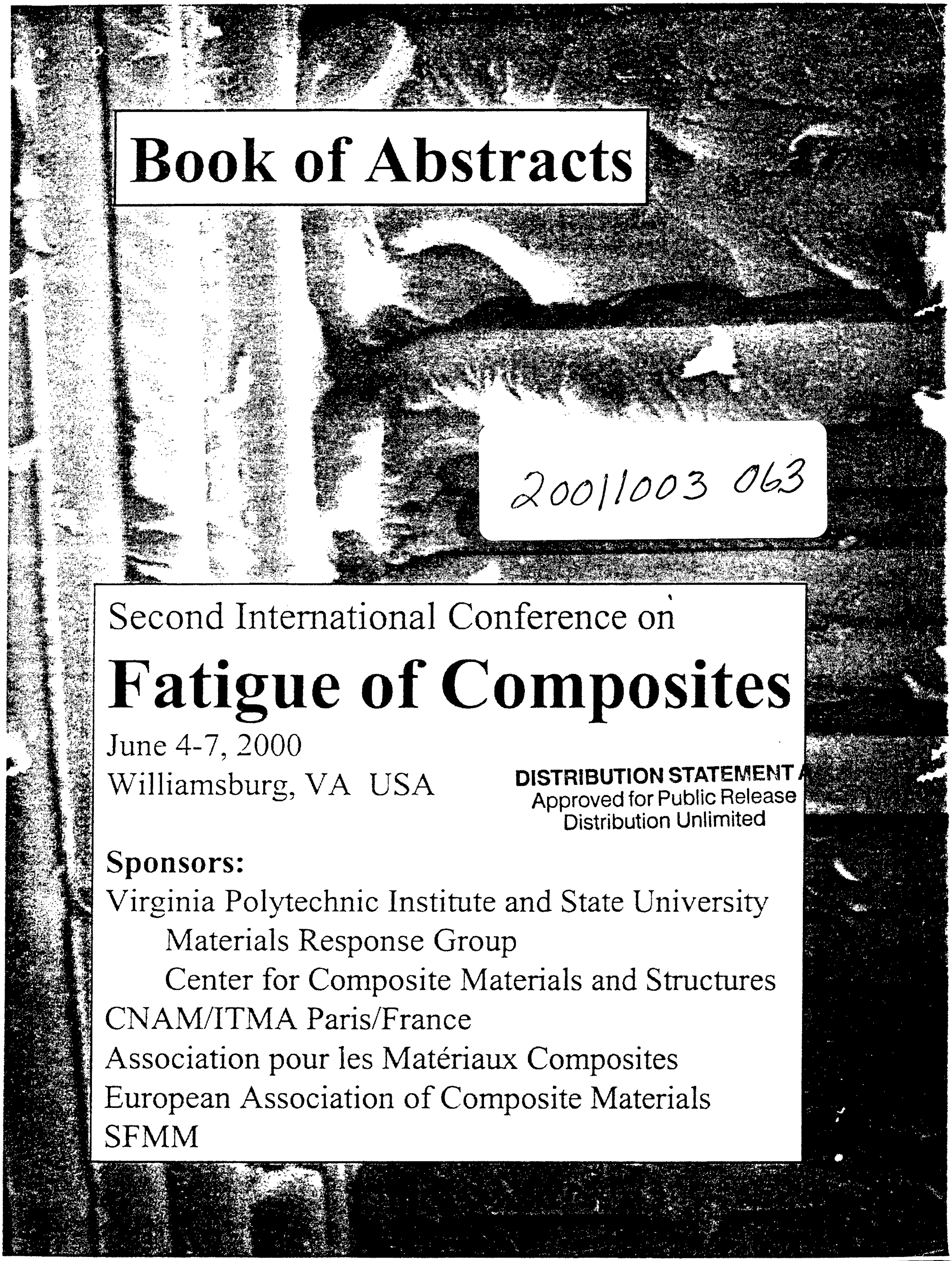

Book of Abstracts

Second International Conference on

Fatigue of Composites

June 4-7, 2000
Williamsburg, VA USA

Sponsors:

Virginia Polytechnic Institute and State University
- Materials Response Group
- Center for Composite Materials and Structures

CNAM/ITMA Paris/France
Association pour les Matériaux Composites
European Association of Composite Materials
SFMM

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13. ABSTRACT *(Maximum 200 words)*

On June 4-7, 2000, the Second International Conference on Fatigue of Composites was held in Williamsburg, Virginia, USA. The first such conference was held in June 1997 in Paris, France. The present conference built on that foundation, by providing a forum for a limited number of leading reports from numerous countries around the world to present and discuss the science and technology of this subject

Composite materials have "come of age" in the applied community. Dental materials, medical prosthetics, high performance turbines, fuel cells, and many other engineering systems are critically dependent on composite materials. Most of these applications involve applied environments that change with time, and many applications involve time- variable severe environments (mechanical, chemical, and thermal). Fatigue, as a discipline, has become the study of the changes in the properties and performance of materials and material systems as a result of the application of such time-variable applied environments. It was the intent of the organizing committee that this conference, the only one of its kind, bring together the world's best experts and convene the community of interested scientists and engineers to advance the field of Fatigue of Composite Materials.

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Second International Conference on Fatigue of Composites
Williamsburg, Virginia, USA

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The conference was highly successful, and all of the goals were met. Experts from 15 countries gathered at the Williamsburg Hospitality House for the conference. As a group, they were literally the core of the best scientists, engineers, faculty and students in the area of the fatigue of composite materials from around the world. The papers were consistently of high quality. Delegates to the conference represented universities, industries, and national organizations from essentially all of those countries. Session chairs, who organized the topical areas, came from the U.S., Canada, France, Spain, Belgium, Japan, and Germany. A banquet was held on the evening of the second day of the conference, with about 125 in attendance. The Keynote address for the banquet was given by Gene Camponeschi (U.S. Naval Surface Warfare Center) on the topic of "Meeting US Navy Ship Requirements with Composite Materials, Past, Present and Future." A book of abstracts was available at the meeting.

This conference was the result of much effort on the part of members of the local organizing committee, especially the Materials Response Group (MRG) at Virginia Tech. Co-sponsors of the event included the MRG, the Department of Engineering Science and Mechanics, and the Center for Composite Materials and Structures at Virginia Tech; the U.S. Air Force Office of Scientific Research; CNAM/ITMA; SFMM, and the Association pour les Materiaux Composites in France; and the European Association of Composite Materials. The next such conference is expected to be held in Germany, possibly at the University of Kaiserslautern.

Proceedings of the conference will be published as a special issue of the *International Journal of Fatigue*, published by Elsevier. Ken Reifsnider, General Chair of the conference, is Editor-in-Chief of that Journal. Virginia Tech has a record of strong leadership in the area of composite materials and fatigue of materials in general. The conference was an important feature of our leadership in those areas.

Preface

Second International Conference on Fatigue of Composites
Williamsburg, Virginia, USA

The abstracts that follow represent the research reported at the Second International Conference on Fatigue of Composite Materials. The first such conference was held in June 1997 in Paris, France. The present conference builds on that foundation, by providing a forum for a limited number of leading experts from numerous countries around the world to present and discuss the science and technology of this subject.

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Session 2: Damage Evolution and Environmental Effects — 2.0

Chairs: **Albert Cardon (Free Univ. of Brussels—BELGIUM)**
Alan Plumtree (Univ. of Waterloo—CANADA)

(Location: Westminister Ballroom B)

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Chairs: W. Steve Johnson (Georgia Institute of Technology—USA)
Javier Llorca (Polytechnic Univ. of Madrid—SPAIN)

(Location: Westminister Ballroom A)

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Dinner on Your Own

Tuesday, June 6

NOTE: Sessions run concurrently.

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Chairs: **Jack Lesko (Virginia Tech—USA)**
Chuck Bakis (Pennsylvania State Univ.—USA)
Nobuo Takeda (The Univ. of Tokyo—JAPAN)

(Location: Westminister Ballroom B)

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Chairs: Ken Reifsnider (Virginia Tech—USA)
Norbert Himmel (Univ. of Kaiserslautern—GERMANY)

(Location: Westminister Ballroom B)

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Chairs: **Norbert Himmel (Univ. of Kaiserslautern—GERMANY)**
John Whitcomb (Texas A&M Univ.—USA)

(Location: Westminister Ballroom A)

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12:15	LUNCH	

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Chairs: **E. T. (Gene) Camponeschi (Naval Surface Warfare Center—USA)**
Scott Case (Virginia Tech—USA)

(Location: Westminister Ballroom A)

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Chair: Didier Baptiste (ENSAM—FRANCE)

(Location: Westminister Ballroom A)

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Wednesday, June 7

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Chairs: **Rajiv Naik (Pratt and Whitney—USA)**
Ramesh Talreja (Georgia Institute of Technology—USA)

(Location: Westminister Ballroom B)

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Chairs: **Jack Lesko (Virginia Tech—USA)**
Vasyl Harik (Univ. of Delaware—USA)

(Location: Westminister Ballroom B)

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12:15	LUNCH	

Session 1: Matrix Cracking and Delamination

Fatigue Initiation and propagation in natural and synthetic rubbers

C. BATHIAS – CNAM PARIS
K. LE GORJU HUTCHINSON – CHALETTE SUR LOING

Elastomeric matrix composites are usually reinforced by mineral particles such as carbon black and sometime by long metallic or organic fibers. In absence of fiber, rubbers can be considered as nanocomposites.

In service conditions, the fatigue damage of rubbers is a combination of:

- Mechanical damage
- Chemical damage
- Thermal damage

Experience shows that, in cycle loading, rubbers are damaged to the point of formation of one or several cracks which then propagate. As for metal, it is recommended to study separately initiation of cracks and then their propagation. Generally speaking, the fatigue resistance is affected by chemical transformation such as crystallisation. It means that compression loading is an important factor. To show this effect, an axisymetric hour - glass shape specimen (D=25 mm) is proposed to test rubbers. It has been found a large effect of the mean stress on the fatigue strength depending of the chemical composition of the materials and of crystallisation transformation if it appears.

