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13. ABSTRACT (Maximum 200 words)

The principal goal of this research is development of new techniques leading to improvement of damage and penetration resistance of laminated composite structures, such as Army vehicles and their armor. The focus is on control and retardation of damage and fracture in fibrous composites, through modified fabrication procedures that include fiber prestress that can be applied with available filament winding or fiber placement equipment. Novel optimization techniques were used to find fiber prestress magnitudes in individual plies, that accommodate loading-induced ply and local stresses within initial and subsequent damage envelopes both inside and at laminate free edges. Stress relaxation in prestressed laminates with viscoelastic matrices, together with creep deformation under constant rate loading or large changes in temperature are included in our results. Applications of fiber prestress have been identified and explored in compressive prestressing of ceramic/FRP armor plates for improved resistance to projectile penetration. Design of composite-reinforced gun barrels can also be performed using the results of this investigation.

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1. FOREWORD

Research objectives. The principal goal of this research is development of new techniques leading to improvement of damage and penetration resistance of laminated composite structures, such as Army vehicles and their armor. The focus is on control and retardation of damage and fracture in fibrous composites, through modified fabrication procedures that include fiber prestress that can be applied with available filament winding or fiber placement equipment. Analysis of specific deformation and damage processes, and their suppression by residual stresses that are created by release of optimized fiber prestress, are the basic research objectives that enable applications in design and fabrication of composite structures. Another set of objectives relates to understanding of damage mechanisms and their interactions during damage evolution in both particulate composites and laminated plates. The damage and failure mechanisms include interfacial decohesion, transverse matrix cracking and fiber breaks, as well as spontaneous cavitation and unstable cavity growth and coalescence under triaxial stress states.

Approach. Fiber prestress magnitudes in individual plies are sought for accommodation of loading-induced ply and local stresses within initial and subsequent damage envelopes, and for reduction of stress concentrations at laminate free edges. The desired ply prestress magnitudes are found by novel optimization techniques that provide for maximum applied load ranges under constraints imposed by fiber and matrix strengths. Stress relaxation in prestressed laminates with viscoelastic matrices, together with creep deformation under constant rate loading or large changes in temperature are included in our results. The damage evolution processes are modeled with the transformation field analysis method which represents the local field changes caused by different damage modes by equivalent eigenstrains. This approach regards the damage equivalent eigenstrains together with thermal changes, moisture absorption and inelastic strains as an interacting load set, applied together with the mechanical loads to an undamaged material or structures

Significance – Army value. Improvement of damage resistance by optimized fiber prestress can increase efficiency of laminated composite structures and thus help in reducing overall weight of weapons, armor, vehicles and helicopters. The procedures developed in our research yield optimized prestress magnitudes that, when released, create residual stresses which translate and expand initial damage envelopes both inside and at free edges of laminated plates and cylindrical shells, to safely accommodate a prescribed program of loading. Applications of fiber prestress have been identified and explored in compressive prestressing of ceramic/FRP armor plates for improved resistance to projectile penetration. In this case, the ceramic plate is encapsulated in a laminate enclosure that has been fabricated with an optimized prestress distribution. Design of composite-reinforced gun barrels and cylindrical pressure vessels with optimized fiber prestress can also be performed using the results of this investigation.

2. STATEMENT OF THE PROBLEMS STUDIED

This research program explored several new approaches to damage modeling and control in both particulate and fibrous composites, and in particular, in composite laminates. In all systems, we have analyzed evolution and/or suppression of predominant damage mechanisms, such as interfacial decohesion, matrix cracking and fiber breaks. Our accomplishments, described in more detail below, can be briefly summarized as follows:

(1) In a series of papers, some of which predated the present effort and are listed in Section 7-Biography, we have developed the theoretical background for damage control in laminated composite plates and shells by optimized fiber prestress applied prior to and released after matrix cure. This work has shown that both resistance to damage under tension, and compressive strength of laminates can be substantially improved by judicious application of fiber prestress that can be applied with available fiber placement or filament winding equipment. The increase of compressive strength is due to reduction of fiber waviness, which is well-known to impair compressive strength of unidirectional plies. Our work outlines procedures for evaluation of the optimized prestress distribution that keeps the total stresses within the laminate and at free edges within limits prescribed by applicable strength criteria. It also shows the effect of time-dependent matrix deformation on partial relaxation of the residual stresses.

