COMPOSITE STRUCTURES

Theory and Practice

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Composite Structures: Theory and Practice

Peter Grant and Carl Q. Rousseau, editors

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Each paper published in this volume was evaluated by two peer reviewers and at least one editor. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of the peer reviewers. In keeping with long standing publication practices, ASTM maintains the anonymity of the peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM.

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Foreword

This publication, *Composite Structures: Theory and Practice,* contains papers presented at the symposium of the same name held in Seattle, Washington, on 17–18 May 1999. The symposium was sponsored by ASTM Committee D-30 on Composite Materials. The symposium co-chairmen were Peter Grant and Carl Q. Rousseau. They both served as STP editors.

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Overview

The Symposium on "Composite Structures: Theory and Practice" sponsored by Committee D-30 on Composite Materials, was held in Seattle on 17th and 18th May 1999. This topic was a departure from the traditional D-30 symposia themes of "Design and Testing" and "Fatigue and Fracture." The reasons for this were to focus more specifically on structural certification/qualification issues, and to garner more interest and participation from government and industry experts. As stated in the Call for Papers, "The objective of this symposium (was) to bring together practitioners and theoreticians in the composite structural mechanics field, to better understand the needs and limitations under which each work."

The Symposium was structured around seven general topics (the various sessions), seven invited speakers on these or more global issues, the Wayne Stinchcomb Memorial Award and Lecture, and a wrap-up panel discussion with the invited speakers. The following paragraphs provide brief overviews of all of the papers included in this STP, as well as comments on the panel discussion and additional oral presentations given during the Symposium.

Professor Paul Lagace opened the Symposium with an invited talk on "Technology Transition in the World of Composites—An Academic's Perspective." Professor Lagace provided the attendees with an insightful and entertaining overview of some of the more popular composite structures research topics over the years, and some of the resulting successes and/or barriers to practical use. No technical publication in this STP was warranted for Prof. Lagace's editorial subject.

Structural Damage Tolerance

Lincoln USAF/ASC, gave an invited talk and related paper that reviews the development of procedures used by the United States Air Force in the qualification of composite structures. He also reviews Navy programs, and the resulting Joint Service Specification Guide. The challenges in future certification initiatives, in particular, the need to reduce cost and address changes in manufacturing processes are discussed. He proposes a re-examination of the building-block process and a critical review of probabilistic methods.

Dr. Larry Ilcewicz, FAA National Resource Specialist for Composites, gave an invited talk on his previously published "Perspectives on Large Flaw Behavior for Composite Aircraft Structure." This presentation gave an authoritative overview of low-velocity impact and discrete source damage threats, certification requirements, and structural response. No technical publication of this work was possible for this STP.

Olsson, Asp, Nilsson, and Sjogren review, in the main work performed at the Aeronautical Research Institute of Sweden (FFA), of studying the effects of impact upon composite structures. Both damage resistance and damage tolerance are studied, along with an assessment of the effects of global buckling.

Anderson presented a practical approach to design-specific compression strength-after-impact certification. The application cited was that of a carbon/thermoplastic light helicopter tailboom.

Skin-Stringer Behavior

Greenhalgh, Singh, and Nilsson investigate the behavior of damaged skin-stringer panels under compressive loading. Analysis and test of delamination growth are compared through the use of finite element and fractographic analysis. Local delamination and global buckling are modeled through the use of a moving mesh technique. The effects of embedded skin defects, with respect to size and location, are studied. Guidelines for realistic modeling and damage tolerant design are presented.

Rousseau, Baker, and Hethcock perform a parametric study of critical compression-after-impact (CAI) strength variables for three-stringer panels, and demonstrate practical global-local analytical tools to predict initial buckling and CAI strength. A particular benefit to this paper is the large size of the experimental three-stringer CAI panel database (39 specimens), which should be of use to future analysis validation exercises.

Krueger, Minguet, and O'Brien present a simplified method of determining strain energy release rates in composite skin-stringer specimens under combined in-plane and bending loads. In this method, a quadratic expression is derived for the two relevant fracture modes, and three finite element solutions are used to determine the quadratic coefficients. Both linear and geometrically nonlinear problems are evaluated. The resulting quadratic expressions for energy release rates are in excellent agreement with known linear solutions, and satisfactory agreement over a wide range of nonlinear loading conditions.

Dr. Andrew Makeev (co-author Armanios) gave an oral presentation on a global analysis for separating fracture modes in laminated composites. An exact elasticity solution with approximated boundary conditions for self-similar delamination growth was used. The predicted mode ratio was compared with existing results for eight-ply quasi-isotropic laminates under axial extension. No manuscript is published in the STP for this presentation.