The crack growth rate is studied using linear fracture mechanics as proposed earlier by Rivlin and Thomas. In this case, the strain energy release rate G is substituted for the concept of tearing energy T. The application of fracture mechanics to elastomers generates some difficulties because of the important deformability.

In order to apply a tension-compression loading a thick edge notched specimen is recommended with two lateral grooves (W = 150 mm, B = 25 mm). For low values of ΔT, a threshold can de defined depending of R ratio. It is shown that for high R ratio the fatigue crack would not propagate if the crystallisation transformation is high. At the contrary, if R = -1, the threshold disappears.

A finite element simulation of stresses and strains is presented in order to get a better explanation of the experimental results.

Damage Mechanics Characterization of Transverse Cracking Behavior in Quasi-Isotropic CFRP Laminates with Interlaminar-Toughened Layers

Nobuo Takeda[1)], Satoshi Kobayashi[2)], Shinji Ogihara[3)] and Akira Kobayashi[3)]

Microscopic damage behavior in quasi-isotropic CFRP laminates under tensile fatigue loading is investigated. Damage observation is conducted by using an optical microscope and a soft X-ray radiography. A material used is CFRP with interlaminar-toughened layers, T800H/3900-2, supplied by Toray Inc. The T800H/3900-2 prepreg system has tough and fine polyamide particles on its surfaces, which results in formation of the interlaminar-toughened layers at every ply interface in the laminates. The fiber volume fraction is about 55%. GFRP tabs are glued on the specimens. The laminate configurations are quasi-isotropic $[0/45/90/-45]_s$, $[45/0/-45/90]_s$, $[0/45/-45/90]_s$ and $[45/-45/0/90]_s$ to discuss the effect of stacking sequence on microscopic fatigue damages.

Tensile fatigue tests are run at the stress ratio, R=0, a frequency of 5Hz and with a sine waveform under load control conditions. The maximum stress levels are selected as 80%, 60% and 40% of the static tensile strength of each laminate. During the tests, the testing machine is periodically stopped, and the onset and growth of transverse cracks and delamination are observed by an optical microscope and a soft X-ray radiography. By the edge observation, transverse crack density is measured as a function of the number of stress cycles. By the X-ray observation, delamination onset and growth in the width direction are detected.

To discuss the difference in transverse cracking behavior due to the difference in laminate configuration, the damage mechanics analysis is used. The energy release rate associated with transverse cracking is derived by using the damage mechanics analysis. The Paris-law analysis proves to be valid for the characterization of transverse crack multiplication when the effect of other damage is small.

[1)] The University of Tokyo

[2)] Graduate student, The University of Tokyo

[3)] Department of Mechanical Engineering, Science University of Tokyo, Yamasaki, Noda, Chiba 278-8510, Japan

TITLE : **FATIGUE CRACK PROPAGATION IN CONTINUOUS GLASS FIBER/POLYPROPYLENE COMPOSITES**

AUTHORS : **M. N. BUREAU*, F. PERRIN†, J. DENAULT* AND J. I. DICKSON†**

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The fatigue crack propagation behavior of unidirectional continuous glass fiber/polypropylene (GF/PP) composites made from pre-impregnated tapes has been studied. Fatigue crack growth rates plotted against the strain energy release rates were obtained using the end-notch flexure (ENF) geometry, the double-cantilever beam (DCB) geometry and the compact tension (CT) geometry. Comparative results revealed the primordial influence of the fiber-matrix interface and the matrix morphology on the crack growth resistance. The distribution of a ductile amorphous PP phase in the crystalline PP matrix appears to be the controlling parameter determining the crack growth resistance in GF/PP composite studied. Fractographic observations clearly showed the role of this phase during fatigue crack propagation. The processing conditions are related to the microstructure of the composite and the resulting mechanical performance.

MODE I AND II DELAMINATION FATIGUE CRACK GROWTH BEHAVIOR OF ALUMINA FIBER/EPOXY LAMINATES IN AIR AND IN LIQUID NITROGEN

Masaki HOJO*, Satoshi MATSUDA**, Bodo FIEDLER*, Shojiro OCHIAI* and Hiroshi AOYAMA***

* Mesoscopic Materials Research Center, Graduate School of Engineering, Kyoto University, Kyoto 606-8501, Japan
** Department of Chemical Engineering, Himeji Institute of Technology, Himeji 671-2201, Japan
*** Mechanical Engineering Laboratory, Hitachi, Ltd, Tsuchiura 300-0013, Japan

ABSTRACT

Alumina fiber(ALF)/epoxy composites are possible candidates for the structural components of superconducting magnets because of their low thermal conductivity in addition to their higher specific strength and modulus. Since laminate structures are applied to the load support system for superconducting magnets, the evaluation of interlaminar strength both under static and fatigue loadings at cryogenic temperature is essential from the view point of structural integrity.

In the present study, mode I and II interlaminar fracture toughness and delamination fatigue crack growth behavior were investigated with unidirectional ALF/epoxy laminates. The fracture toughness values at 77K were higher than those in laboratory air at room temperature (RT) both under mode I and II loadings.

The fatigue crack growth under mode I loading was rather controlled by the maximum load, and its contribution was higher at 77K (Fig. 1). The fatigue fracture mechanism under mode II loading at 77K was controlled by the maximum load, and was completely different from that at RT where the crack growth was rather controlled by the cyclic load (Fig. 2). Then, the increase of the fatigue crack growth resistance at 77K from that at RT was observed only under stress ratio, R=0.1.

The difference of the fatigue fracture mechanism due to the test temperature and the loading mode was discussed on the bases of microscopic fracture mechanism considerations. The remarkable change of the fracture mechanism under mode II loading from RT to 77K was responsible for the above mentioned difference of the controlling fracture mechanical parameter,

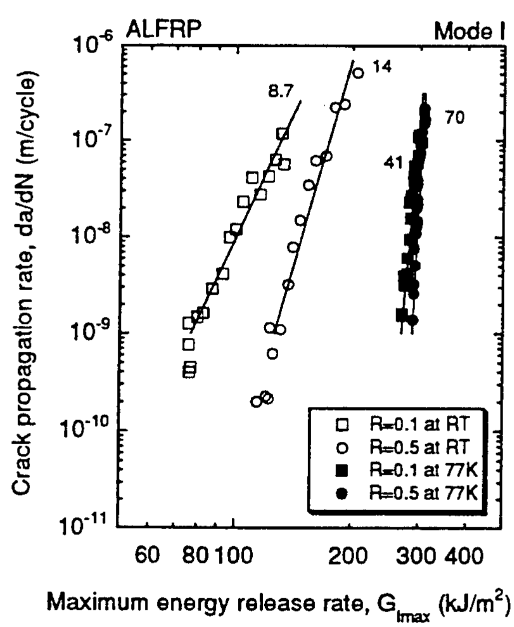

Fig. 1. da/dN-G_{max} relation under mode I at RT in air and 77K in liquid nitrogen.

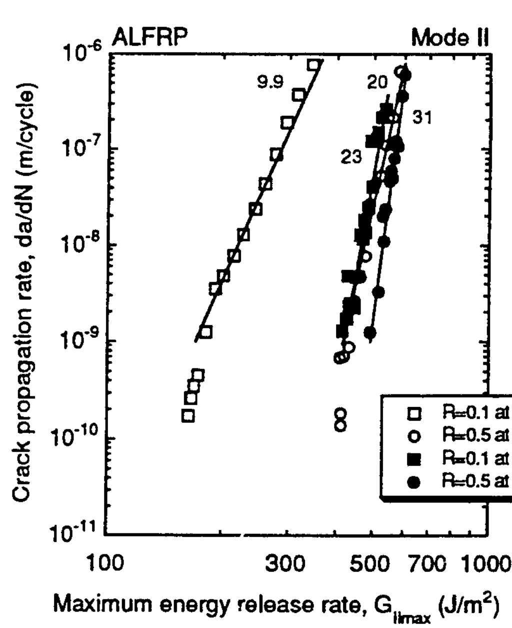

Fig. 2. da/dN-G_{max} relation under mode II at RT in air and 77K in liquid nitrogen.

MATRIX CRACKING AND FAILURE OF GLASS FIBER REINFORCED EPOXY TUBULARS UNDER BIAXIAL CYCLIC LOADING

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Abstract

Fiber reinforced composite piping and downhole tubing are seen as an attractive alternative to products made from conventional materials due to their corrosion resistance and light weight. The reluctance in adopting composite materials, however, is due to a limited understanding of their long-term behavior and failure characteristics. The purpose of this study is to investigate the leakage behaviour of glass fiber reinforced epoxy tubes under monotonic and cyclic biaxial loading. Biaxial monotonic and cyclic tests were performed on $[\pm 45°]_S$ tubular specimens in the tensile-tensile biaxial regime. Leakage failure stress, failure locations, and macroscopic failure modes were found to be dependent upon the applied biaxial loading ratio and loading type (monotonic versus cyclic). While monotonic tests were seen to fail by abrupt leakage (burst), all cyclic tests failed by weepage. Matrix damage accumulation, as measured by cyclic creep strain and elastic stiffness reduction, was compared to leakage initiation life. Although leakage was seen to occur after the initial crack saturation, no distinct correlation was found between leakage initiation life and the measured damage parameters.

Multi-Directional Stiffness Degradation Induced by Matrix Cracking in Composite Laminates

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Based on the multi-directional damage theory presented in this paper, a model for the prediction of the stiffness degradation of composite laminates induced by matrix cracks is proposed, which focuses on the study of elastic properties of laminates before character damage state (CDS) defined by Talreja, R. and Reifsnider, K. L. From fracture mechanics the load transfer from the ply containing cracks to virgin ply is found, and then the relationship between stiffness degradation of basic matrix cell which contained a single crack under the general stress state (σ_L, σ_T, τ_{LT}) and the cracks density is found. Here the stiffness property includes E_L,E_T, and G_{LT}.

