaces of the physical system.
- Generate a theory representing all these observations.
- Model and simulate the systemic behavior.

The scope of a theory is now to make sure that it is always consistent with the observed facts. A theory in this approach is not verifiable by any experiment, but can be refuted and destroyed by a negative experiment.

3.1.2 *Behavior Characterization for Prediction*

Physical system modeling can be abstracted as a mathematical system defined by a relationship on a set of parameters or observables[6] that span a parameter space. According to systems identification theory [6,9], when there are observables that are measurable, any relationship among them is identifiable. The main goal of system identification is to end up with an analytical representation for predicting the state of a system in terms of input and output parameters. In some cases special input parameters that are controllable are called control parameters while the outputs are called dependent variables, and the remaining input parameters are called independent variables [6,10]. In cases where there is such preassignment of the role of the participating parameters, the mathematical relations between the input and the output parameters take a functional form. The endeavor of determining this functional form is what traditionally is known as system identification and the resulting mathematical representation is called a model of the natural system [6]. An identified system implies that a model has been established that allows the computation of outputs (or the exact state) of a system under a known set of input and control variables. This is the essence of prediction of future system behavior. Thus, behavior is equated with knowledge of the outputs of a system under the influence of known inputs.

3.1.3 *Axioms of Enrichment*

An examination of the epistemologic history of theory building indicates that when it comes to modeling physical system behavior, there are three particular axioms that most technical professionals knowingly or uknowingly utilize. These axioms, which enrich our ability to construct useful models, are:

- *The Axiom of Continuous Behavior:* As any set of observable parameters associated with attributes of a system varies continuously, every other parameter used to describe behavior attributes of a physical system varies continuously as well. This asserts that a neighborhood can always be defined at every point of the parameter spaces and that this neighborhood is locally flat. This axiom is mainly responsible for permitting interpolation between known or measured values of observed behaviors.
- *The Axiom of Composition Behavior:* For any system that is comprised of a collection of individual components, the behavior of the collection can be inferred by the sum of the behaviors of the individual components through a composition rule. This axiom is responsible for allowing us to form the continuous hypothesis in continuum mechanics and allows us to think of structures as collections of individual chunks of material.

• The Axiom of Zero Order of Reality: During the process of making measurements of parameters associated with a system, it is expected that under identical combination of parameters the measurements will yield identical values. This axiom is responsible for allowing us to pursue the modeling of a system with the certainty that the created model will be useful in the future.

These three axioms have been used as well in the present work.

3.2 Measuring Composite Structural Response

Acquiring massive amounts of facts in the form of experimental data requires amplification of the human ability to perform experiments. In this spirit, hydraulic, electric, and computational power have been combined to amplify not only the human ability for deforming material specimens, but also the ability to gather and process sensor data faster than the actual experiment can take place. The degree of automation employed in material testing through the combination of computational and testing machine technologies has evolved extensively in the last 30 years. Robotic testing machines were developed to achieve industrial rates of acquisition of facts about material behavior.

3.2.1 *Robotic Testing Machines*

The first documented event [11] marking the marriage of (hybrid) computer technology with a servohydraulic testing machine was in 1964 at NRL. It was used to control crack velocity when measuring the dynamic characteristics of plexiglass in real time. This effort initiated the automation of experimentation allowing a few parameters to be measured and controlled at the same time to subject the specimen under test to a load path that was impractical to achieve by human operation alone. This technology involved a single degree of freedom and the time for preparing the specimen and setting it up in the test fixture was long. A human operator was still required and was the slowest part of the experimental process. The great percentage of today's testing machines are descendants of this first computer-machine combination. Human involvement and the high cost (in time and money) of specimen preparation make this kind of technology useful only for non industrialized low efficiency operations.

The first representative of the next generation of automated testing machines was the In Plane Loader System (IPLS) capable of 3 degrees of freedom loading. This machine, built at NRL in 1974, is shown in Fig. 2.This system was capable of applying two translations and one rotation, all in the plane of the specimen and all displacement controlled. Simultaneous measurement of the boundary tractions and displacements allowed the experimental measurement of energy absorbed during the accumulation of strain induced damage in real time. This system evolved to accept a stack of 30 specimens at a time and is being used today for the experimental determination of the Dissipated Energy Density function for organic matrix composite materials for the purpose of material characterization. An evolutionary and more complete description of the IPLS is given in [12-16].

An entire IPLS test takes about 10 seconds. Five of these seconds are spent installing the specimen in the grips. As a result, the specimen testing rate can be 360 specimens/hour. 120 specimens are required to characterize a material. At this rate data can be collected for 12 different materials per hour. The overall daily production rate for an 8 hour day is therefore 960 specimens, or 96 different materials, or 24 materials systems (since 4 layup angle combinations are used for each fiber-resin combination). The total number of experimental points per fiber-resin combination is 6000. Each loading path corresponds to 2.4 Kbytes of data while 288 Kbytes are acquired for each material system. The daily throughput of the acquisition process approaches 20.74 Mbytes/day.

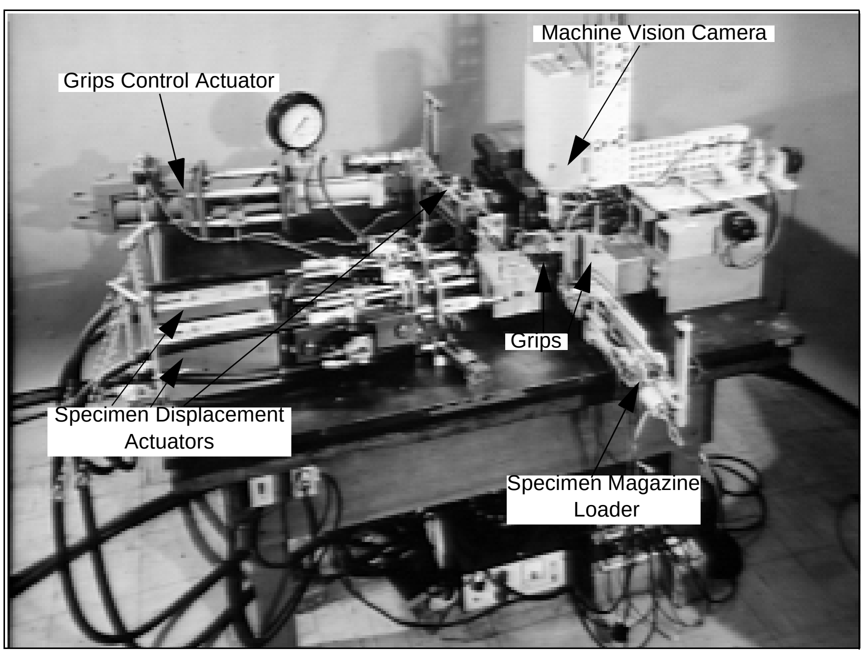

Fig. 2.The In Plane Loader testing machine as it exists today.

In order to address issues of larger specimens, out of plane loading and whole field strain measurement, a new generation of six degree of freedom testing machines was developed at NRL. The first version used six actuators with analog controlled valves, mounted on an I-beam frame. This machine was completed and tested in 1983. A robotic arm was used to insert and remove specimens. Both data acquisition and control processes were increased to six degrees of freedom. The large open frame of this machine allowed actuators to be placed parallel to three orthogonal axes to simplify the conceptual mapping between operator displacements and specimen motions. This simplification appeared advantageous in the planning stage; however, it was not necessary considering that actuator control would be handled by computer, rather than by a human, and created disadvantages.