Rotorcraft and Propeller Structural Qualification Issues

Altman, Reddy, and Moore in an invited paper, present the rationale for substantiation of the fiberglass/epoxy V-22 proprotor yoke using a "fail safe" methodology. Significant delaminations were observed in fatigue tests on both prototype and production components within the "safe life" goal of 30 000 hours. "Fail safe" qualification of other Bell Helicopter composite yokes is reviewed. In these components delamination is shown to be a benign failure mode. "Fail safe" substantiation methodology results in a lower life cycle cost.

Dobyns, Barr, and Adelmann discuss the RAH-66 Comanche airframe building-block structural qualification program from testing at the coupon level to full scale static test of the complete airframe structure. Testing discussed includes bolted joints, sandwich structure, crippling specimens, fuselage-sections, and design specific tests. The interaction of the building-block test results with detail design is shown to be important.

Caiazzo, Orlet, McShane, Strait, and Rachau develop a method for predicting key properties of composite structures containing ply waviness, several times the ply nominal thickness. These "marcelled" regions have been observed in thick components. This analytical tool is intended to be used to disposition parts containing these defects. The validity of the method is demonstrated in correlation with test data.

Murri studies the effect of ply waviness upon the fatigue life of composite rotor hub flexbeams. Delamination failure of test specimens having these "marcelled" regions occurs at significantly shorter fatigue lives than in similar specimens without marcels. Geometrically, nonlinear analysis addressing interlaminar normal stresses shows the critical influence of the degree of marcelling. A technique is presented for acceptance/rejection criteria of marcels in flexbeams.

Smith and Mattavi show that unique challenges exist in the development of design allowables for a resin-transfer-molded (RTM) propeller blade. They show that coupon level tests successfully provide data for elastic constants, effects of batch variability, effects of adverse environments, and for the shape of fatigue curves, but do not provide enough guidance for the design of full scale structure in the absence of full scale test data. The number of full-scale tests needed is greater for a RTM blade or structure than for a metal blade or standard prepreg structure.

Bolted Joint Analysis

Iarve and Mollenhauer use a 3-D displacement spline approximation method to evaluate an observed stacking sequence effect upon the pin-bearing strength of two quasi-isotropic laminates. A qualitative agreement is obtained between predicted stress distributions and experimental damage observation. The analysis identifies critical transverse shear and normal stresses.

Qing, Sun, Dagba, and Chang propose an approach for the design of bolted composite joints based on a progressive damage model. The computer code, 3DBOLT/ABAQUS, is capable of predicting joint response from initial loading to final failure. The effects of bolt clamping force and area, and joint configuration upon joint response are summarized.

Bau, Hoyt, and Rousseau present work aimed at developing better numerical predictions of open hole compressive strength, a key structural design driver currently determined experimentally. First, experimental results for a wide range of carbon/epoxy laminates are studied and the predominant lamina-level failure modes isolated. Secondly, a progressive damage 2-D finite element code developed by F. K. Chang at Stanford, is evaluated relative to the large set of experimental data. It is concluded that the progressive damage model yields good results for hard laminates exhibiting 0°-ply-dominated failure modes, but improvements to matrix/off-axis-ply-dominated failure modes are required.

Sawicki and Minguet investigate the effects of fastener hole-filling and hole clearance upon the strength of composite bolted joints loaded in compression. Experiments show three primary modes of failure, which vary depending upon the bolt diameter, hole diameter, and bearing-bypass loading ratio. Strength predictions based upon progressive damage finite element analysis demonstrate reasonable agreement with experimental trends.

Test Methods

Mr. Rich Fields, ASTM D-30 Vice-Chair, made an invited oral presentation on "An American Perspective on International Standardization of Composites." This sensitive subject covered recent D-30 experience with ISO TC61 as well as the author's opinions of the relative merits of ASTM versus ISO approaches to consensus standardization. This briefing was well-attended by ASTM leadership, including Jim Thomas, President. No technical publication in this STP was warranted for Mr. Field's editorial subject.