Forward the model set up for a cell is extended to the relationship between the stiffness property of a ply and the evolution of cracks in the matrix by application of the finite element method (FEM). As the stiffness degradation of laminates differ from each, so the stress of laminates will be redistributed. Then the load of laminates was recalculated and the stiffness of the whole composite laminates degraded due to the cracks is predicted. Since the material properties under general stress states are given, this model can be used to predict the fatigue properties of multidirectional laminates. Two examples are presented in this paper to demonstrate the capacity of prediction, and shows that prediction is in a good agreement with the experimental E-modulus data for glass fiber reinforced epoxy composite laminates under cyclic loading.

Key words: Multi-directional damage, Stiffness degradation, Matrix crack, CDS

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INFLUENCE OF SPECIMEN PREPARATION AND SPECIMEN SIZE ON TRANSVERSE TENSION FATIGUE CHARACTERIZATION FOR GLASS EPOXY COMPOSITES

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ABSTRACT: The influence of specimen polishing and specimen configuration on transverse tension fatigue life of glass epoxy lamina loaded in three and four point bending was examined. Specimens are often polished before mechanical testing to remove inherent manufacture and handling flaws. This technique has been shown to improve results when testing metals, but the effect of this procedure has not yet been evaluated for composite materials. Results showed that specimens with polished machined edges and tension-side bending failure surfaces had lower fatigue lives than unpolished specimens when cyclically loaded at equal stress levels. Fatigue life was also sensitive to testing configuration, where fatigue life decreased as the volume of material subjected to maximum tensile stress increased, due to the classical weakest link effect.

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Session 2: Damage Evolution and Environmental Effects

MODELLING OF FATIGUE BEHAVIOUR OF LAMINATED COMPOSITE MATERIALS

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This paper propose a model to characterize the fatigue behaviour of laminated composite structures when they are submitted to different loading level tests. Using observations at different scales in the material, we show that the different types of damage appear physically and geometrically in the same way under static and cyclic loadings. In that case, it is possible to use a formulation already developed for static loadings and to extend it to the cyclic case. Experimental data are used to describe the cumulative damage process leading to a damage law. After identification of the constants of the model, we propose the numerical simulation of two-level fatigue tests on a cross-plied specimen. The results are compared with the associated experimental tests.

FATIGUE DAMAGE EVOLUTION IN OFF-AXIS UNIDIRECTIONAL CFRP

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ABSTRACT

Fatigue life and microscopic damage mechanisms have been evaluated for a unidirectional carbon fibre reinforced epoxy matrix composite under off -axis cyclic bending. Optical and scanning electron microscopy was used to observe the development of cracks. There was a large variation in fatigue life for the same applied maximum normal stress. The scatter was found to be dependent upon the ease with which coalescence of microcracks took place. Damage was also assessed from changes occurring in the elastic modulus and the energy absorbed per cycle. Of the two, the latter displayed more variation during the matrix cracking.

Microcrack initiation associated with stress concentrations arising from fibre-matrix stress and strain field interactions were observed. These cracks usually started along the fibre axis.

Two types of damage evolution were observed and these were related to the microcrack density. Type I damage evolution was associated with a low microcrack density since interfacial and matrix cracks which formed early coalesced quickly. Consequently the fatigue life for a given stress level was short. The basic feature for Type II damage was the presence of randomly distributed coplanar and wavy microcracks, particularly in the resin rich areas. In this case, coalescence was delayed and the subsequent fatigue life was much longer.

Keywords: Fatigue life, damage-life diagram, S-N curve, CFRP, microcrack density, energy absorbed per cycle, *SEM and optical microscopy.*

Effects of Loading Frequency and Environment on Delamination Fatigue Crack Growth of CFRP

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The delamination crack growth behaviors under iso-thermal and thermo-mechanical fatigue were investigated with unidirectional CF/epoxy laminates (Toray P3060-15). Thickness of the laminates was 8 mm. Initial notch was introduced by inserting Teflon film between prepregs. Tests were conducted either in air or in water. DCB and ENF specimens were employed for Mode I and Mode II fatigue crack growth tests, respectively. The crack growth tests were conducted under constant ΔK conditions.

Mode I fatigue crack growth

During constant ΔK tests, the loading frequency was changed to examine the effect of loading frequency on crack growth rate in air. Independent of the loading frequencies, the cycle-based crack growth rate was almost constant, and it can be concluded that Mode I fatigue crack growth is cycle dependent in air. In water, however, the time-based crack growth rate was independent of the loading frequencies, and the Mode I fatigue crack growth is considered to be time dependent in water.

Under variable test temperature, the crack growth rate drastically decreased when the test temperature decreased from higher than 50 °C to lower than 50 °C. The crack growth behavior was not affected by other type of temperature change.

Thermo-mechanical fatigue tests were conduced either in air or in water. The highest test temperature was 70 °C and the lowest test temperature was 35 °C. The fatigue crack growth rates, da/dN, in thermo-mechanical fatigue at the stress ratio, R, of 0.5, the crack growth rates in out-of-phase fatigue test were higher than those in in-phase fatigue test. Under iso-thermal fatigue loading at 35 °C or 70 °C, crack growth rates were too high to measure, *i.e.*, specimens fractured just after starting fatigue tests at ΔK of 0.52 MPam$^{1/2}$. It means that the crack growth rates in both types of thermo-mechanical fatigue tests were lower than those in iso-thermal tests in air.

The delamination fatigue crack growth rates for R = 0.1 were not constant with crack extension. It indicates that the crack tip shielding by fiber bridging is larger for lower stress ratio. The growth rates in both types of thermo-mechanical fatigue were lower than the lowest growth rates for iso-thermal tests. The growth rates under in-phase thermo-mechanical fatigue were lower than under out-of-phase thermo-mechanical fatigue. These behaviors are the same as those at R=0.5.

In water, the crack growth rates for the iso-thermal fatigue tests were higher for lower temperature in water. The rates for the themo-mechanical fatigue test were almost the same value as those for the iso-thermal fatigue test whose test temperature was equal to that at the maximum load for the themo-mechanical fatigue test.

Mode II Fatigue Crack Growth

Since time-based crack growth rate, da/dt, was independent of the loading frequencies, the Mode II fatigue crack growth is considered to be time dependent either in air or in water.

The growth rate at 25 °C was higher than that at 70 °C. Contrary to Mode I Fatigue crack growth, no effect of test temperature change was observed in Mode II fatigue crack growth.

Effects of temperature on delamination growth in a carbon/epoxy composite under fatigue loading

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The interlaminar fracture and fatigue properties of HTA/6376C carbon/epoxy at room temperature and at elevated temperatures will be discussed. Delamination growth in mode I, mode II and mixed mode under fatigue loading has been studied at room temperature, and the same tests are now carried out at elevated temperatures. The tests at room temperature revealed high slopes of the modified Paris plots, and threshold values of the strain energy release rate for delamination growth were therefore determined. For the pure mode II loading the fatigue threshold was found to be only 10% of the critical strain energy release rate in static tests.

Fractographic analysis of the failure surfaces by scanning electron microscopy gave insights into the micromechanisms of delamination growth. The fracture surfaces generated in fatigue loading at room temperature were similar to the ones in static loading at room temperature for all three load cases (mode I, mode II and mixed mode). The low fatigue threshold for the pure mode II loading was explained by microscopical observations of the specimen edges. In static loading shear cusps formed at the specimen edges at load levels well below those required for delamination growth in a static test. However, the shear cusps only formed in the vicinity of the edges, due to the high strain energy release rate at the specimen edges, and it could therefore be argued that the ENF specimen is not appropriate for determination of fatigue threshold values of the strain energy release rate.

As mentioned above, the tests at elevated temperatures are on-going. When these tests are ready, the slopes of the modified Paris plots, threshold values, shear cusp formation, amount and size of matrix rollers, etc will be compared to the results from the room temperature tests.

Interactions between cyclic loading and creep in polymer matrix composites

A.H. Cardon & P. Bouquet

Polymer matrix composites exhibit local and anisotropic, global time dependent effects. That viscoelastic-viscoplastic behaviour is strongly influenced by environmental parameters such as temperature and moisture diffusion. As consequence the application of those polymer related material systems in structural components is only realistic if we are able to predict the life time durability and residual structural integrity after an imposed loading history. The viscoelastic-viscoplastic behaviour is important under quasi static loading conditions and not so crucial for pure fatigue loading.

As was shown by Bax, [1], and later by Qin, [2], the interaction between static loading and some cyclic loading may result in the acceleration of the creep evolution, related to the introduction of some damage. This interaction can be predicted by some viscoelastic-viscoplastic damage model, as proposed by Cardon et al., [3].

In order to study this accelerating effect, combined static and cylic loading were applied on a unidirectional reinforced graphite epoxy system (920C-TS-5-42 CIBA-GEIGY, now Hexcel), in the transverse direction, $[90]_8$, and on laminates, $[\pm 45,(90)_2]_S$.

The laminates were tested under uniaxial and biaxial loading conditions. The strain and damage evolution was followed by different non destructive inspection methods.

The results of those tests will be presented and the influence of the cyclic loading on the creep behaviour will be discussed.

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Authors' Names:

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Title of Paper:

Influence of Molecular Variables on the Durability of a Thermoplastic Glassy Polyimide

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ABSTRACT: Durability and long-term performance are among the primary concerns for the use of advanced polymer matrix composites (PMCs) in modern aerospace structural applications. For a PMC material subjected to long-term exposure at elevated temperatures, the viscoelastic nature of the polymer matrix will contribute to macroscopic changes in composite stiffness, strength and fatigue life. Over time, changes in the polymer due to *physical aging* will have profound effects on the material's viscoelastic compliance, hence affecting its long-term durability. It would be advantageous, therefore, if structural designers and material developers could accurately account for physical aging and elicit a desired macroscopic mechanical response from the material by optimizing specific parameters at the microscopic level.

Towards this end, an experimental study was undertaken to compare the effects of two material-level parameters: molecular weight and crosslink density on the viscoelastic behavior and physical aging of an advanced polymer. Five distinct variations of each parameter were used to evaluate the differences in mechanical performance of a glassy thermoplastic polyimide. The physical aging behavior was isolated by running sequenced, short-term isothermal creep compliance tests in tension. These tests were run over a range of sub-glass transition temperatures. The material constants, material master curves and aging related parameters were evaluated using time/temperature and time/aging-time superposition techniques.