Starting in 1993, yet another new six degree of freedom loader system (6DLS) was designed and constructed at NRL. The testing machine was built with a hexapod architecture developed originally for flight simulator platforms. The hexapod architecture made the machine more compact, far stiffer (less prone to energy storage by deformation of the machine itself), and easier to disassemble for modification or relocation than the previous machine. In 1996, in fact, the original analog controlled actuators of the prototype machine were replaced with longer stroke, digitally controlled actuators with minimal changes needed in other structural parts of the machine. A view of the 6DLS as it existed in 1996 prior to installation of the digital actuators is shown in Fig. 3. The main features of this system are:

- This is a displacement controlled machine that can simultaneously apply any loading path in the 6D space of three displacements and three rotations, imposed by long stroke digitally controlled actuators.
- Larger and thicker specimens for material identification can be tested.
- The grips and the grip base subassembly are modular and allow multiple configurations for the sake of exposing real instrumented structural components (much larger than typical specimens) to predefined loading paths.
- A six camera machine vision subsystem will use oblique incident photoelasticity to perform real time whole field measurements of specimen surface strains.

This is a system which has been designed to evolve to the third generation of testing machines; a multidimensional generalized loader system (MDGLS) in that additional capability for measuring non-mechanical conjugate pairs of material behavior will be added. This, in accordance with the current episte-

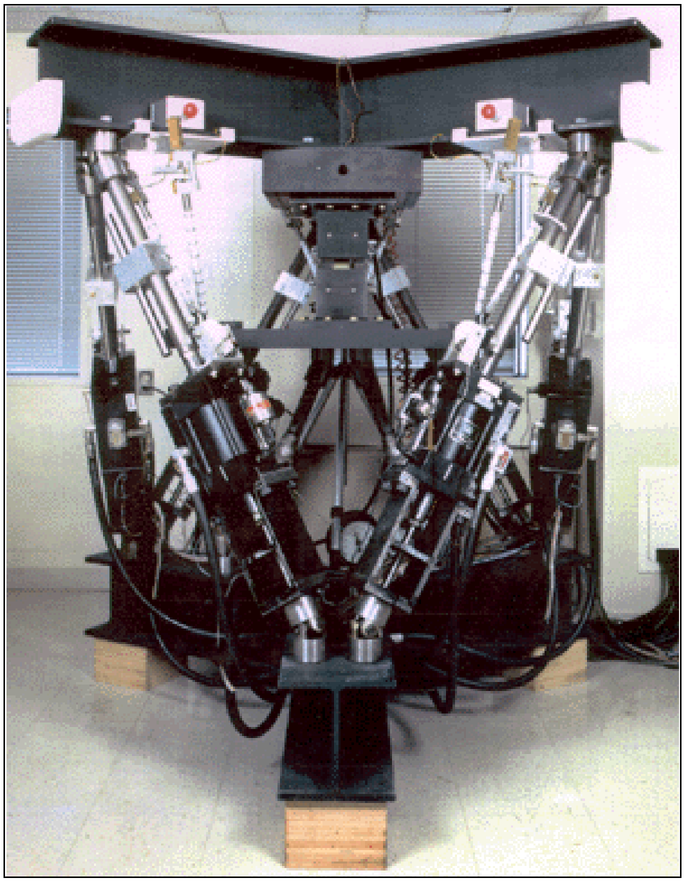

Fig. 3.The 6-D Loader testing machine as it exists today.

mologic approach, will afford the opportunity of using the loader to identify physical systems under the simultaneous action of thermal, electromagnetic, substance diffusion, and mechanical loading effects. NRL has been working on a coupled field theoretic representation of observed material behavior since 1991. The MDGLS will allow a system identification approach to this area parallelling that already used successfully for the 3D in-plane loader and the 6D loader system.

3.2.2 *Specimen Considerations*

Composites associated with various applications range through a wide variety of materials. Each different combination of matrix, fiber, fiber coating (for matrix-fiber interphase), layup angle, stacking sequence, etc. corresponds to a different material. The approach discussed here is specifically tailored to organic matrix composites. Approximately 100 material systems with fibers ranging from Kevlar to IM7 graphite and several thermoset resins and thermoplastic organic polymers have been tested and characterized with the approach discussed here. A complete list of all the materials tested up to now can be found in [13].

The specimen geometry was designed to satisfy the following requirements:

- The characteristic dimensions should be large enough relative to fiber diameter and lamina thickness to ensure that the material could be analyzed as either a single mechanically equivalent homogeneous anisotropic monolithic material, or a collection of layers of varying orientations of such materials.
- The overall specimen size should be small enough to keep material costs at a manageable level.
- Strain riser(s) should be present to guarantee that high strain regions occur well away from all specimen boundaries.

3.2.3 *Procedure*

The objective of the In Plane Loader System (IPLS) is to control the rigid body motion of the boundary of the specimen that is held by the movable grip and at the same time measure the boundary displacements and tractions. Because the actuators are constrained to move in a plane parallel to the specimen, the resulting motion involves only three degrees of freedom relative to any frame of reference on that plane. The grip motion can be resolved into three basic components: sliding (shearing) u_0, opening/closing u_1, and rotation u_2. Specified combinations of actuator displacements, therefore, map into particular combinations of these three basic motions.

In order to visualize the loading space it is advantageous to think in terms of a three dimensional displacement space with coordinates (u_0, u_1, u_2). The issue then is how to select a representative family of paths that cover the space and how to sample along each path. It was decided to cover the boundary displacement space with a set of 15 uniformly distributed radial loading paths as indicated in Fig. 4. Note that because of geometry and material symmetry about the axis along the notch(es), only the half space corresponding to positive slid-

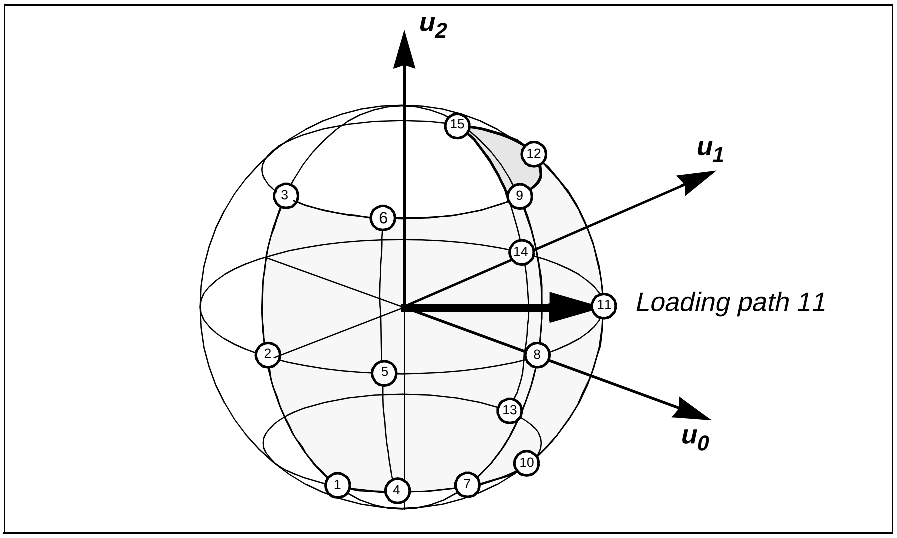

Fig. 4. Loading space and its spanning from 15 discrete loading paths.

ing displacement (u_0>0) need be considered. The required set of observation points is generated by sampling along each path. A particular test in which the actuator motions are continuously varied corresponds to a specific path in this space. Only 15 specimens are required, and 50 observations per loading path are obtained from a single specimen.