(2) We have shown that fiber prestress should be useful in improving penetration resistance of ceramic armor plates in Army vehicles. In this case, the ceramic plate is encapsulated in a wrap-around laminate manufactured with application of optimized fiber prestress. By solving the optimization problem for this application, we have shown that several common composite systems and layups can be utilized to encapsulate the ceramic plates and induce there very high biaxial compressive residual stresses, approaching 1000 MPa. Available experiments show significant elevation in dynamic compressive strength of ceramics at much lower prestress levels of about 200 MPa.

(3) Using the transformation field analysis method developed in our earlier papers, we have formulated a method for analysis of damage in heterogeneous microstructures that evolves in interaction with mechanical loads and phase eigenstrains, such as those caused by thermal changes, moisture absorption, inelastic deformation or phase transformations. Both stress and energy-based damage evolution criteria were applied, together with failure criteria based on spontaneous cavitation in the matrix and on stability of the cavities created by interfacial decohesion.

(4) Models for evolution of damage in laminates, developed in part with the methodology described in the preceding paragraph, are being completed and will be submitted for publication in the near future.

3. SUMMARY OF THE MOST IMPORTANT RESULTS

3.1 Damage control by release of fiber prestress

Prestressing of structural components for improvement of internal stress distributions and overall deflections is widely used in concrete structures, and to a lesser extent in steel structures. In a typical application, high-strength cables are built into the structure during construction, and then prestressed such that compressive residual stresses are introduced into parts which have relatively low tensile strength. Under load, the applied stresses superimpose with those generated by prestress, resulting in lower tensile stresses in the precompressed parts, and in higher stresses in the prestressed cables.

Prestressing of fibers in composite plies and laminates, which offers a similar approach to stress redistribution has attracted only limited attention. Prior to our work, no serious attempt has been made to develop an analytical methodology for evaluation of optimized fiber prestress values that would generate residual stresses which, in superposition with stresses caused by applied loads, contribute to damage retardation or supression. The residual stresses that are caused in the plies by release of the fiber prestress forces are best understood as stresses caused by mechanical in-plane tractions, applied at the edges of each ply, that cancel the fiber prestress forces in that ply. Both compressive and shear stresses are applied in this manner. Inside the laminate, away from the free edges, this unloading step has the same effect as a uniform overall stress generated by through-the-thickness integration of the said ply tractions. However, at free edges of the laminate, the effect on free-edge stresses must be analyzed for the unloading tractions in each ply, adjusted by subtracting the inactive components that cause uniform in-plane strains in all plies.

Indiscriminate application of fiber prestress may induce residual stresses which accelerate damage initiation and growth. Since the forces needed to apply significant stresses to fiber tows are relatively small, about 100 lbs./tow, often within the capacity of conventional equipment used in filament winding or fiber placement, unknown magnitudes of fiber prestress and residual stresses may be present in many composite materials and structures.

In our work, we examined the effect of fiber prestress on residual stresses in symmetric composite laminates loaded by uniform overall in-plane stresses and uniform changes in temperature. First, a model of the fabrication process was designed. In this model, different magnitudes of uniform fiber prestress can be applied to the fibers of symmetrically located pairs of plies, prior to matrix cure at the curing temperature. After matrix solidification but before cooling, the matrix is nominally free of stress. This is followed by cooling of the laminate to room temperature, with the fiber prestress forces still applied, and possibly under in-plane deformation constraint and transverse pressure, as would be applied, for example, in a hot press. Additional residual stresses may be caused if inelastic deformation takes place during cooling. Finally, the pressure and in-plane constraint are released and the prestress forces are removed. The laminate is now free of overall loads, but supports internal residual stresses caused by fiber prestress and by the thermal change and inelastic deformations.