Although aging shift rate was relatively insensitive to the changes in molecular weight, it was shown that the time-temperature superposition shift rate was a strong function of molecular weight, exhibiting a critical molecular weight transition about $\overline{M}_w$~22000 g/mol. The molecular weight variations provided information about the dominant microstructural mechanisms with the high molecular weight materials deforming in a ductile manner but exhibiting brittle failure, with the antithesis for the lower molecular weights. The crosslink density variations provided information about network structure imperfections.

The viscoelastic model was used to make long-term predictions of compliance including the effects of physical aging. Accuracy of the long term predictions was attributed to the sensitivity of the aging shift rate to temperature, indicating that other mechanisms can affect aging rather than the volumetric changes induced by enhancing the molecular mobility through acceleration by temperature. Optimization of long-term durability through changes in the material parameters will be discussed and specific examples based on the experimental data will be presented.

Key Words: physical aging, molecular weight, crosslink density, viscoelasticity, composites.

Enviro-Mechanical Durability of Polymer Composites

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Abstract

The objective of this project was to evaluate and model the effects of moisture, temperature, and combined hygrothermal aging on the durability of a graphite/epoxy woven composite material system. Durability studies were carried out on a woven graphite/epoxy system. This particular composite material is targeted at applications in areas of the aircraft industry where operating environment is of concern. For instance, the material system would serve well in an aircraft engine where operating temperatures and moisture conditions differ from storage temperatures and moisture conditions. In order to make use of such a material in aircraft design, however, designers must be able to estimate the strength and life of the material as a function of operating conditions. Therefore, fatigue and residual strength testing was carried out on the composite material in question with the objective of developing a residual strength based life prediction model. Testing was conducted at an elevated temperature of 120°C (typical engine operating temperature) and at a moisture condition of 85% relative humidity at 29°C (typical aircraft storage condition). In addition, in an effort to simulate the alternating operating and storage conditions that would be imposed on the material as part of an aircraft engine, fatigue testing was also conducted in conjunction with alternating temperature and moisture conditions. A life prediction approach based on ideas given by Reifsnider and colleagues [1, 2, 3] was to be developed which accounted for changing moisture and temperature conditions during fatigue loading. In this case, the approach called for the evaluation of the effect of fatigue at each individual environment on the strength of the material. The results could then be combined to predict the fatigue life of the material under periodically changing environments. To this end, the experimental portion of the study required that residual strength be determined for material fatigued under the moisture and thermal conditions separately. To verify the life prediction, residual strength data was also collected for material fatigued in conjunction with moisture/thermal (hygrothermal) cycling. Results presented in this work will be focused on material previously aged (in an unstressed condition with) hygrothermal cycling to study the effects of aging on the fatigue life of the composite. Damage mechanisms and failure modes were determined through fatigue testing, residual strength testing, and nondestructive evaluation.

Experimental testing showed that the initial and residual tensile properties and fatigue life of unaged material were virtually unaffected by any of the imposed environmental conditions. However, fatigue damage progression and accumulation were found to vary with temperature and with different fatigue stress levels. In general, the major fatigue damage mechanisms included transverse cracking, delamination and longitudinal microcracking at fiber bundle undulation regions, and interply delaminations. Transverse cracking and delamination increased with fatigue cycles throughout most of the fatigue life of the material. The major quasi-static damage mechanism was transverse cracking.

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Bolt Bearing Fatigue of Polymer Matrix Composites at Elevated Temperature

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Composites are being considered for a number of high temperature applications (350F). Joining polymer matrix composites to be used at high temperatures in highly loaded structures may be challenging. Mechanical fasteners have been used for many years to join composites. However, the bolt bearing fatigue behavior at high temperatures, significant loads for a long period of time needs to be studied. Thus is the purpose of this research.

A 64 ply thick quasi-isotropic laminate of IM-7/PETI-5 composite was studied. The matrix material is a thermoplastic. The paper will present bolt bearing fatigue data taken at 350F and two different stress ratios and three different cyclic frequencies. The paper will also discuss two different specimen designs: one more traditional pin load transfer and the other a push on the bolt type. Advantages and disadvantages of each are discussed. Fatigue damage mechanisms are documented using radiography.

THE EFFECTS OF STRESS RATIO AND TEMPERATURE ON THE OPEN-HOLE FATIGUE BEHAVIOR OF ADVANCED POLYMER MATRIX COMPOSITES

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ABSTRACT

One of the critical technical issues for the realization of the supersonic transportation (SST) is to ensure the long-term high temperature structural integrity of advanced polymer matrix composite system. This research has been conducted as a part of long-term durability performance of composite and structures in Japan Supersonic Research Program for 2nd Generation Supersonic Civil Transport. The final goal is achieved through long-term and short-term tests under conditions simulating SST flight, development of associated predictive and accelerated test methods, and assessment of durability performances for design. This paper is focused on open-hole fatigue behavior for the interesting and candidate composite materials.

The materials chosen for this research are carbon fiber reinforced, toughened BMI, G40-800/5260, and thermoplastic polyimide, IM600/PIXA-M and thermosetting polyimide, MR50K/PETI-5, quasisotropic $[-45/0/+45/90]_{4s}$ symmetrical laminates. The response to stress ratio R=0.05(tension/tension), R=-1(fully reversed, tension/compression) and R=20(compression/compression) loading has been investigated at a room temperature and 177□ in a dry air by examining their fatigue lives, damage initiation and propagation, and their residual fatigue strength. Cyclic stress-strain curve and stiffness measurements indicate a significant difference in the response of these materials depending on the stress ratio and stress level. There is also quite an influence of test temperature on fatigue lives. This difference in the response suggests that fatigue damage initiation and propagation mechanisms play different roles in defining fatigue life. Finally, the possibility of predicting the residual fatigue lives is discussed in detail using the integrated modeling and simulation techniques on the basis of fatigue damage mechanism.

Session 3: Metal Matrix and Composite Systems

MICROMECHANICAL MODELLING OF THE FATIGUE BEHAVIOUR OF METAL MATRIX COMPOSITES

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ABSTRACT

In order to increase resistance of materials used in structural parts, a lot of researches have been carried out to include reinforcement with proper compatibility. The manufacturing processes of metal matrix composites with discontinuous reinforcement, induce an high heterogeneity of the microstructure which influence the mechanical properties. Prediction tools need to be developped in order to take into account the effect of the microscopical parameters on the mechanical response of the composite. In this way, a micromechanical modelling of heterogeneous media for fatigue loadings, is presented here.

The mechanical properties of the composite are calculated on the basis of the classical Eshelby inclusion problem. For non-diluted solutions, the interaction between inclusions is introduced and the comparison material is made of pure matrix. Applying a uniform strain field on a Representative Volume Element that describe the whole heterogeneity of the composite, average stress and strain fields in the phases are obtained with the Mori & Tanaka mean field theory [1]. The extension in elastoplasticity is achieved with an incremental method, using tangent stiffness tensors and derived relations, following Hill's approach [2].

Since the inclusions are ellipsoids and remain elastic, the plasticity of the matrix is solved with the consistency equation and the flow rule. The calculation is based on the non-linear kinematic model involving internal variables as developed by Lemaitre & Chaboche [3], introducing both isotropic and kinematic hardening of the matrix. This allows fatigue loading predictions on a macroscopic scale, taking into account microscopic cyclic hardening or softening of the metallic constituent. The numerical resolution of the constitutive equations is inspired by the works of Burlet & Cailletaud [4]. The radial return method is used for local integration in the matrix and the REV equilibrium is assumed by iterations : instantaneous localisation tensors and tangent stiffness tensors are calculated again at each step with an isotropic approximation.

Therefore, for each macroscopic strain increment, average plastic strain increment in the matrix is known and homogeneisation provides the average stress increment in the composite.

The composite material is constituted by a Al - 3,5% Cu alloy matrix, reinforced by Al2O3 short fibers with different volume fractions. The isotropic and kinematic hardening parameters of the matrix are identified on the FEM calculated hysteresis loops for a composite with 13% of particulates, since a simple tensile test is not sufficient to determine the cyclic behaviour.

The calculated cyclic stress-strain curves are in good agreement with the experiments and the micromechanical model leads to good stabilisation of the cycles.

The loading path within the matrix can be pointed out, showing the multidirectional stress state. The influence of volume fraction on the plastic strain amplitude in the matrix is of interest for predicting behaviour in higher cycle fatigue. The tension / compression stress state is then compared between particulates and matrix during a cycle.

Predictions of the hysteresis loop for a randomly oriented short fibers composite, A356 / Al_2O_3 fiber are shown. Influence of fiber orientation distribution illustrate the sensitiveness of the model with respect to the microscopic description and morphology of the constituents.

It has been observed that damage occurs during loading and plays an important role on the lost of stiffness and the number of cycle at failure.

The damage mechanisms are identified at the reinforcement scale, by in situ tensile tests made inside a scanning electronic microscope. They are modelled and integrated in our model, at the micro scale. This approach leads to three dimensionnal behavior law taking into account damage evolution.

To identify the local damage law at the micro scale, tensile tests are performed inside the S.E.M.. For a given load, the number of cracks in the particles is dertermined. The measurment of the cracks density evolution with the applied strain leads to the identification of the stastistical damage law taking into account the scatter of the microstructure. For an Al-Al2O3 composite under tensile load, we predict with our model the evolution of the number of broken fibers with the load.

To model the damage evolution, the broken fibers are removed from the composite and replaced by new penny shape inclusions. By an incremental procedure, it is possible to build the entire hysteresis loop, simulating a macroscopic fatigue test. The stiffness tensor of the composite and its evolution with damage is then modelled and is in good agreement with the experimental values. The evolution of the anisotropy due to damage has been shown.

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INFLUENCE OF THE REINFORCEMENT MORPHOLOGY AND THE MATRIX STRENGTH OF METAL-MATRIX COMPOSITES ON THE FATIGUE BEHAVIOUR

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Since fatigue failure is the most propable cause of damage in technical applications, it is important to know the influence of the material properties and the service conditions on the fatigue behaviour. Using metal-matrix composites (MMC) instead of unreinforced alloys, the governing parameters, like volume fraction or reinforcement morphology and size, can be varied. The present study deals with the dependence of matrix strength and reinforcement shape, respectively, on the low-cycle fatigue behaviour of MMCs in a wide temperature range.