The locus of the end points of all loading paths for the same increment is a half sphere as shown in Fig. 4, where loading path 11 at an arbitrary increment is presented as an example.

The process of computing the total dissipated energy is based on the boundary displacements and tractions that are measured at each increment imposed by the IPLS along each loading path. More details are presented elsewhere [13,14]. One specimen per loading path is used initially and the procedure is then repeated for a total of two specimens per loading path. As a demonstration of repeatability, Fig. 5 shows the results of the two specimens used for loading path 11. The RMS error observed between the two specimens for the same loading path has never exceeded 5%.

A similar procedure, with higher dimensional loading space, is planned for the 6DLS in the near future.

4. AUTOMATION OF MODELING

4.1 Computational Technology effects on modeling

In the discussion of the effects of computational technology for modeling and model utilization, it will be assumed that the set of equations that captures the relationship between the input and the output will be the mathematical model that corresponds to the physical behavior of the system under consideration.

Usually, the process of system identification contains two main stages. The first stage establishes an analytical representation of the functional relation-

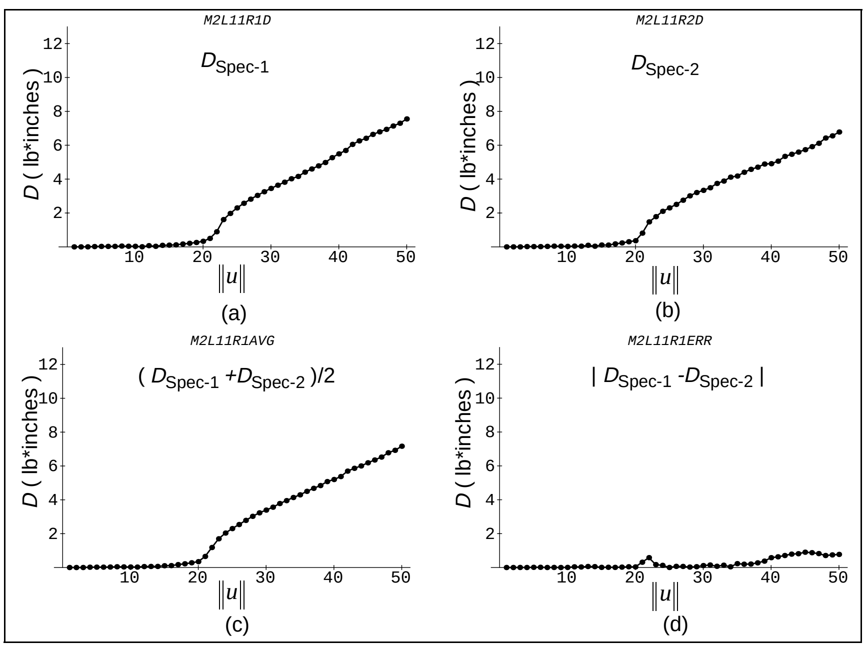

Fig. 5. Measured dissipated energies for specimen 1 (a), specimen 2 (b), their average value (c) and the absolute difference between the two (d), for material 2 (AS1, 6501-6, +/- 30 ^{o}) and loading path 11.

ship. The second stage determines the free coefficients that fix the relationship for the given input/output pairs. The latter is usually achieved through the solution of the system of equations that capture the model. In the context of structural mechanics, the model equations includes partial differential equations (PDEs) that are solvable by reduction to algebraic systems of linear equations.

4.1.1 *Labor of Numeric Calculations*

At MIT in 1930 [17,18], Vannevar Bush had the Differential Analyzer ready to solve up to sixth-order differential equations using analog mechanical integrators. Such large special purpose machines remained relatively rare, however. Despite the appearance of the first programmable digital computers in the 1940's, computation during the years up through and including the Manhattan Project for the most part meant people with either Marchand calculators or slide rules and adding machines. To solve field equations representing models of physical systems in one or two dimensional spaces, rooms full of people worked in parallel using relaxation techniques custom made to accommodate the technology. Programming for these computers often took the form of seating diagrams and instructions for each step of the computation, including passing papers with intermediate results.

The appearance of the transistor by 1948 led to their use in computers by 1956 [18]. Coupled with early advances in magnetic core memory, transistors led to the so called second generation computers that were smaller, faster, more reliable, and more energy efficient than their predecessors. Second generation computers also replaced machine language with assembly language, allowing abbreviated mnemonic programming codes and symbolic addresses to replace binary codes filled in directly by the human programmer. Programming awkwardness still remained a barrier to applying computers to problems, although extremely clever and motivated programmers could solve problems of considerable complexity. For the most part, however, no structural mechanics or materials modeling was attempted with assembly language.

4.1.2 *Numeric vs. Symbolic*

It was not until 1952, the year of the first compiler (the “A-0”, developed by Grace Murray Hopper), that the first symbolic processing became available in the procedural semantics sense of being able to use variables. However, only after 1957, the year that John Backus and colleagues at IBM delivered the first FORTRAN compiler to Westinghouse, did generic symbolic programming become available in a form easily understandable by engineers involved with structural mechanics. There began efforts to transition finite difference relaxation techniques for solving PDEs to a programmed form under FORTRAN. However, no capability was available for solving equations in pure symbolic form, in terms of parameters and input variables of the problem.

It looked as if the laboriousness of the previous stage was present again at the new level of more capable technology. This was the case until 1959, when John McCarthy developed LISP as a new language for *Artificial Intelligence*. LISP allowed the construction of the first symbolic programs. However, it was not till the 1960's that the first attempts to automate theory formation and scientific discovery appeared. One of these attempts by Gerwin [19] led to modelling and simulating the process of inferring laws or functions given the knowledge of specific data points. Lenat [20] developed AM, a system that rediscovered concepts from number theory. It was the BACON system [21] in the early 1980s, by Bradshaw, Langley and Simon, that was successful in utilizing a data driven methodology to rediscover physical laws (i.e., ideal gas, Coulomb's, Kepler's third, Ohm's etc.).

The process of using computational power to perform laborious non-numerical activities associated with mechanics and engineering applications has evolved to the state where symbolic technology and heuristic systems are used for optimization and management of large numerical codes [22].

Today, the existence of efficient symbolic algebra systems such as *MACSYMA*, *Mathematica*, *Maple*, *Axiom*, etc. allow use of symbolic modeling techniques in constitutive equation generation [22,23]. Recently, public domain numerical solution implementations for solving field problems by finite element methods have become available in “contemporary” codes. These codes depart from the FORTRAN legacy in the sense that they use object oriented technology for algorithmic encapsulation [23].

In response to an early recognition of the possibilities of an evolving computational technology, an alternative medium for theory representation was developed at NRL [24,25]. This medium was based on a three dimensional representation of algebraic structures called solution graphs. These structures were used in representing directed tensorial equations.

4.1.3 *Program Synthesis*

In all of the cases mentioned above, the human researcher was required to encode a specific algorithmic implementation in some programming language of choice. The laborious process of human programmer involvement thus reappeared for each new technological level. As a step beyond this, a fair amount of work has been applied in the 1990's towards automated synthesis of computer software, in some cases already optimized for specific compilers and hardware architectures [26]. Systems like SINAPSE [27] and ELLPACK [28] generate source code implementing numerical techniques (finite differences and finite elements) for solving systems of PDE's. Custom technology of this type is what has been used at NRL in composite materials research for automated model generation.

4.2 Material Behavior Encapsulation

NRL has developed an approach to characterize strain induced material damage [13-16]. This approach was motivated by a need to model failure behavior in composites on a continuum basis and a need to relate failure to material constitutive behavior. The goal of such an approach is to permit accurate modeling of the progressive loss of stiffness and concomitant inelastic behavior.