Micromechanical analysis of this fabrication processl in laminates provides the residual stress magnitudes as functions of the applied stresses and relevant material properties. The effect of these stresses on onset of damage and damage development is best visualized by initial and subsequent failure maps. These maps are constructed for selected in-plane overall stresses, typically in uniform biaxial tension and uniform axial tension and in-plane shear stress planes. Each map consist of branches that represent a critical local stress, defined in each ply by a selected failure criterion. We had used the critical stress criterion, which provides a family of straight line failure branches for transverse and longitudinal ply strengths. More advanced criteria yield both straight and curved line branches. In any case, the internal envelope of these branches is the initial damage envelope of the laminate. These internal envelopes translate and expand by branch position changes after release of fiber prestress, and also during damage evolution.

The S-glass/epoxy and AS4/Epon 828 carbon/epoxy systems in (0/90)s and (0/$\pm$45/90)s layups were analyzed in applications. Initially, different levels of prestress were applied to some or all plies of the laminates. The residual stresses caused by release of fiber prestress caused significant translations of the individual ply strength branches representing onset of transverse cracking in the matrix. One result of these branch translations is an overall translation of the damage envelope, approximately in the direction of the overall prestress vector. Another important result is an expansion of the damage envelope that is caused by relative translations of the branches. This effect was found in both systems, and was particularly significant in the highly anisotropic carbon/epoxy system.

We also found the prestress-induced increment of fiber stress retained after unloading to be quite small, and thus not extracting a major penalty from the effective fiber strength, and by implication, from laminate strength.

The thermal residual stresses caused by cooling from the curing temperature are relatively small in the glass-epoxy system. In our analysis, these stresses are evaluated by first creating a uniform strain field in the laminate, by superimposing certain in-plane mechanical strains unto the thermal strains in each ply. This uniform field is easily evaluated. The added tractions are then reversed and superimposed with those that remove the prestress forces; causing both uniform internal and free edge residual stresses.

3.2 Reduction of free edge stresses by optimized fiber prestress

Several methods have been developed over the years for analysis of local stress distributions at free edge of composite laminates subjected to mechanical loads. Results of specific applications of such methods, as well as experimental observations indicate that extensive ply delaminations can be initiated by the free edge stresses. In our work, we have shown how these methods can be applied to problems involving fiber prestress, and also application of thermal and other transformation strains in the plies. Moreover, we have developed procedures for optimal selection of fiber prestress magnitudes in individual plies, that minimize the total free edge stresses generated by prescribed thermo-mechanical and transformation loads.

The transformation loads that can be applied to a laminated plate are stress-free strains or eigenstrains, e.g., hygro-thermal strains, inelastic strains or those caused by a phase transformation. Damage-induced strain changes and even fiber prestress release can also be modeled by certain equivalent eigenstrains. In our approach to this problem, each of these strains is regarded as uniform or piecewise uniform through the thickness of each ply, but possibly different from ply to ply. The total loading problem can be decomposed into two separate parts. First of these is the standard evaluation of interior fields by a selected lamination plate theory. At the free edges, the resolved equilibrium tractions of the interior field are reduced to zero. This is equivalent to applying these tractions with reversed signs at the free edges, and to superimposing this solution with that of the interior field. The second problem is formulated as a Saint-Venant's problem, for a self-equilibrated, piecewise uniform distribution of free edge stresses applied to individual plies, which generates zero interior field. The advantage of this formulation is that the laminate does not experience any overall deformation under the self-equilibrated traction distribution applied at the free edges. Therefore, this part can be solved independently of the first part, as a plane strain problem on a plane perpendicular to the free edge.