The low-cycle fatigue behaviour of the composites AA6061-T6 reinforced with 20 vol.% alumina particles and short fibres, respectively, and pure aluminium reinforced with short fibres has been investigated at temperatures between T = -100 °C and T = 300 °C. The symmetrical push-pull fatigue tests were carried out in total-strain control mode at a constant strain rate with applied total-strain amplitudes between $\Delta\varepsilon_t/2$= 0.001 ... 0.01.

The comparison of the cyclic with monotonic stress-strain curves established both cyclic hardening and cyclic softening, depending on the applied strain range and on the test temperature, respectively. While in the case of the highest temperature of T = 300 °C, all composites exhibit pronounced cyclic softening, this behaviour is different at lower temperatures. Cyclic softening was only found at low levels of strain amplitude for the composites with the precipitation-hardened matrix alloy. With increasing strain amplitudes, cyclic hardening was found.

The cyclic deformation curves show initial cyclic hardening for a few cycles and subsequently cyclic softening until fatigue failure. The amount of initial cyclic hardening was more pronounced for the short fibre reinforced samples and at higher applied total strain amplitudes, respectively.

The difference of shape (particles and short fibres) at comparable volume fractions of the reinforcements and for a given matrix influences the fatigue life more than the strength of the composites. The particulate reinforced material exhibits longer fatigue lives than the short fibre reinforced alloy for all applied total strain amplitudes and temperatures, respectively.

Comparison of the composite with a soft matrix (pure aluminium) with that with the peak-aged matrix, both reinforced with short fibres, shows that the decrease of the matrix strength (and thus the lower strength of the composite) leads to an extension of the fatigue life at higher strain amplitudes. With increasing temperature the life times of both composites become more similar.

The results of the experiments and of the accompanying microstructural investigations reveal the influence of matrix strength and reinforcement morphology on the low-cycle fatigue damage and failure of metal-matrix composites.

Experimental and numerical study of the low-cycle fatigue behaviour of a cast metal matrix composite

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Abstract

The uniaxial mechanical behaviour of a particulate reinforced metal matrix composite, AS10U3NG + 10%Vol.SiC_p, has been studied experimentally and numerically. The experimental study was carried out using a fatigue testing machine in situ in a scanning electron microscope. This testing device allows to follow the evolution of the surface damage in low-cycle fatigue regime. Interfacial debonding between aluminium alloy matrix and particles, reinforcement and precipitate fracture were observed during cycling. Fracture surface observations revealed small dimples, particle-matrix debonding and broken particles in the final fracture region. All these damage mechanisms were incorporated in an axisymetric unit cell model, with the aim of predicting the uniaxial low-cycle fatigue behaviour ($R_\sigma = -1$) of the composite, thanks to a finite element analysis. Calculations were conducted without and with initial thermal residual stresses resulting from cooling, due to the mismatch between the thermal expansion coefficients of the two phases. The matrix ductility, corresponding to void nucleation and growth, was taken into account using the Gurson model. The numerical study exhibits also the effect of volume fraction, of particle size (in the case of particle fracture) and of aspect ratio on the micromechanical and homogeneized behaviour of the composite.

ELEVATED TEMPERATURE FATIGUE OF DISCONTINUOUSLY-REINFORCED METAL-MATRIX COMPOSITES: A REVIEW

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The dispersion of ceramic reinforcements in metallic matrices increases the elevated temperature strength as well as the creep resistance. This was a good starting point to use DRC in structural components operating at elevated temperature and subjected to cyclic loads (e.g. connecting rods and cylinder liners). As a result, the fatigue performance of these composites at elevated temperature was studied in detail, The results of these investigations constitute a fairly coherent body which is reviewed here.

The paper is divided in four sections. The first one describes the micromechanisms of cyclic deformation in these composites at elevated temperature from the mechanical and the microstructural viewpoints. The second and third sections are devoted, respectively, to analyze the nucleation and propagation of fatigue cracks. These results are used to rationalize in the last part the overall fatigue performance at elevated temperature under high-cycle and low-cycle fatigue conditions as well as thermo-mechanical loading. The advantages and limitations of the composites in respect to the traditional metallic alloys are emphasized as well as future developments to optimize their fatigue behaviour.

Observations of Fatigue Damage Process of SiC/SiC Composites at Room and Elevated Temperatures

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ABSTRACT

Two-dimension-woven Chemical-Vapor-Infiltrated-SiC/SiC is suitable for high temperature structural applications due to its superior high temperature properties. The SiC/SiC composite is reinforced by long fibers which result in high fracture-resistance. Pull-out and fiber bridging are main toughening mechanisms in this composite based on the previous studies. However, fatigue damage processes and method for evaluating fatigue damage have not yet been clear.

In this work, fatigue tests were carried out to study fatigue mechanisms of SiC/SiC composite material. Two kinds of materials were tested: One is "Enhanced SiC/SiC" with boron additive for enhancing the high temperature crack growth resistance. The other is "Standard SiC/SiC". In-situ observation by SEM (Scanning Electron Microscope) has done during fatigue test at room and high temperatures to investigate fatigue crack initiation and growth behaviors. Fatigue tests were conducted under cyclic loading of sinusoidal wave with frequencies of 1 and 10 Hz and a stress ratio of 0.1 in vacuum atmosphere at room temperature and 800℃. The changing of rigidity during fatigue test was investigated to evaluate damage of fatigue. The present results showed that fatigue lives of notched specimens were shorter than those of smooth specimens. However, fatigue cracks were occurred not only from the notch tip, but also from pores apart from the notch tip. Therefore, fatigue behavior of SiC/SiC composite materials can not be estimated based on the linear fracture mechanics. Fatigue crack initiation and growth behaviors were strongly influenced by the direction and density of fiber bundle at the fatigue crack tip. Damage processes were classified into four types. The modulus of rigidity was reduced with advancing fatigue damage. Final fatigue failure occurred when the modulus of rigidity was reduced to 90% of the initial values for all the specimen tested. The modulus of rigidity may be one of the measures for estimating fatigue damage of SiC/SiC composite material.

Post-Impact Fatigue Damage Growth in Fiber-Metal Laminates

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Abstract

Fibre-metal laminates (FMLs) represent a significant evolution in aircraft structural materials. These materials are hybrid laminates of metal sheets with fibre-reinforced polymer layers. This provides a combination of low density, fatigue damage growth resistance, impact damage tolerance and high static strength that is extremely well suited for aerospace structures. Currently FMLs are experiencing increasing use as secondary airframe materials in applications such as control surfaces, cargo hold floors and doors. They are also being considered for numerous primary structural (fuselage, empennage, wings) applications in aircraft under development or in production.

Full characterization of the properties of these laminates is required before they can be certified for primary airframe applications. Therefore, the Fibre-Metal Laminate Durability Project was established as a jointly funded project between Bombardier Aerospace, the Institute for Aerospace Research (IAR) of the National Research Council Canada (NRC) and Carleton University (Ottawa). The aim of this project is to characterize the impact resistance, post-impact residual strength and multi-site damage growth behaviour of GLARE (GLAss REinforced) fibre-metal laminates.

Following the impact event there is a plastically deformed dent in FML panels that acts as a stress concentration and as an initiation site for damage growth. Due to the residual deformation in the panels the growth mechanism is significantly more complicated than that reported by other researchers in flat FML panels with holes or notches. One particular laminate of interest is GLARE-4-2/1 which consists of two outer layers of 2024-T3 aluminum and three unidirectional plies of S2-glass reinforced epoxy in the following lay-up [2024-T3/(0°/90°/0°)/2024-T3]. This lay-up is typical of what would be used in pressurized fuselage applications where a biaxial stress state exists.

Non-destructive inspection techniques such as a penetrant enhanced x-ray process developed at IAR and ultrasonic C-scan were employed to characterize the fatigue damage growth at various stages. Initially, crack-growth actually proceeds parallel to the loading axis from the centre of the dent. This only proceeds until the crack reaches the edge of the dented region. Cracks also develop perpendicular to the loading direction and are associated with large regions of delamination between the aluminum layers and the fibre layers. The fibre layers bridge the crack tip and contribute to a residual fatigue life significantly higher than that observed in monolithic aluminum specimens. To better understand the crack growth mechanisms the stress state in the dented region needs to be examined in detail. The results of the experimental testing and a proposed modeling approach will be reported in this paper.

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IMPACT DAMAGE GROWTH IN COMPOSITES UNDER FATIGUE CONDITIONS MONITORED BY ACOUSTOGRAPHY

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Acoustography is a novel ultrasonic imaging technique in which the ultrasound that passes through a test piece from a broad sound source is imaged by a liquid crystal screen acousto-optic detector. Its advantage is that large area real-time ultrasonic images can be produced without the need for scanning. An acoustography system [1] has been adapted to image defects in samples whilst they are subjected to fatigue in a dynamic mechanical testing machine. The samples studied are of aircraft carbon fiber composite which have been impact damaged at the "barely visible impact damage " (BVID) level. The aim of the work is to determine "safe" zero damage growth fatigue lives of the composites. The integration of the acoustography imaging system and the fatigue testing machine will be explained. The data taking and image analysis procedures developed to provide quantitative measures of damage size as a function of fatigue cycles will be outlined. Damage growth data will be presented.
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Delamination growth in fatigue loaded impacted specimens

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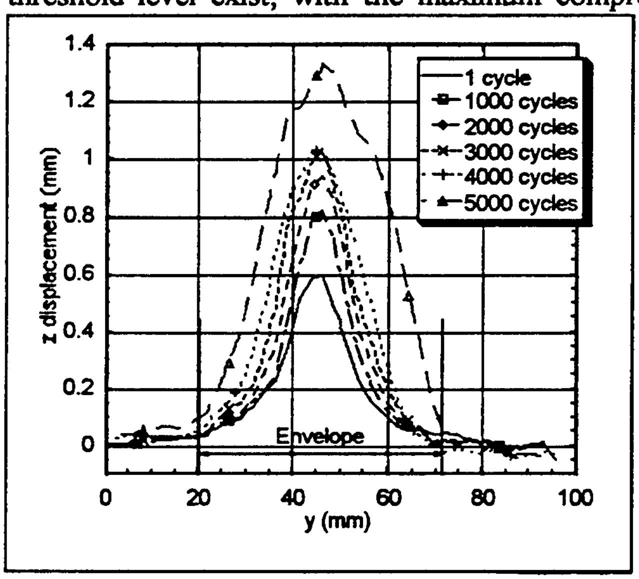
Abstract
Undamaged composites usually have a large failure strain. But, even a small impact damage will decrease the failure strain substantially. Therefore, rather low strain levels are used in aeronautical structures. During the service life of aircraft-composite structures they will be subjected to impact damage. Usually, the certification requirement for such damages is that no delamination growth is allowed. Since repair is expensive it is important to be able to predict if a given damage will grow during the remaining service life. If delaminations will grow repair is necessary. This makes it important to study the delamination growth of impacted composites during fatigue loading.