The procedure involves the determination of a dissipated energy density function which will play the role of a potential function that encapsulates the material behavior and that only depends on the strain vector and the material used in the structure, according to:

$$\phi(\tilde{\varepsilon}, m) = \phi(\tilde{\varepsilon}, \tilde{c}) = c_1(m)\chi_1(\tilde{\varepsilon}) + \ldots + c_n(m)\chi_n(\tilde{\varepsilon}) = c_i(m)\chi_i(\tilde{\varepsilon}) \qquad (1)$$

Here, c represents the vector of the material-dependent coefficients c_i, and χ_i represents the basis functions depending only on strains ε and defined at a total of *n* distinct points distributed over the strain space.

Equation (1) can be thought as being an interpolation function allowing evaluation of ϕ on points other than the ones used to define the basis functions.

Its volume integral equals the energy dissipated during loading due to the various internal failure events, and its value at any point in the material is regarded as a measure of load induced internal damage. The dissipated energy density function is connected through the total energy offered into the system when loaded and the recoverable energy, through the relationship:

$$\int_0^{u_r} t_u q_v dq^v - \frac{1}{2} t_s u_t u^v = \int_{\partial V} \phi(\varepsilon_i(x_j)) dx_j \tag{2}$$

The dissipated energy density function captures the collective behavior of these failure mechanisms without requiring an explicit knowledge of these mechanisms. Moreover, it can also be related to local stiffness changes which characterize nonlinear structural behavior. The left hand side of equation (2) is determined through an automated experimental procedure that involves the IPLS or the 6DLS. Since the left hand side of Equation (2) represents the total energy dissipated due to strain induced damage in the entire specimen, the right hand side represents the same. However, in the case of right hand side it is noticeable that the Dissipated Energy Density function is only a function of local strains in the material. The structural effect is introduced only through the integration limits. This fact is the one that allows the decomposition of structural behavior and material behavior. The enrichment axiom of composition of behavior is expressed through Eq. (2).

The construction of this function from a sum of basis functions as shown in Eq. (1) reduces the problem to the determination of the coefficients of these basis functions. This is a classical optimization problem with inequality constraints where the objective is to minimize the error between the left and the right hand sides of Eq. (2) (objective function). This is a standard problem in quadratic programming and is readily solved using well established numerical techniques [13,15]. The computed coefficients are subsequently stored in a data base for the material data. After this step the dissipated energy density is fully defined and, given a strain field, can be evaluated at any point of any structure made of one of the characterized materials. This fact is at the heart of the simulation technology evolving at NRL for the past 5 years.

5. AUTOMATION OF PRESENTATION (SIMULATION)

5.1 Simulation Purposes

5.1.1 *Means for Scientific Data Visualisation*

The process of presenting the model-predicted behavior of a system as a function of varying control or input variables has been called behavior simulation. In the early days, data graphing on appropriate paper was the visualization technology of the period. As computer peripherals like printers, plotters and vector displays started appearing in the 1960's and 1970's, more data could be plotted. In most cases the plots were two dimensional distributions of one state variable (or system behavior output) versus a system behavior input or control parameter. These first visualizations were used for studying the pathology of system behavior.

In the late 1960's the first three dimensional data representations appeared as two dimensional projections. Libraries for plotting biparametric surfaces in three dimensional spaces started appearing as supersets of the previously existing two dimensional ones. One of the earliest attempts, if not the first, for automation of the process for three dimensions, was developed at NTUA [29]. This facility was a macro language system for drawing families of 3D entities by the use of CALCOMP plotters with Data General mini computers. It was used to visualize arbitrary degenerate surfaces, along with the caustic surfaces reflected or diffracted when a light beam impinged on them.

5.1.2 *Means for Enriched Interaction*

The study of behavior of physical systems was limited by the rates of producing visual representations. There was a lack of interactivity imposed by the low speed of hardware and software. The first systems would permit very limited variation of control parameters due to the lack of interactivity. However, by the 1970's the first commercial interactive systems appeared, employing vector display systems along with various pointing devices (joysticks, data tablets, control dials, etc.) This allowed creation of the first structural behavior systems for simulating predicted behavior [30]. Now, behavior prediction could be visualized through interactive variation of parameters and responses from the visualization system. It has been established [31] that in order for most people to consider an action-reaction pair as an interactive operation, the time lapsed between the two should be of the order of 2 to 3 seconds for most people. How much a visualization system can achieve in these 3 seconds determines the effectiveness of the simulation in getting the character of the response across to the human end user.

5.1.3 *Virtual Prototyping*

Today the efficiency of computational and visualization technology is very high compared to that of just 3 years ago. It is possible to embark on the process of optimizing design of a structure on the basis of the short time length required from parameter change to recomputation and display of behavior. A 5000 degree of freedom structure can be transformed in 3D space interactively while the colors representing the intensity of the visualized field change as a function of the loading combination. This can be achieved today with a low-end workstation.

As a consequence of the rapid evolutions of hardware and software, it is realistic today to talk about designing an environment for virtual prototyping. Such an environment is under construction at NRL, among other activities, with levels of ease of use and completeness varying by activity. At NRL the goal is to allow designers and domain experts to construct virtual prototypes of a product based on optimization of the product's behavior parameters under known constraints. A description of a system architecture for achieving these purposes follows.

5.2 Dissipated Energy Density Simulator

The dissipated energy density functions of materials, once identified through testing, can be encapsulated in a way that allows simulation of structural behavior for a structure made out of these materials. Current workstation technology allows for dynamic, interactive use of such simulation. A schematic representation of the data flow involved on the first generation of NRL simulator appears in Fig. 6

5.2.1 *Specimen Dissipated Energy Distribution*

An example representing dissipated energy density within IPLS specimens under the fourth load increment (of fifty increments) for the fifteen load paths appears in Fig. 7. Icons below each specimen show the combination of the three basis cases (two translations and a rotation) used for constructing the load applied to the specimen by the IPLS. Essentially identical results are obtained with the 6DLS if it is restricted to in-plane loads and reactions. A complete set of in-plane stimulus-response data for a material would consist of 100 figures like Fig. 7, or 400 figures for a complete characterization of a fiber-resin combination in four layup angle combinations.

Fig. 7 clearly indicates the power of (and the need for) taking paths through the entire three dimensional space of load parameters. Many observations on specimen behavior become apparent that are contrary to the “intuitive” ones suggested by experience with homogeneous specimens.