Another major simplification of the free edge problem was found by decomposing the actual transformation field into a uniform strain field and an auxiliary free edge traction field. The latter constitutes again a Saint-Venant's problem for a self-equilibrated piecewise uniform ply traction distribution at the free edge. This approach unifies the solution procedure for any free edge problem. It also offers a very simple method for evaluation of the fiber prestress distributions that exactly cancel free edge stresses caused by a distribution of transformation strains. For example, free edge thermal stresses caused by cooling from processing temperature can be cancelled by such prestress, which can be actually found from a simple formula.

Applications have been developed for typical glass-epoxy laminate layups. loaded by mechanical loads, and both uniform thermal changes and gradients. In each case, a fiber prestress distribution was found that minimizes an objective function representing the free edge stress components responsible for the three crack opening modes at ply interfaces. The optimization procedure for evaluation of prestress distribution in individual plies maximizes the allowable mechanical load amplitude, while keeping both interior and free edge ply stresses within allowable limits. Significant rearrangement and expansion of the damage envelopes can be achieved with the optimized fiber prestress. The free edge stresses actually reach vanishing values when the laminate is subjected to both maximum load and fiber prestress, and remain within strength limits when the laminate is free of mechanical loads.

Result of selected applications to several laminate stacking sequences, layups and composite systems show that fiber pretress can be effectively used to mitigate concentrations of both mechanical and thermal residual stresses at free edges of most laminates.

Additional work in this area included an investigation of stress relaxation that may be caused in prestressed laminates by viscoelastic deformation of the matrix. In this regard, we have analyzed the effect of both linear and nonlinear matrix creep on stress relaxation in prestressed laminates at both ambient and elevated temperatures, and under constant loading rates. The overall laminate and local ply responses are all derived in terms of fiber and matrix strains in each ply, with a hierarchical model based on our transformation field analysis method. The method uses certain influence functions that describe interactions between inelastic and thermal strains at micro- meso- and macroscale. A system of equations for the micro-scale stresses is then obtained, consistent with the constitutive relations and local loading histories of the phases. Using recent experimental data on creep of a thermoset matrix, we found only small reductions of fiber prestress under sustained loading. Experiments on prestress and relaxation effects on residual stresses in laminates would be very desirable, but could not be completed in the present program.

3.3 Encapsulation of ceramic armor plates in prestressed laminates

An application of fiber prestress has been identified in the upper hull structure of the composite armored vehicle. Embedded in this design is a ceramic armor tile plate, supported by a laminated plate. Earlier ARO-supported research on high-velocity projectile penetration experiments on compressed and contained ceramic specimens suggest that dynamic strength of the ceramic increases substantially with confining pressure. Therefore, encapsulation of ceramic armor tiles into crossply or quasi-isotropic laminates with optimized fiber prestress that induces such confining pressure should increase their resistance to penetration.

We have developed and analyzed a fabrication model for the prestressed plate, which accounts for the prestress relaxation caused in the already deposited plies by prestress applied in the next ply of the stacking sequence. An optimized distribution of prestress forces in individual plies has been found such that the compressive stresses in the ceramic armor reach a maximum at a selected ower-wrap thickness.

Large confining pressures can be generated by prestressed carbon/epoxy and aramid/epoxy laminate over-wraps of about the same total thickness as the armor plate. For example, 1500 MPa of biaxial compression can be supported in a 0.75 in. thick alumina armor plate by six 0.1 in. thick plies of a AS4/3501-6 carbon epoxy laminate wrapped over in a crossply layup. The AS4/3501 Hexel fiber has good creep-rupture resistance, and should retain the prestress for lifetime of the armor plate. Some other carbon fibers, such as Toray T-1000 could sustain even higher long-term stresses. Stress relaxation due to matrix viscosity is negligible in this configuration, because the fiber prestress is supported almost entirely by the inviscid ceramic plate.

This approach may improve penetration resistance by several orders of magnitude.. Of course, if the laminate is locally penetrated by a projectile on one side of the armor plate, some unloading will take place. Its extent will depend on the size of the opening relative to the plate area. In larger plates, this may not be significant, and the time needed for the unloading wave, originating from the outer edges of the plate, to reach the impact point may well exceed the time needed for absorption of the projectile by the ceramic. This concept should be tested on actual specimens of prestressed armor, so that the potential benefits can be evaluated.