An experimental study on delamination growth during fatigue loading has been made on carbon fibre/epoxy laminates, HTA7/6376. Both a quasi-isotropic and a zero-dominated lay-up have been studied. The damages were introduced by impacting the laminates at 30 J, followed by ultrasonic C-scan to determine the extension of the delaminations through the thickness. The fatigue loading was performed under constant amplitude loading at R=-1 and R=-5, $R=\sigma_{min}/\sigma_{max}$. The buckling shape of the specimens was determined with digital speckle photography (DSP) during fatigue loading. DSP is an optical technique for whole field measurement of the 3D displacement field. The used measurement system provided simultaneous measurement on both sides of the specimen. In some specimens the delamination growth was followed by repeated C-scans that made it possible to determine which delaminations that grew and their shape.

A comparison of loading at different R-values indicates that the amount of tensile load has little or no influence on the delamination growth. The experiments also shows that a threshold level exist; with the maximum compressive strains lower than this level, no fatal delamination growth will take place. The image presented here shows measure-ments by DSP of buckling at maximal compressive load over a cross-section of the specimen. The specimen failed after 5242 cycles. Previously, a semi-analytical model has been developed for calculating the shape and energy release rate of local delamination buckling. The observed delamination growth will be compared with predictions from buckling calculations, where the energy release rate of different delaminations will be calculated.



Spectrum Fatigue of Composite Bolted Joints

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Abstract

Modern aircraft uses a large amount of composites in their primary structures. Those composites are often thick and highly loaded. Making bolted joints the preferred joining technique. Since composite structures are subjected to spectrum fatigue loading it is important to have a good understanding of the spectrum-fatigue properties of composite bolted joints. Spectrum-fatigue testing takes a lot of time since many low-amplitude cycles are included in the spectrum. Therefore, it is important to try to eliminate spectra in order to reduce the number of cycles and testing time. Fatigue experiments have been carried out on double overlap composite bolted joints with 6 titanium hexagon bolts. Specimens were loaded with a close to symmetric spectrum. The spectrum is a realistic spectrum for a fighter aircraft. Three different versions were used, one spectrum which was not eliminated, one which was eliminated to 30%, and one which was eliminated with 50%. The spectrum which was eliminated with 50% had less than 10% of the cycles left compared with the uneliminated one. The results of the spectrum fatigue loading is also compared with constant amplitude results. It can be considered the ultimate elimination when a spectrum is translated into constant amplitude loading. The results from the spectrum loading are compared with expected results from Miners rule. Specimens were also tested in constant amplitude fatigue at $R=-0.2$ and $R=-5$. The results show that it is possible to eliminate the spectrum with 50% without affecting the fatigue life. The constant amplitude testing showed that the fatigue life is longer for $R=-5$ than for $R=-0.2$. This is due to the quasi-static failure load being larger in compression than in tension. The dominant failure mechanism was bolt failure with some cases of net-section failure. Analysis showed that first bolt failure usually occurred for one of the bolt rows which would suggest that it transferred the largest amount of load of the three bolt rows.

Session 4: Experimental Methods and Results

Characterization of Microscopic Damage in Composite Laminates and Real-Time Monitoring by Embedded Optical Fiber Sensors

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Abstract

Light-weight composite material systems have been progressively used as structural members in various applications. However, more use has been proposed as primary structural members under severe operating conditions. In such applications, durability evaluation and health monitoring systems are two key technologies to be investigated.

The author has been proposing a so-called "experimental micro-mechanics of composites" to bridge the gap between material fabrication and macroscopic mechanical properties. Based on in-situ observation using optical, scanning electron, and/or scanning acoustic microscopes with loading devices, microscopic deformation and damage has been quantified. Moreover, theoretical models have been established for damage evolution. These efforts can provide the methodology for the durability evaluation or the damage tolerance design of composites.

In real applications, since the strains applied to the composite structures are random and uncertain, the real-time strain monitoring is necessary to predict the present damage status in composites based on the above durability evaluation method. If the damage can be detected by using sensors, more reliable estimation of the damage status or the residual life can be made.

The authors have been applying embedded optical fiber sensors to detect and monitor the transverse crack evolution in composite laminates. Two kinds of optical fiber sensors have been embedded along the reinforcing fibers in one ply so that the transverse cracks in the near-by 90-degree ply can be detected. One is plastic optical fibers (POF), where the loss in optical power is generated by local deformation of POF due to transverse cracking. The other is fiber Bragg grating (FBG) sensors, where the local strain distribution within the FBG gage length (typically 10 mm) due to transverse cracking alters the power spectrum of the light reflected from the FBG sensors. The measured change in power spectrum can be well correlated with the theoretical value derived by theoretical two-dimensional strain distribution and optical wave propagation theory. Thus, embedded optical fiber sensors are found to be a powerful method to detect and monitor the transverse crack evolution in composite laminates.

In-Situ Scanning Electron Microscopic Study of Fatigue Small Crack Closure

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Abstract

In situ scanning electron microscope observation of the process of fatigue small crack growth and fatigue crack closure on aluminum alloy 7075 has been made. The SEM photographs have been taken to record small crack growth, crack path profiles, plastic deformation field at crack tip, and crack closure in wake of crack tip. Analysis of the photos show that roughness induced crack closure played an important role in crack closure among plastic induced, roughness induced, and fretting debris induced crack closure mechanisms. It is found that not only can fracture surface contact prematurely before minimum load as proposed before by many authors, but also fracture surfaces can touch at maximum load, which can be a more interesting phenomenon.

Key words: Aluminum alloy; Fatigue small crack; Roughness; Serrated crack path; Fretting debris; Plasticity; crack tip opening displacement, Crack closure.

THREE STAGES OF FATIGUE CRACK GROWTH IN GFRP COMPOSITE LAMINATES

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ABSTRACT

Multiple fatigue crack growth behaviour has been studied in model transparent GFRP laminates. Detailed experimental observations have been made on the growth of individual fatigue cracks and on the evolution of cracks in off-axis layers in $(0/90/\pm45)_S$ and $(\pm45/90)_S$ laminates. Three stages of fatigue crack growth in the laminates have been identified: Initiation, Steady-State Crack Growth (SSCG), Crack Interaction and Saturation. The results show that SSCG rate is essentially constant under constant load, independent of crack length and crack spacing. Finite element models have been developed and used to calculate the strain energy release rates associated with the off-axis matrix cracking. A correlation has been achieved between fatigue crack growth rates in off-axis layers and the total strain energy release rates.

Fatigue behaviour of carbon/epoxy laminated composites

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This study presents the fatigue behavior of laminated composites carbon/epoxy made of unidirectional plies. In the case of laminated composites, there are many rupture and damage mechanisms : micro-cracking of the matrix, fiber-matrix debonding, transverse rupture, fiber rupture, delamination. All these mechanisms make behavior modelling complex for static and cyclic loadings [Reifsnider]. All of them were studied and described by various manners and in particular by meso-models (scale of the plies and interfaces) and by the damage mechanics for monotonic loading [Ladevèze], [Allix].

In this work, an extension of this kind of meso-model is proposed for cyclic loading at low stress level. The field of validity of the exposed model is limited to the first intra-laminar macro-crack and does not describe the phenomena of delamination. The behavior of the laminate after this first macro-crack, which propagates quickly on the scale of the structure, would require a calculation on the scale of the structure. The suggested modelling differs from the approaches which integrate the macro-cracks in the behavior of the laminate [Thionnet].

The model is based on the damage mechanics which uses internal variables making it possible to describe the progressive loss of rigidity of the ply. The evolution of these damage variables depends on the initial and cycled loadings. It is supposed that the mode of rupture in the direction of fibers does not depend on the cyclic loading. Two damage variables are introduced for transverse traction and shearing. Non-elastic strains are taken into account via a model of plasticity. The identification of the coefficients of the model is obtained by tests on tubular specimens. The choice of this kind of specimen makes it possible to avoid the edge effects which can cause delaminations.

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Key Words:

Composites - Fatigue - Laminate – Damage – Modelling

FATIGUE BEHAVIOUR SIMULATION OF INDUSTRIAL COMPOSITE PARTS

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KEY WORDS : Fatigue - Damage model - Iterative approach - Identification of fatigue parameters.

INTRODUCTION

The evolution of composite behaviour during fatigue loading is characterized by micro-cracks propagation, especially matrix type ones, associated with phenomena of redistribution of stresses between fibres and the matrix but also between the various constitutive layers of the composite material [1].

The first studies carried out in this field by many autors [2,3] were related to the identification of these damage phenomena by using simple tests on specimens (tensile, bending test ...). Interesting works were also carried out in the field of fatigue behaviour modelling and evaluation of the lifetime of these specimens. But, when one approaches the forecast of the fatigue life of the composite parts in use, the problem becomes more complex. Indeed, in this field we do not know how to apply the results obtained on specimens to the industrial parts in a systematic way. In this case the evaluation of the lifetime is always done by experimental fatigue tests [4], implying a heavy investment. To resolve this problem, an approach aiming to predict the fatigue life is necessary. It must :

- be based on a damage model accurately representing the process of degradation and not on a criterion of rupture as for metallic materials,
- take into account all the material and test parameters,
- take account of the dispersion of the data,
- take into account the phenomenon of stress redistributions at the time of damage evolution process of the material.