5.2.2 *Smart Structure Simulation*

One can picture a situation in which the user of a composite structure, if given

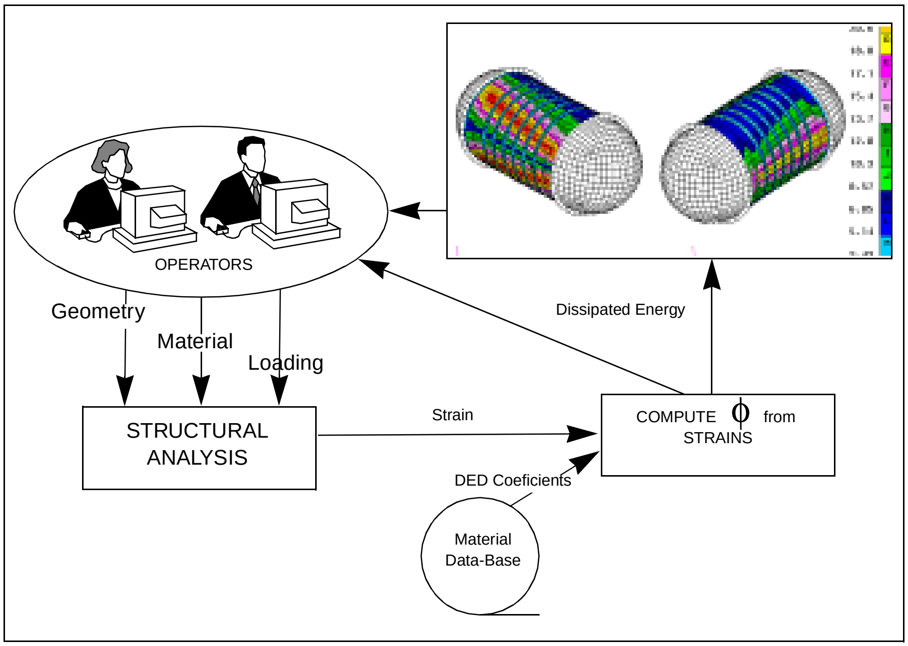

Fig. 6. Logical architecture of first generation dissipated energy density simulator

access to a dissipated energy density contour map of the structure, associates places of low dissipated energy density with good health of the material at such places. In the context of smart structures, dissipated energy density can be computed as a measure of structural health at every point in the structure from lifetime strain histories measured by a distributed sensor system. It is known that the accuracy and completeness of such health monitoring would vary from place to place in a way that depends on the location, orientation, and number of available strain histories. It is not known yet the extent to which such health monitoring would be limited if some portion of the past strain history were unavailable and the ability to subject the structure to diagnostic load cases were restricted.

A variation of the simulator presented previously has been developed [32,33] to make it easier to display the dissipated energy density maps in a dynamic fashion for a variety of parameters that may be dynamically varied by the user or by the simulated environment.

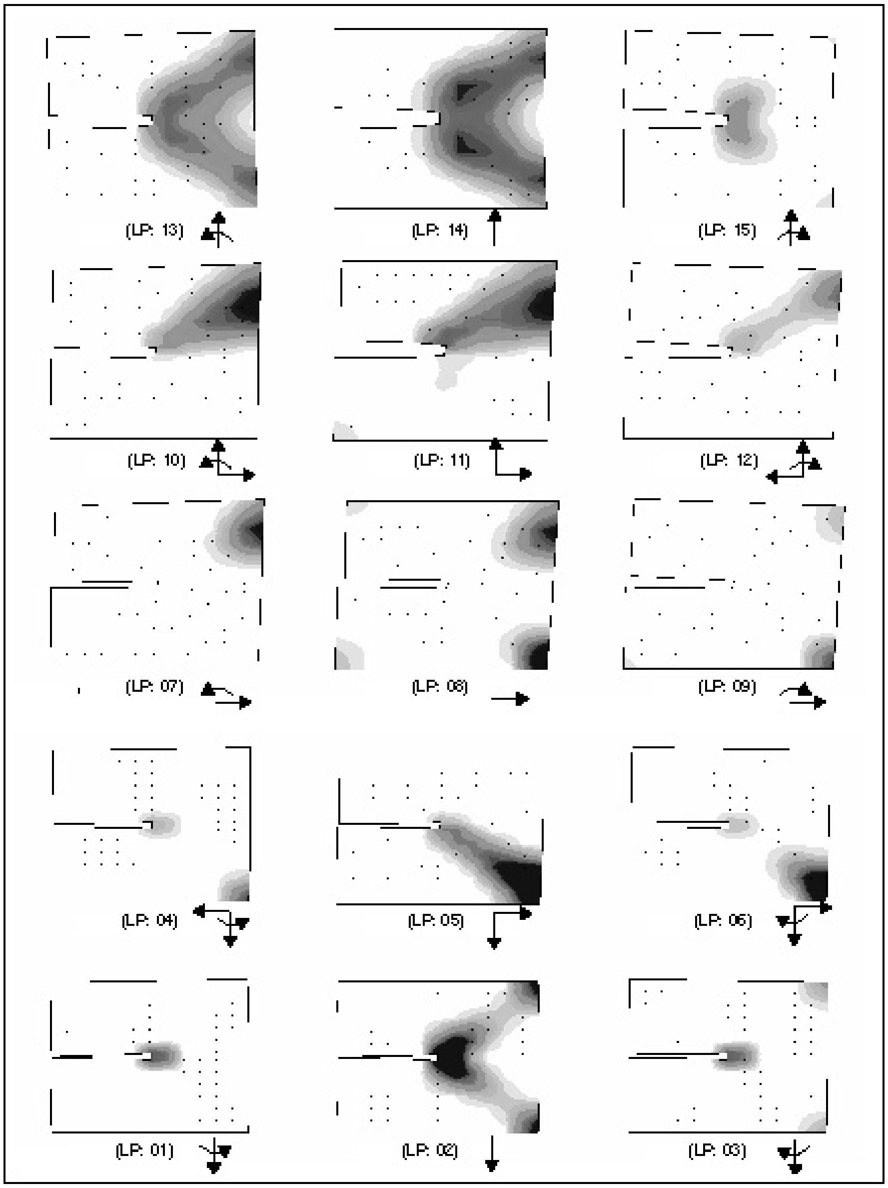

Fig. 7. Distributions of dissipated energy density on the IPLS specimen for material AS1/3506-1 [+/- 30^{o}], for all load paths 1-15.

The modeled geometry is that of a cylinder with 8 I-beam stiffening rings that are attached on the internal wall of the cylinder. Cylinder and stiffeners have been modeled to consist of an AS4/35016 25(0^o)/67(+/- 45^o)/8(90^o) laminated composite thermoset material. Two hemispherical end caps and the joining rings have been modeled as made of steel.

Three basis loading cases were selected: external hydrostatic pressure to capture the effect of depth, and bending about the two transverse axes in order to capture maneuvering events and moderate standoff underwater explosions. Combinations of these three cases represent a large class of actual loading events. The upper right window of Fig. 6 shows a representative dissipated energy density distribution (left and right views) when a remote explosion has occurred at a distance on the right of the structure. The extended simulator [32,33] was developed to allow acquiring, visualizing, and interactively controlling the error between actual field quantities associated with certain load cases not explicitly included in the basis and the "sensed" field quantities inferred from measured sensor readings fitted only to the basis loads. This extended simulator was used to envisage the effect of different sensor arrangements on the spatial distribution of error between "sensed" and actual strains on the structure [34] for such out-of-basis loads. It was observed that for many sensor placements, the error distribution for dissipated energy density appeared much smoother and more forgiving than the error distribution for either individual strain components or combinations such as the RMS strain.

5.3 Coupled Multi-Physics Simulation

Although many different variation of the coupled multiphysics problem have been addressed at NRL, only the one relating to the fluid-structure interaction will be discussed here. Design of complex structures in motion within fluids, such as airplanes and submarines, is a field that has been heavily influenced by available computational technology. Several difficulties played a limiting role on what could be achieved in this field for many years. Realistic models of full structures or even structural components require a great many degrees of freedom. The difficulty of modeling highly detailed structural geometries as well as that of solving millions of equations have been the main limiting factors. Consequently, up to a few years ago, the effect of the fluid on the structure was computed with fluid codes based on the assumption that the structure was a rigid body in the fluid mesh. The fluid codes were computing pressure profiles that subsequently and through a very laborious process were used as loading conditions in structural codes for solving the structural problems.

However, the evolution of high performance computing (HPC) and high speed networking has been very rapid recently. The current state of the art allows modeling of the coupling between structure and fluid.