Martin and Rousseau compare mode I delamination growth behavior at a 0°/0° ply interface with that of a 0°/45° ply interface in glass/epoxy tape. The motivation for this work was that most structural delaminations occur at dissimilar ply interfaces, such as 0°/45°, while the ASTM standard coupon delamination test methods all utilize unidirectional coupons (in order to minimize residual and free-edge stresses). Martin and Rousseau observe in their experimental work that fiber-bridging is similar in both lay-ups (unexpected for the 0°/45° configuration), delaminations grow in a self-similar manner (i.e., do not jump to other ply interfaces), and static critical strain energy release rate, G_{Ic}, from the 0°/45° lay-up exhibits a lower mean and higher scatter (on a small sample size) than the unidirectional configuration. Both specimen designs yield similar fatigue delamination onset results. A useful sidelight to this work is the development of a general method of designing multidirectional laminated delamination coupons that minimizes bend-twist coupling, free-edge, and residual stresses.

Piggot reviews several ASTM D-30 standards, concentrating on the aspects of shear dominated failures. He applies his knowledge of the failure of polymers when subjected to shear loading, and shows that these failures are in fact tensile in nature. He presents a case for a re-evaluation of D30 standards, which involve apparent shear failures.

Schuecker and Davidson present a timely study on the effect of friction on the calculated mode II fracture toughness of the proposed ASTM standard four-point end-notch flexure (4ENF) coupon test. This finite element-based study shows that frictional effects, while present, do not fully account for experimentally observed differences in G_{IIc} between the 4ENF and other mode II test methods.

König, Kreüger, and Rinderknecht present both two-dimensional higher-order plate and three-dimensional layered solid-finite element results in a multidirectionally-laminated end-notch flexure test coupon. The results suggest that width-wise variation in both magnitude and mode ratio of strain energy release rates along the crack front contribute to the shape of the delamination front as well as the final unstable delamination growth. Comparison with experimental results shows that global delamination growth in this case of pure shear (combined modes II and III) is correctly predicted by Griffith's criterion.

Brunner and Paradies (in a paper submitted for publication in this STP, but not presented at the Symposium) evaluate several different T-joint sandwich designs, made from balsa-wood cores having carbon fiber reinforced polymer facesheets. In addition to load-displacement and strain gage data, the test program makes extensive use of acoustic-emission techniques. These techniques monitor early onset of damage and accumulation up to final failure. The specimens were subjected to quasi-static tension and compression loads.

Bucinell and Roy develop a test method for evaluating the properties of closed-section composite laminates. Analysis and test demonstrate that the configuration accurately develops compression properties, and that buckling modes are suppressed. The authors suggest that other laminates be evaluated, and a round-robin test program performed to demonstrate reproducibility of the method.

Owens, Schmidt, and Davis present test methods for generating design properties for skin-to-spar type composite bonded joints, loaded in both shear and pull-off. Data acquisition techniques were developed to capture initial and localized failure modes. The use of a 3-D textile reinforcement is shown to provide improvements over typical unreinforced cocured joints.

Strength Prediction

Hart-Smith, in an invited paper, presents a critical review of fiber-reinforced composites unnotched failure criteria both as taught in academia and as used in practical applications. His criticisms center on the use of interactive failure theories in progressive ply-by-ply failure analyses. He shows that the inhomogeneity of fiber reinforced materials invalidates the use of these theories, and makes a strong recommendation that both the use and teaching of these cease. A strong case is made for the use of separate mechanistic models for failures in the fibers, matrix and at the interfaces.

Dr. Christos Chamis (co-authors Patnaik and Coroneos gave an oral presentation on the capability of an integrated computer code entitled Multi-faceted/Engine Structures Optimization, M^P/ESTOP. The discipline modules in this code include: engine cycle analysis, engine weight estimation, fluid mechanics, cost, mission, coupled structural and thermal analysis, various composite property simulators, and probabilistic methods to evaluate uncertainty in all the design parameters. He described the multifaceted analysis and design optimization capability for engine structures. Results illustrated reliability, noise, and cascade optimization strategy. Both weight and engine noise were reduced when metal was replaced by composites in engine rotors. No manuscript is published in the STP for this presentation.

Peck develops closed form 2-D solutions for the displacements, strains, and stresses in curved and laminated orthotropic beams due to both mechanical and thermal loading. The solutions are exact and thus equally applicable to both solid laminates and sandwich structures. Sample calculations for aluminum honeycomb beams having graphite/epoxy facesheets, predict anticipated failure modes.

Chatterjee uses damage mechanics to develop an approach for inelastic analysis of structural elements made from laminated fiber composites of a brittle nature. This method is used to predict behavior beyond initial damage for a pressure vessel and also address the hole size effect. He suggests that use of this approach to address environmental effects still requires material characterization at the appropriate environments.