The purpose of this study is within this framework and is to present and develop an iterative method allowing modelling of the damage evolution due to fatigue. The iterative character of this method makes it possible to update the behaviour law of composite material throughout the simulation of fatigue.

METHOD - THE ITERATIVE APPROACH

first we have defined damage modes by introducing macroscopic damage variables d_{ij} and also by using a coherent potential of dissipation. Then we have determined the laws of evolution of these variables by introducing the thermodynamics of generalized standard materials. These laws were expressed according to the coefficients of the dissipation potential, the state of updated stresses (related to the damage state) and of the material behaviour (1).

$$\frac{\partial d_{ij}}{\partial N}=\frac{\alpha_{ij}\beta_{ij}}{1+\beta_{ij}}\left[f(\sigma_{ij}(N),C^0_{ijkl},d_{ij})\right]^{\beta_{ij}-1} \quad ij=11,22,12 \qquad (1)$$

These laws were identified starting from the results comming from the bibliography[5] which were injected into the iterative procedure on the level of calculation of the damage state. This enabled us to update the homogenized behaviour law of the material which is a function of the damage variables already defined. In order to be able to calculate the stress field and complex structural strains, a numerical method integrating a finite element code was developed[6].

The results obtained starting from the bibliography allowed a partial identification of the α_{ij} and β_{ij} coefficients, consequently an experimental methodology for a more complete identification was set up. This experimental protocol is based on tensile fatigue tests of unidirectional specimens in the fibres direction in the aim to identify the damaging modes related to the longitudinal stress. In the same way, tensile fatigue tests on specimens with 90¡ fibre orientation and [+/-45°]s laminates are in hand respectively to identify the damaging modes related to the transverse and shearing stresses. In this communication, after a brief recall of the model[6], we detail the experimental procedure and the methodology of identification of the dissipation potential coefficients.

The first results of identification of α_{11} and β_{11} resulting from the tests of characterization on a unidirectional glass/epoxy composite material elaborated in compression will be presented. These parameters once injected into the iterative approach will be used to validate the model on two cases of fatigue loading. The first application will relate to a fatigue test in 3 points bending on a specimen elaborated in compression and using same material as the tensile tests. The second simulation is a case of fatigue loading on an industrial structure (spring leaf). The numerical and experimental results will be compared to the level of the stiffness loss and Wšhler curves. The experimental results are supplied by Renault.

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CYCLIC SHEARING BEHAVIOUR
OF A UNIDIRECTIONAL GLASS/EPOXY COMPOSITE

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For unidirectional composite materials, the high longitudinal resistance is accompanied by a high sensitivity to other modes of loading, in particular shearing. Then, in-service ruptures are frequently caused by low transverse tensile or shearing loads, which are sometimes neglected in structure analysis. This paper deals with the characterisation of the cyclic shearing behaviour of unidirectional composites.

A comparative analysis of the different testing procedures described in the literature has led to the development of a new shear testing device. It is designed to perform shear tests according to the different orientations of the specimen under monotonic or cyclic conditions. It avoids transverse traction and scattering due to the use of different specimen geometries. A finite element modelling of the unnotched specimen in the device was used to optimise the grip geometry, to choose the material to be used for tabs, and to evaluate the stress and strain field homogeneity.

The material investigated is a unidirectional glass-epoxy composite, with a 60 % fibre volume, elaborated in an autoclave by IMFL-ONERA. Interlaminar and intralaminar shearing behaviours are compared under monotonic and cyclic conditions, the fibre direction being in both cases along the load axis. All the tests are conducted on a servo-hydraulic testing machine. Monotonic tests are carried out at a constant rate under stroke control, cyclic tests under load control, with a sinusoidal waveform and a load ratio of 0.1.

The monotonic shear characteristics of the material are determined, the fatigue resistance is analysed and the role of the interply is discussed. The fracture surfaces are observed by scanning electron microscopy and the rupture modes are described. Finally, the fatigue behaviour is compared to the fatigue results obtained under three point bending with predominant shearing [1].

[1] See paper proposed by F. Roudet and S. Degallaix. This Conference.

FATIGUE OF GLASS/EPOXY COMPOISTE IN THREE-POINT BENDING TEST WITH PREDOMINANT SHEARING

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Unidirectional and multilayers composites are usually solicited in bending, and often fail by interlaminar shearing. Therefore, the fatigue behavior of glass/epoxy unidirectional composite under is studied using three-point bending test under predominant shearing, without neglect tensile/compressive stresses. New experimental conditions were imposed to respect theses stresses, as diameters of fixed rollers (∅ 10 mm) and loading roller (∅ 22 mm) than the span/ thickness ratio (L/h = 7.5). Tests were carried out on a 10 kN servocontrolled hydraulic testing machine ESH. They were controlled in displacement with waveform sinusoidal at constant amplitude deflection (0.5 mm $<f_a<$0.8 mm), with a 10 Hz frequency, and an initial deflection ratio $R_f = 0.1$. During fatigue tests, the load was recorded under the loading roller. The evolution of the load during the test present three phases. The first, evolves during few cycles (a maximum of 200 cycles) and corresponds at a lost of load of 4 %, compared to the initial load. The second phase, up to 90% of the fatigue life, shows a progressive decrease in the load. The third phase, observed at high deflection amplitude, appears at about 10 % of load decrease. It shows a sudden load fall. From macroscopic point of view, the specimen was damage by mode II delamination which appears in the vicinity of the middle plan of the specimen. This delamination starts near the loading roller and rapidly moves towards either end of the specimen. Under low amplitude ($f_a = 0.5$mm), the tests were stopped at 10^7 cycles, during the second phase. The deflection amplitude curve in relation to the fatigue life at 10% of stiffness lost shows the dispersion inherent to this type of material and allows to define a pseudo-fatigue-life in terms of deflection (f_D). Analytic study of this curve, based on Fournier model's (FOU92), allows this modeling in terms of maximal deformation vs fatigue life at 10% of stiffness lost. Experimental results are well account with this analytic model. Nevertheless, at the end of each test, caulking was observed under each rollers. This caulking was started at the beginning of the first phase, and induces a decrease of R_f and of the deflection amplitude during cycling. Even, it is very interesting to note in analytic study that the results of the curve is not changed if caulking is taking account.

Effects of Stress Waveform and Water Absorption on Fatigue Strength of Aramid fiber/Epoxy composite

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The influences of stress waveform and water absorption on the tension-tension fatigue fracture behavior were investigated using aramid fiber reinforced epoxy matrix composite (Kevlar49/#2500), having an ±45°angle-ply stacking sequence. The fatigue tests were performed for specimens preconditioned in dry air (dry specimens) and specimens which were immersed in deionized water at 80℃ for three weeks (wet specimens). Sinusoidal, negative pulse and positive pulse waveforms are used for fatigue tests. For pulse waveforms, stress was changed in a triangular manner with a constant stress change rate of 720MPa/s (shown in Fig.1). The stress cycle frequency was 1Hz with a stress ratio R of 0.1 for all stress waveforms. S-N curves are shown in Fig.2. For dry specimens, the fatigue strength under negative pulse waveform was the highest. The fatigue strength decreased in the order of sinusoidal waveform, positive pulse waveform. The fatigue strength of wet specimens was much smaller than dry ones. The maximum displacement of negative pulse waveform is larger than that of positive pulse waveform and the compliance of negative one is smaller. The alignment of fibers to longitudinal direction, which results from the maximum stress hold time, causes smaller compliance. This is the reason for the longer fatigue life of negative pulse waveform. The fracture surface was closely examined using a scanning electron microscope (SEM).

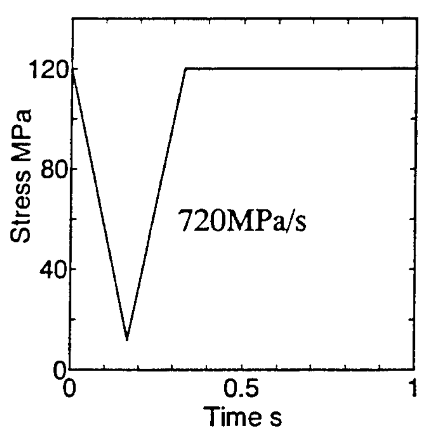

Fig.1 Example of negative pulse waveform.

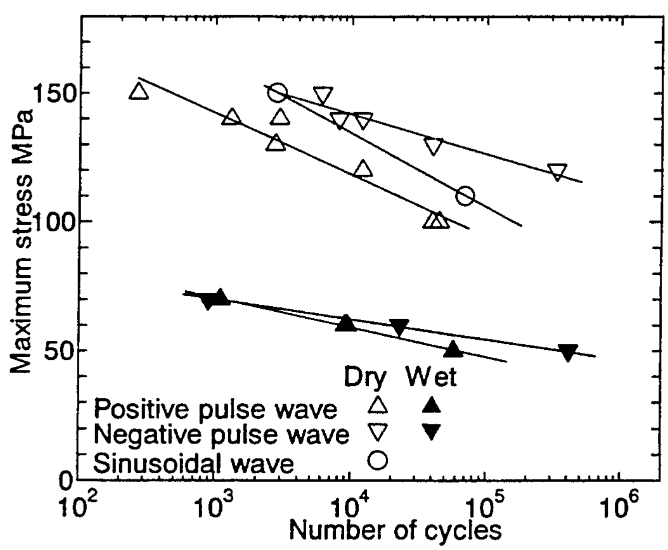

Fig.2 S-N curves.

Fatigue & Durability of Infrastructure Composites

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Polymers are making their way into the civil infrastructure through various innovative applications. As they do their performance under combine environmental and mechanical service environments must be quantified. The mechanisms and kinetics associated with their changing properties must be identified and understood in relation to their base constituents.