5.3.1 *Modeling*

In order to predict the dynamic response of a rigid or flexible structure in a fluid flow, the equations of motion of the structure and the fluid must be solved simultaneously. The most difficult part of handling the fluid/structure coupling numerically stems from the fact that the structural equations are usually written with material (Lagrangian) coordinates, while the fluid equations are typically written using spatial (Eulerian) coordinates. Therefore, a straightforward approach to the solution of the coupled fluid/structure dynamic equations requires moving at each time step at least the portions of the fluid grid that are close to the moving structure. This can be acceptable for small displacements of the structure, but may lead to severe grid distortions when the structure undergoes large motion. Recently, several different approaches have emerged as an alternative to partial regridding in transient aeroelastic computations. Among these the most noteworthy are the corotational approach [35,36], dynamic meshes [37], and the Arbitrary Lagrangian Eulerian (ALE) [38] formulation.

The moving mesh can be modeled as an independent field with its own dynamics. Therefore, the coupled transient aeroelastic problem can be formulated as a three-field rather than two-field coupled problem: the fluid, the structure and the dynamic mesh, in the form of the following semi discrete PDEs

$$\frac{\partial}{\partial t}(A(x,t)W(x,t)) + \tilde{F}_c^c(W((x,t),x,\dot{x})) = \tilde{F}^d(W(x,t)) \tag{3a}$$

$$M\frac{\partial^2}{\partial t^2}u + f^{int}(u) = f^{ext}(W(x,t)) \tag{3b}$$

$$\tilde{M}\frac{\partial^2}{\partial t^2}x + \tilde{D}\frac{\partial}{\partial t}x + \tilde{K}x = K_c u(W(x,t)) : \tag{3c}$$

where: W is the fluid state vector, A results from the finite element/volume discretization of the fluid equations, $\tilde{F}_c^c$ is the convected vector of numerical convective fluxes, $\tilde{F}^d$ is the vector of numerical diffusive fluxes, u is the structural displacement vector, f^{int} is the vector of internal forces on the structure, f^{ext} is the vector of external forces on the structure, M is the finite element mass matrix of the structure, and $\tilde{M}$, $\tilde{D}$ and $\tilde{K}$ are fictitious mass, damping and stiffness matrices associated with the fluid moving grid and constructed to avoid parasitic interaction between the fluid and its grid, or the structure and the moving fluid.

5.3.2 *Solution Procedures:*

Heterogeneous time integration procedures for fully-coupled transient computations require “time marching” through a combination of staggering and subcycling procedures [39]. The opportunity for implementing the fluid and structural solvers on multiple processors of different computers in a heterogeneous environment suggests a staggering procedure where both disciplines are advanced in parallel. This enhances the speed of the simulation by allowing interparallel processing on top of the intraparallel computations; the speed comes at the expense of a deterioration in accuracy, especially in the structure solution. However, this trade-off of accuracy for speed may be desirable in a preliminary design.

At every time step, the corresponding linearized system of equations is solved via the FETI (Finite Element Tearing and Interconnecting) substructuring method [40,41]. The FETI algorithm is an optimal domain decomposition iterative algorithm which is based on a saddle point variational principle. It incorporates a mechanically sound preconditioner and a natural coarse grid operator that propagate the error globally, accelerate convergence, and ensure performance independent of mesh size and number of substructures. Hence, the FETI method is well suited for massively parallel implicit computations.

Fig. 8 shows the planned distribution of subdomains of both the structure and the fluid on different supercomputing machines connected through the “very high speed Backbone Network Services” (vBNS) among the NFS supported supercomputer centers in the USA. This is the first time that vBNS will be used for a mechanics research application.

The massively parallel viscous flow solver used is based on a mixed finite volume/finite element formulation [42]. An ALE formulation is incorporated in this fluid solver to obtain the benefits previously described.

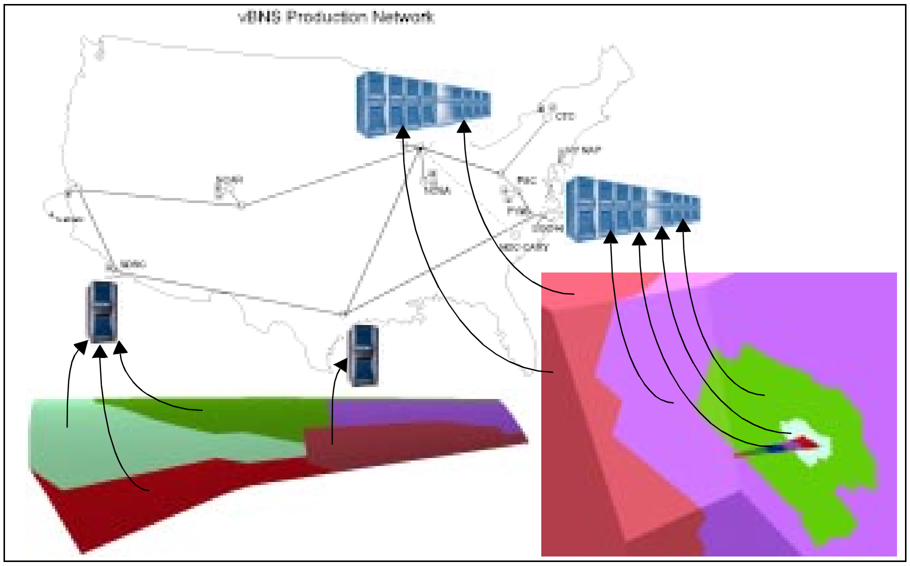

Fig. 8. Domain decomposition of structure and fluid, and their distribution at different supercomputing environments via the vBNS

The computational approach outlined above requires the explicit prediction of the motion of the fluid grid points on the fluid/structure interface once the motion of the structure has been determined, and the transmission of the pressure loads from the fluid side of that interface to the structural nodes that lie on it.

The fluid and structure meshes have two independent representations of the physical fluid/structure interface. This creates the problem that the fluid and structure interfaces are not identical, and their discretizations do not coincide.

These issues have been addressed through MATCHER, a parallel software module that generates the data structures needed for handling arbitrary and nonconforming fluid/structure interfaces in transient aeroelastic computations.

5.3.3 *Simulation Results*

Subsonic linear unsteady aerodynamics and solution algorithms have been reasonably successful in predicting flutter boundaries for Mach numbers up to 0.6 or 0.7. However, linear theory has been unable to account for the effects upon transient loads of aerodynamic shape, high angles of attack, detaching and reattaching flows, moderate to low dynamic pressure, or maneuvering conditions [43]. In an attempt to account for material nonlinear behavior due to strain induced damage, NRL's simulator is being extended to solve coupled fluid/structure problems. A composite airplane wing was modeled and an analysis was performed to obtain strain fields which were used to compute dissipated energy density. The fluid subdomains (8) ran on 8 processors of an *Origin 2000,* while the one domain of the structure ran on one processor of a *Power Challenge*. This was a scaled down version of the discretized model. Its characteristics were: 27,872 nodes and 159,073 tetrahedral elements for the fluid, plus 456 nodes and 1,756 mixed shell and beam elements for the structure. This problem ran in approximately 2 seconds per loading condition.

Fig. 9(a) presents the distribution of dissipated energy density under the skin in the spars and beams, while Fig. 9(b) presents the skin distributions.

6. NEW ROLE FOR THE EXPERT

To demonstrate how the role of the expert can be changed by dynamic computational simulation, the case of predicting burst pressure of deliberately flawed, internally pressurized composite vessels will be discussed.