Barbero and Wen develop a methodology to estimate the strength of fiber-reinforced composite production components, utilizing minimal characterization data. Compression strength is related to shear strength and stiffness, and fiber misalignment, which is measured from actual production parts. The method is validated through comparisons with test data.

Environmental Effects

Lubke, Butkus, and Johnson study the long-term durability of a toughened epoxy used to bond graphite/bismaleimide composites. Test data are presented addressing the effects of temperature, environmental exposure, and adherend type on the toughness of these bonded joints. The combination of prior environmental exposure and low test temperature resulted in severe degradation of fracture toughness.

Reynolds and McManus present experimental observations of microcracking damage in PETI-5 and PIXA-M composites exposed to realistic hygro-thermal cycling. With these materials moisture cycling is shown to play a critical role in moisture distribution. Levels of moisture near surfaces and free edges exhibit a cyclic pattern, often with a benign level in the laminate interior. Time at moisture is the dominant factor in material degradation. For these materials damage is shown to be limited to the free edges.

Plenary Session

Starnes, Nemeth, and Hilburger in the final invited paper, present the results of an experimental and analytical study of the effects of initial imperfections on the buckling response of thin unstiffened graphite-epoxy cylindrical shells. The nonlinear finite element code is shown to account for accurately both traditional and non-traditional shell imperfections and load variations. It is proposed that the nonlinear analysis procedure can be used as a basis for a shell analysis and design approach.

Stinchcomb Lecture

Dr C. C. Poe (NASA Langley Research Center) who was the recipient of the Wayne Stinchcomb memorial award gave this lecture, which was not published in the STP. He reviewed a test program aimed at developing damage tolerance allowables for a stitched resin-film-infused material. The material was that used on the NASA Advanced Subsonic Technology (AST) Composite Wing Program, and consisted of IM7 and AS4 fibers in the 3501-6 resin, stitched transversely with Kevlar-29 thread. Tests were conducted in the three fiber directions, and on four different thicknesses to replicate the wing skin from tip to root. The configurations included compact, extended compact, and center notched tension specimens. Normal and shear strains were calculated on fracture planes using a William's type series representation of strain fields for plane anisotropic crack problems. A characteristic distance for ultimate tension and shear was calculated, and an interaction equation determined.

Panel Discussion

The panelists were Drs. Chris Chamis (NASA Glenn Research Center), John Hart-Smith (Boeing), Larry Ilcewicz (FAA), Paul Lagace (MIT), Jack Lincoln (USAF), and Jim Starnes (NASA Langley Research Center). The format included introductory remarks, five questions, to which each panelist had three minutes to respond, and one audience comment on each question. The following were the questions and related general comments.

1. Will composite structures experience more widespread aerospace use due to increased: (a) weight savings or (b) cost savings? Why? General consensus was that reduced cost is the one item that would lead to more widespread use of composites. Comment was made that the General Aviation industry was reducing cost relative to traditional aluminum structure through the use of composites.

2. Can the cost/cycle time of aerospace composite structural substantiation be significantly reduced? If so, by how much? If not, why? General response was yes. However, comments were made that there is not enough understanding of failure modes. We need better analysis methods, education of practicing engineers could be improved, and we need to share specifications.
3. What flight safety/damage tolerance issues will dominate composite structural airworthiness debates 20 years from now? What should we do now to address these issues? We have developed methods based on metals behavior and do not recognize the brittle nature of composites. We need a probabilistic approach to design. We need developments in NDE, and need to address the weak bond issue. Long term aging issues may become important.
4. What emerging analytical tools will be in widespread use 20 years from now, and what near-term initiatives should be pursued to enable their development? We need to develop computer stimulation of the fabrication process and couple this with the other issues. We need design/cost models from early design through to the end of lifetime. Knowledge regarding nonlinear effects in structures, and progressive failure analyses need to be developed. Education was again brought up as an issue. Development of artificial intelligence and self-diagnostic structures was mentioned. We need to solve production problems quickly.
5. How much standardization (of design guidance, test methods, material specifications, etc.) is appropriate for high performance composites, and why? We need to be careful when standards are cast in concrete (this was really emphasized), and must understand the standard. We need educated (education again !!) standardization. We need common databases and need to banish multiple purchase specifications (an example was given of 12 different purchase specifications for one material). We need standards for processes.

The session was moderated by C. Rousseau.

Summary

In summary, the editors feel that the papers in this STP reflect a good cross-section of the current state of the art in composite structures technology. The editors would like to thank the following session chairs for their advice and assistance and in seeing that the sessions rain in a smooth and professional manner:

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