3.4 Damage evolution in particulate and fibrous composite systems

Interfacial debonding or decohesion of reinforcements from the matrix is a frequent damage evolution mode in materials with tough, ductile matrices. Our model of this process is based on the transformation field analysis method that simulates stress changes caused by local debonds by those caused by equivalent eigenstrains. The damage-equivalent eigenstrain magnitudes were derived from a spring-layer model of an imperfect interface. These and other eigenstrains representing thermal and inelastic strains are regarded as loads acting in superposition with mechanical loading on an elastic, perfectly bonded composite material. Eigenstrain interactions are described by certain influence functions that enter in a system of equations for local stresses in the matrix and bonded or debonded reinforcements. Damage nucleation and evolution are described by critical stress and energy criteria. Moreover, failure criteria based on nucleation of cavities in the matrix, and on stability of the cavities created by interfacial decohesion have been incorporated into the model.

Available experimental results obtained for several volume concentrations of glass spheres in an elastomer matrix were analyzed with the model, and the observed response was well described with a single set of model parameters. The simulations indicate that stress-controlled damage nucleation is the source of a stable damage process, usually in systems with a low volume fraction of reinforcements. However, damage in systems with high concentrations of inclusions is more often controlled by availability of released strain energy. When this does become available, damage can take place at many sites at the same time, hence the overall response is unstable.

The state of stress has a significant influence on mode transition; higher triaxiality favors the energy-controlled damage mode. New and often unexpected interactions and transitions between the two damage modes at different reinforcement densities have been visualized in an overall stress plane of a uniaxial normal and transverse isotropic stress.

Spontaneous cavitation in the matrix, even in the proximity of reinforcements, does not appear to present a significant risk. However, the cavities created by damage evolution do remain stable only under a limited range of loads, that include the simple tension test. Even small additions of a transverse tension component may lead to early failure bycavitation instability. Therefore, simple tension test data may not provide a reliable performance prediction under multiaxial loads.

The results indicate that both stiffness and strength defined by resistance to damage nucleation in particulate composites with ductile matrices should be enhanced by reducing the reinforcement size and by increasing its volume fraction. In contrast, improved ductility accompanied by lower stiffness and strength should be expected in systems with lower volume concentrations.

A similar study is in progress on damage evolution in laminates, where transverse cracking and fiber breaks are the important damage modes. At low crack concentrations, the damage process is controlled by a stress-type criterion which estimates strength of the largest flaws. Energy availability dominates the process at higher and saturation crack densities. Analytical estimates of energy release by the tunneling cracks are not available for other than crossply (0/90/0) layups. Therefore, numerical evaluations were generated for several typical tree-layer laminate combinations, where a cracked ply is surrounded by plies of different and not necessarily symmetric orientations. These results show that energy release in a given ply is often strongly influenced by the orientation of the adjacent plies, and they provide more accurate energy release estimates in laminates with different stacking sequences.

Initial simulations of damage evolution in laminates have been undertaken with these improved energy estimates. In contrast to the typical assumption of periodic distribution of transverse cracks prior to reaching the saturation state, we assume a completely random distribution of potential flaw sites. This leads to damage evolution rate predictions that agree well with many experimental observations. One of the main conclusions of this study is that damage initiation and evolution are inhibited in laminates made of thin plies, where the transverse tunneling cracks can release only limited amount of energy.

4. LISTING OF PUBLICATIONS AND PRESENTATIONS

4 a. Journal articles and book chapters

G. J. Dvorak and A. P. Suvorov (2000), "Effect of fiber prestress on residual stresses and onset of damage in symmetric laminates." Composites Science and Technology, **60,** 1129-1939.

G. J. Dvorak (2000), "Composite materials: Inelastic behavior, damage, fatigue and fracture," Intl. Jnl. Solids and Structures, **37**(1&2), 155-170.