6.1 Pressure Vessel Simulation

The physical problem involved the study of undesirable events in the life cycle of composite pressure vessels. As a practical matter, the vessels are stored depressurized and ready for use for most of their life and are pressurized only briefly by their own contents when put to use. Nicks or dings in the shell of the depressurized vessel are occasionally produced by accidents involving forklifts, dropped tools, or rigging and handling errors. It is not acceptable to pressure test the damaged but loaded vessel, nor is it practical to unload, test, and reload the vessel. The customer wanted a way to determine, with high confidence and based solely on measurements of the profile and dimensions of the types of flaw typically encountered, the extent to which the vessel's burst pressure would be affected. The approach followed to resolve the problem of this kind of mechanically induced aging included

- design and construction of two distinct families of pressure vessels: Family A was made out of IM7/HBRF55A (fiber/resin), 90^o +/- 22^o laminates, with 50 cm diameter and 50 cm length; Family B was made from T40/LRF205 (fiber/resin), 90^o +/- 29.5^o laminates, with 30 cm diameter and 80cm length,

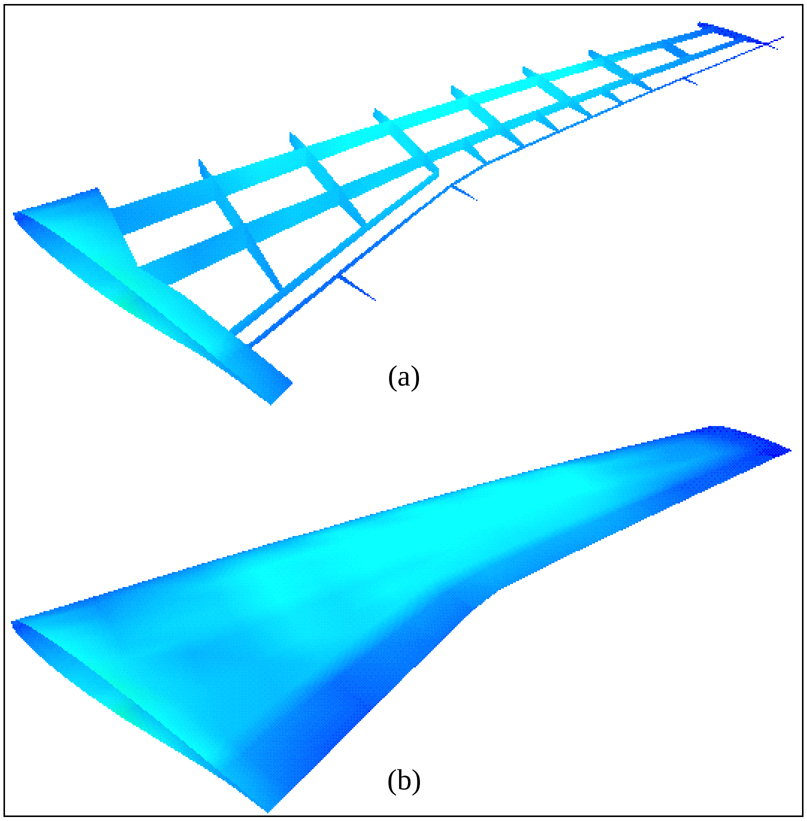

Fig. 9. Distribution of dissipated energy density for an arbitrary material, for the case of coupled fluid-structure interaction. Internal substructure view (a), and external skin view (b).

- characterization of the dissipated energy density characteristics of the materials used, based on specimens cut from custom made flat panels of the materials,
- modeling and simulation of the pressure vessels using NRL's methodology,
- gouging circular and triangular gouges of various depths on the surface of the vessels at mid-height, to simulate impact damage,
- experimental testing to establish the burst pressure of the various unflawed and flawed vessels, and
- prediction of the burst pressure from the dissipated energy density simulation technology.

All steps of this procedure except the gouging and burst testing were conducted at NRL.

6.2 Dynamic Failure Criterion Formation

According to the traditional methodology, the burst pressure could be predicted by associating the observed failures with any of the critical quantities found in one of the available failure criteria. The fact that there exist more than 30 failure theories [44] for laminate composites indicates that the various domain experts have arrived at different evaluations of their personal definitions for “failure”. This appears consistent with Aristotelian logic and the contemporary definition of a criterion as the representation of a mapping; the mapping is from a collection of perceptions from the physical world on the one hand to a collection of judgements in the conceptual world on the other. The fact that a criterion is embodied in an equation or inequality does not make its validity universal. Rather, the embodiment just makes its validity assertable by the author, like any other predicate relationship.

A main theme at NRL has been to focus on providing users with the ability to form new concepts (including criteria for behavior) based on automated production of stimuli from interactive simulated environments. The justification for this approach is the common experience that knowledge acquired “by discovery” is typically more active and useful than any other form.

Discovery, on the other hand, is directly associated with the human ability (some might say the human compulsion) to form new concepts by using abstraction to combine older concepts and new stimuli. It could be argued that the immediacy and emotional power of discovery come from its long standing evolutionary benefit to humans; new concepts have increased an individual's control of the environment. By its nature, discovery is not complete until one has a sense that the new concept has been validated by interactions other than those which originally gave rise to the concept. This implies that an interactive environment is necessary for discovery. An increase in stimuli has been proven to lead to increased rates of acquiring “by discovery” knowledge.

In this spirit, the following scenario was used for developing a criterion: Two experts in the domain of structural mechanics interacted with NRL's simulator for the internally pressurized vessels. It was decided that they would not use any preconceptions about previously known failure criteria, and that they would just interact with the simulator by “flying” over the control parameter spaces while observing the behavior --including dissipated energy density-- of the structure.

The simulator was implemented by a two noded data flow network in the form of an "Iris *Explorer*" visual program. As the parameter of internal pressure was varied, the distribution of the dissipated energy density over the vessel was observed to evolve and to be affected by the presence of a flaw. The following observations were made:

- The areas of high dissipated energy density appeared as a four-lobed region extending outside the gouged region (see Fig. 10),
- The distribution grew, but remained similar in shape as pressure was raised.
- 90% of the total dissipated energy in the vessel was distributed in the four lobed volume around the gouged area.
- After a certain pressure, the area of high dissipated energy density stopped growing. This familiar saturation effect was taken to indicate that beyond a certain level no more energy could be dissipated in the affected material volume.

These initial observations motivated redefining the color lookup table for the dissipated energy fringes to a two color table in order to allow focusing on rates of change of area. It was noticed that:

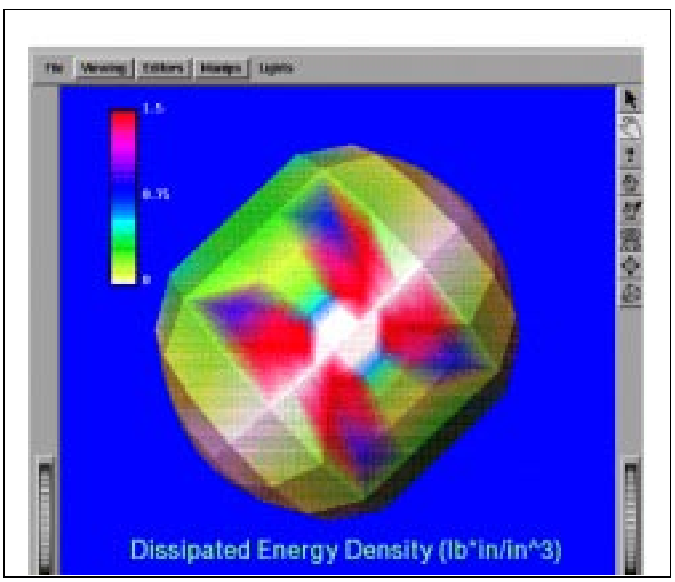

Fig. 10. NRL's simulator view of the rendering window, for a composite pressure vessel with a circular gouge.