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4 b. Conference presentations

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"Interfacial decohesion in two-phase composite systems," The 1998 Intl. Mechanical Engineering Congress and Exposition, Anaheim, CA, November 18, 1998.

"Transformation analysis of damage in composite laminates," The 1998 Intl. Mechanical Engineering Congress and Exposition, Anaheim, CA, November 18, 1998.

"Transformation field analysis of damage evolution in composite laminates," 15th Army Symposium on Solid Mechanics, Myrtle Beach, SC, April 12, 1999.

"Damage evolution in composite laminates," 4th Conference on Constitutive Laws for Engineering Materials and Structures, Troy, NY July 30, 1999.

"Prestress applications in composite structures," Seminar at Army Vehicle Technology Group, NASA Langley Research Center, Hampton, VA, December 2, 1999.

"Fiber prestress in laminated composite structures," Seminar at the Mechanical Engineering Department, University of Maryland Baltimore County, March 3, 2000.

"Damage evolution and prevention in composite materials," Introductory Symposium lecture at ICTAM 2000, the 20th Intl. Congress of Theoretical and Applied Mechanics, Chicago, IL, August 29, 2000.

"Damage evolution in composite materials," Workshop on Recent Advances in Continuum Damage Mechanics of Composite Materials, ENS de Cachan – CNRS - Universite Paris 6, France, September 21, 2000.

"Damage analysis and prevention in composite materials," Mechanics Colloquium at Northwestern University, October 6, 2000.

"Prestress applications in composite structures," The 2000 Intl. Mechanical Engineering Congress and Exposition, Orlando, FL, November 10, 2000.

"Damage retardation and control in composite laminates," Mechanics Colloquium at Arizona State University, March 2, 2001.

"Current state of research in solid mechanics," AAM/NSF Workshop on Future Directions in Solid Mechanics, Northwestern University, March 30,2001.

"Prestress applications in composite structures," European/USA Initiative on Structural Integrity of Composite Materials and Structures, Capri, Italy, May 22, 2001.

"Damage analysis and prevention in composite materials," Seminar at the Politecnico di Milano, Italy, May 29, 2001.

"Prestress applications in composite structures," Keynote Lecture, International Conference on Composites in Material and Structural Engineering, Czech Technical University, Prague, June 3, 2001.

"Damage control in composite laminates," Seminar at Army Research Laboratory, Aberdeen, MD, June 13, 2001.

"Evolution of interfacial decohesion in particulate composites," The 2001 Intl. Mechanical Engineering Congress and Exposition, New York, NY, November 12, 2001.

"Evolution of interface decohesion in composite materials," Plasticity '02, The Ninth International Symposium of Plasticity and its Current Applications, Aruba, DWI, January 4, 2002.

"Stress relaxation in prestressed laminates" 14th U.S. National Congress of Theoretical and Applied Mechanics, Blacksburg, VA, June 24, 2002.

"Transformation field analysis of damage evolution in inelastic composite materials," Keynote Lecture at WCCM5- World Congress on Computational Mechanics, Vienna, Austria, July 7, 2002.

"Damage control in composite laminates," DCAMM Symposium on Challenges in Applied Mechanics, Copenhagen, Denmark, July 26, 2002.

4 c. Papers to be published

Suvorov, A. P. and Dvorak, G. J. "Damage-induced stiffness and energy changes in composite laminates."

Dvorak, G. J. and Suvorov, A. P. "Damage evolution by interfacial decohesion and cavity growth in composite materials."

5. LIST OF SCIENTIFIC PERSONNEL

Alberski, T., Graduate Research Assistant, Ph.D. completed in 2000

Dvorak, G. J., Wm. Howard Hart Professor of Mechanics, Principal Investigator

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Yang, L. Graduate Research Assistant

Zhang, J, Graduate Research Assistant , Ph.D. completed in 2002

6. REPORTS OF INVENTIONS

No patent applications have been initiated on the basis of this research program

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