• The rate of increasing area where energy was dissipated was slowing down to almost zero at some levels earlier than the complete saturation.
• The total dissipated energy stopped increasing after a certain volume of the material had been affected
• There was a value of the total energy that could not be exceeded.

In an attempt to capture these observations, the following criterion was postulated:

In a composite structure that includes a dominant flaw and is mechanically loaded in a n-dimensional loading space L^n *with a loading vector of magnitude* $|L|$*, failure is defined to be attained when for a dissipated energy density function* ϕ *there is a characteristic volume of the material* V_c *where this energy is being absorbed due to damage and the following conditions are met:*

$$\frac{dV_c}{d|\underset{\sim}{L}|} = 0, \qquad \frac{d^2}{d|\underset{\sim}{L}|^2}V_c = 0, \qquad \frac{d}{d|\underset{\sim}{L}|}\int_0^{V_c}\phi\, dv = 0, \qquad \int_0^{V_c}\phi\, dv \ge d_{cr} \tag{4}$$

where, d_{cr} *represents the critical value of dissipated energy.*

6.3 Burst Pressure Prediction Results

In order to test how well this criterion performs in terms of failure being equated to burst, the following procedure was performed.

One of the two families of pressure vessels was chosen to select a specific vessel that was tested up to burst. This vessel, with a deep (4.5 mm) circular gouge was recorded to burst at an internal pressure of 16.3406 MPa. This value was used to calibrate the simulation parameters. This burst pressure was applied in the simulated environment for this vessel's geometry (including flaw) and material. Controls for the lookup table were set to meet the conditions of the criterion and the critical value of dissipated energy density corresponding to this pressure was computed and recorded as 8618.44 Joules/Meter^3 for vessel of Family A.

Subsequently, the model of another vessel of the same material and dimensions, but with a shallow (2.4 mm) circular gouge was loaded on the simulator. The internal pressure was increased until all equations of the criterion above were satisfied and the previously established value of critical dissipated energy density was reached. At this point the simulated pressure was the predicted burst pressure of 21.029 MPa. The actual burst pressure for this vessel was found to be 21.2703 MPa. The discrepancy between predicted and actual burst pressure for all vessels in the family was found to remain below 1.2%. Similar observations were made when vessels of Family B with different geometry were simulated and when vessels with triangular gouges were predicted using the dissipated energy criterion established from circular gouged vessels. The condition enforced for this case was that the volume of both the circular and triangular gouges was the same. The calibration value of dissipated energy density was done for a vessel with a circular gouge, and was found to be 7239.49 Joules/meter^3. The predicted value of burst pressure for a vessel with a triangular gouge was 15.479 MPa, and the actual was 15.458 MPa, a discrepancy less than 0.1%.

The above scenario demonstrates the idea of dynamic criteria formation as a computer-aided contribution of the human in the research process. Clearly, without the ease of producing stimuli from the simulation environment, it would be very difficult to generate a criterion with comparable success.

7. THE FUTURE

7.1 Physical World

The use of evolving computational technology in the automation of theory formulation, model identification, and predicted behavior simulation has been very beneficial. However, the economic aspects of the research effort have traditionally been ignored. The process of technology transfer has always depended on the availability of tools. Tools used by research establishments tend to be at the edge of technological evolution, and thus more expensive. Most production environments do not have and do not believe they can afford specialized high performance technology. This situation imposes an inherent limitation on the users of a technology.

On the other hand, the period from the first appearance of technology to its becoming a commodity available to many people has been drastically reduced by the fast evolution of computational technology. Some further reduction in lag time has come about because of the reduction in cost of production achieved through automated manufacturing technologies. As a result, more and more advanced technology becomes available to the largest groups of users with less and less delay. The foremost example of such an enabling situation is the recent history of the World Wide Web (WWW) technology. NRL plans to utilize some key WWW technologies to transition its composite material technology from being difficult to reach because of the specialized hardware/software, to becoming available to any of the 70 million WWW enabled users.In particular, the next generation of NRL's simulating technology, currently in development, will use the public domain tools of VRML 2.0 as a 3D visualization language and JAVA as a programming language for capturing behavior in a distributed manner over the Internet. The main idea of this plan, which has already been initiated, is to develop dynamic learning interfaces distributed over the WWW that will allow domain experts to harness the power of distributed supercomputing and industrial material identification in a transparent manner [45].

7.2 Conceptual World

The work performed so far has indicated several opportunities for the use of computational technology to augment the human capacity to consume information, to benefit from the rational process, and to employ the power of self motivated conceptual empowerment.

There are at least two epistemological issues that can been seen as barriers to the establishment of objectivity in modelling. However, the opportunity of harnessing the tremendous growth in computational power presents the alternative of approaching these "barriers" as opportunities for growth in the human capability for efficient problem solving. Both of these issues are very old in terms of the history of epistemology. They were captured by Plato's [46] realization in the *allegory of the cave* that what we perceive is the result of what we sense and how we interpret what we sense. This situation means that we cannot ignore either

- the effects of our "tools" on our observations or,
- the effects of our "interpretations" on our observations.

The first issue covers everything from the effects of the measuring devices to the effects of the language used to encode the observations in the form of a model encoded by a formal system. Models serve the need of capturing "perceived" reality. They appear as the final means for ordering personal experiences. No physical model can be constructed without tapping into a person's experiences and language [47]. As a consequence, many models can be created for the same observations. Formal systems include their own symbols, axioms and provable truths [48] that emanate from the authors' experiences and language, and therefore encode subjectivity. In addition, Godel's incompleteness theorem [49] states that in any formal system powerful enough to support the concept of proof, there will be true statements or theorems that can be expressed within the system but whose proofs are not contained within the system. The Descartes-Hilbert dream of attaining absolute objectivity is therefore unrealizable, since the human rational process is "tainted" by the "prejudices" built into the available methods for describing nature.

The second issue of personalized interpretation of a formal system appears to cover the mechanisms of assigning meaning to the syntactic construct of a model. The first proposed solution of this problem, held by many even today, was the Socratic proposition that before attempting communication, there must be a common dictionary defining the words to be used. However, this is inherently impossible because there are some words especially words for concepts that do not exist in the physical world, which cannot be defined in terms of non-word entities. Defining such "non-elementalistic" [50] words in terms of other words still maintains the problem of defining these other words.

The meaning of words, situations and patterns in nature appears to be a function of an individual's collective experiences, sensitivities and knowledge. It does not exist by itself. It is assigned by the individual. This appears to be true to a point that prohibits the Aristotelian use of the word "is" as an operator to assign meaning to the syntactical construct of a word [50].

It appears that computational technology will continue to be of great help in implementing rationality. It should not be expected to solve the inescapable problem of assigning meaning to a model and communicating that meaning verbally. Rather, its most valuable role may be to lower the cost for individuals to form, interpret, and use models by interacting with stimuli. Computers can present physically realistic interactive stimuli in visual, aural, or even tactile channels. Such channels increase the bandwidth of the human-machine interface because they are not subject to the limits of verbal interaction. By encapsulating prior knowledge in software to make the interactions as consistent with the real world as possible, such virtual environments can lower the barriers domain experts now face in applying computers to our common shared environment. Lowering the barriers and increasing the realism will tend to involve more individuals at higher rates of knowledge acquisition.

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