This discussion will provide an overview of work being carried out at Virginia Tech to quantify these fatigue mechanisms and kinetics as they relate to the materials, microstructure and methods of assembly use to derive the system. Efforts underway to examine the influence of thermoplastic sizings on the durability of carbon/vinyl ester composites will be discussed. Controlling the type of material and its microstructure at the interphase region is shown to strongly influence fatigue performance and environmental resistance. Furthermore, there is evidence to suggest that the interphase/face plays a critical role in controlling freeze thaw durability of polymer composites. Although the matrix controls the weight uptake of moisture in a polymer composite, we believe that unbound water is resident at the interphase and controls the reduction in properties under thermal cycling. Where glass fiber controls the life of a composite structure, it has been determined that a slow crack growth process controls the fatigue process. This process appears to be influenced by temperature but not moisture content.

The culmination of this work is geared toward attempts to provide design engineers tools through which to conceive reliable composite structures under highway and civil infrastructure service environments. Furthermore, the understandings developed through these interdisciplinary efforts will potentially influence the manner in which polymer systems are designed and processed to abate the economic and durability concerns of the industry.

Plate & Tube Bridge Deck Design Evaluation in the Troutville, VA Weigh Station Deck Test Bed

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Jack Lesko, Department of Engineering Science and Mechanics
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Virginia Tech

Abstract

A pultruded plate and tube design is proposed as a replacement for conventional reinforced concrete bridge decks. The proposed deck provides a pre-competitive structure that can be produced from off-the-shelf sections, mass-produced by the leading composite pultruders in the US. Moreover, the design (including the wearing surface) can be extended to other configurations (i.e., different depths) by adjusting tube and plate dimensions to achieve optimal performance under various conditions. Repeatability of this structure is therefore highly likely given proper guidance on extrapolation to other configurations.

Composite deck systems are considered to be favorable replacements for deteriorating bridge decks due to their durability (which means a longer life for the bridge deck) and lightweight (which provides for a faster, cheaper bridge deck replacement and a lighter superstructure). However, because experience with composites in the bridge community is limited and long-term durability data for composite materials are scarce, the development of such bridge systems is still in an experimental phase.

Although many composite bridge deck systems have been proposed in recent years, there is a growing need within the bridge community to understand the performance of such bridge components in actual traffic applications under initial and long-term loadings. Thus, the Deck Test Bed Facility will be used for the evaluation of proposed bridge deck system. The Deck Bed Test Facility will be constructed and the proposed deck installed during the fall of 1999 in the Troutville, Virginia weigh station. This test facility allows for the examination of the durability and structural performance of various bridge deck systems under realistic conditions (environment and load) and in a low risk setting. This paper will report the results of initial, baseline testing of the deck system and the results of periodic load tests of the deck system in the Deck Test Bed Facility.

FIELD TESTING OF THE TOM'S CREEK BRIDGE SUPERSTRUCTURE

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Jack Lesko, Department of Engineering Science and Mechanics
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Abstract

A unique bridge rehabilitation utilizing a hybrid fiber reinforced polymeric composite has recently been completed in Blacksburg, Virginia. This project involved replacing the superstructure in the Tom's Creek Bridge, a rural short-span traffic bridge with a timber deck and corroded steel girders, with a glue-laminated timber deck on pultruded, composite girders. In order to study any changes in structural performance of the bridge over time, periodic load tests (approximately every 6 months beginning in the fall of 1997) of the bridge were and are being conducted. The load tests are conducted with a 3-axle Virginia Department of Transportation dump truck loaded with aggregate and strains in and deflections of the pultruded composite girders are recorded. The recorded strains and deflections are then used to determine if there is any change in stiffness of the girders. The results of the field testing conducted to date will be reported.

In addition, the bridge was built so that the two upstream pultruded beams could be extracted and replaced with new beams. The two upstream beams were extracted during the summer of 1998 (after 16 months of service) and the results of testing these girders (strength and stiffness as compared to as-processed values) will be presented.

Session 5: Fatigue Life Prediction

Fatigue Life Prediction of Laminated Polymer Matrix Composites

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The classical laminated plate theory combined with structural mechanics codes constitute an accepted method for the static analysis of stress and strain states within individual layers of arbitrarily shaped laminated composite structures subject to external loads. In contrast, the fatigue life prediction of such composites subject to cyclic loading is still a problem. This problem is enhanced if in-service loading and, as a consequence, damage accumulation have to be considered.

The subject of the presentation is the development and the experimental validation of a critical element based fatigue life prediction methodology for polymer matrix composites. The objectives for this methodology included the development of an *engineering* approach to the fatigue life simulation problem which allows to consider both arbitrary plane stress states and external load-time histories as well as the capability to model both fibre and matrix dominated fatigue failure processes. Furthermore, the methodology should enable to treat laminate variants as well as should require experimental input from simple experiments and specimen configurations preferably.

To validate the development of the fatigue life prediction methodology a consistent experimental programme was carried out. CFRP and GFRP were used as baseline materials where in CFRP a fibre dominated failure mode was initiated while the polymer matrix dominated the failure of GFRP due to ±45° angle-ply lamination and external pure torsion loading. The CFRP laminates were made from HTA 5131/977-2 prepreg which was conventionally laid-up, cured and post-cured in an autoclave and air-circulating oven. GFRP tubular specimens were produced from E-glass fibres and vinylester resin through wet filament winding.

In the table given below the experimental programme is outlined. The composite systems were characterized on unidirectional (UD) laminates in constant amplitude tests to provide the experimental data for the fatigue life prediction (S-N behaviour, stiffness degradation). Constant and variable amplitude tests including tests similar

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to real in-service load-time profiles on multidirectional (MD) laminates were carried out to validate the simulation results. The development included the validation of the fatigue life prediction for constant amplitude loading, the extension of the critical element concept according to the needs of both fatigue problems considered, and, finally, the development of a method to treat complex variable amplitude loading profiles (denoted as quasi-random in the table below) in the fatigue life prediction.

Fibre tension was the critical failure mechanism in 0°-UD and MD reinforced CFRP under $R_\sigma = 0.1$ tension-tension fatigue. Stiffness degraded in 90° layers by a maximum of 7 % while was less than 1 % in 45° layers and thus neglected. Under 3-stage block loading 0°-UD laminates showed a sequence effect with a remarkable low-high sensitivity which could not be reproduced in MD laminates. To model damage accumulation a non-linear damage parameter could be defined to represent the behaviour of the critical layer in a multidirectional laminate. A pronounced difference in the fatigue damage mechanisms acting in 0°-UD laminates compared to 0° layers within a multidirectional laminate could be observed. Consequently, it had to be concluded that a fatigue damage accumulation model describing the fatigue behaviour of a 0°-UD laminate cannot directly be transferred to represent such a layer in a multidirectional laminate. Constant amplitude fatigue experiments and correspondent simulations of cross-ply laminates showed an acceptable correlation for higher ($N = 10^5 - 10^6$) while an overestimation for lower cycle numbers ($10^2, < N < 10^5$). The fatigue life prediction of 3-stage block loading on cross-ply laminates showed an acceptable correlation with the experimental mean. Although the maximum stress criterion was sufficient to represent the stress effort in the critical 0° layer the simulation of a symmetrical orthotropic laminate with 0°, ±45° and 90° layer orientations resulted in a considerable overestimation of the fatigue life. It should be noted that due to the use of flat specimens in fatigue testing edge delamination affected the experimental results while this damage mechanism could not be regarded in the simulation.

In-plane transverse compressive stress was found to be the dominating failure mechanism in $[\pm 45°]_6$ GFRP tubular specimens under torsion fatigue. Modeling constant amplitude fatigue life with a maximum stress criterion resulted in an unacceptable overestimation of the experimental results by some orders of magnitude. Finally, a multiaxial stress invariant based failure criterion could be derived to achieve a satisfying correlation between experiment and simulation. With this type of failure criterion the discrepancy between the experimental and predicted fatigue life was reduced to less than one decade for constant amplitude loading. Loading profiles similar to in-service load-time profiles showed a consistent minor overestimation compared to the corresponding experiment. Furthermore, the mean error of the fatigue life prediction was found to be rather close to simulation results based on laminate level (non-linear) residual strength and Palmgren-Miner damage accumulation models. The application of the fatigue life prediction methodology to constant amplitude fatigue loaded $[\pm 30°]_6$ GFRP tubular specimens resulted in a reasonable correspondence which indicates the potential to treat alternative stacking sequences under the provision of equivalent fatigue damage and failure processes.

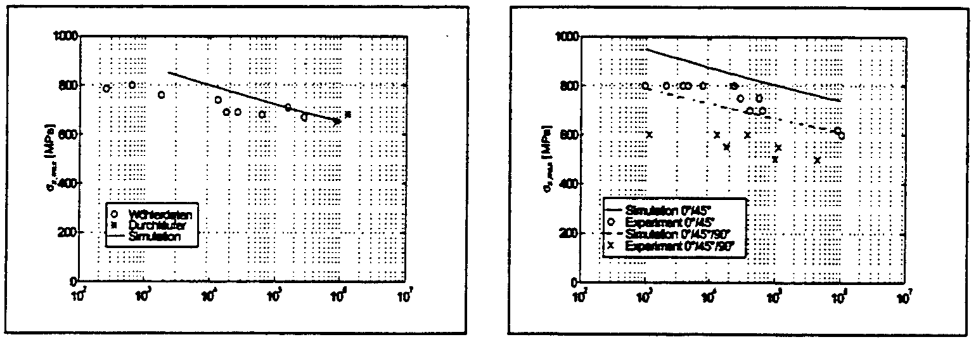
Fatigue test programm (ambient conditions, test frequency 5 Hz, load control)

material	stacking sequence	loading type	amplitude
CFRP	$[0]_8$	$R_\sigma = 0.1$ tension-tension	constant
	$[+/0/-/\underline{0}]_S$		
	$[90/0/90/\underline{0}]_S$		
	$[+/0/-/90/+/0/-/0/+/-]_S$		
	$[90/0/90/\underline{0}]_S$		3-stage block
GFRP	$[0]_4$	$R_\sigma = 0.1$	constant
	$[90]_6$	$R_\sigma = 10$	constant
	$[\pm45]_6$	$R_\tau = 0.1$ $R_\tau = -0.4$ $R_\tau = -1$	constant
		$R_\tau = -1$	2-stage block
			quasi-random
	$[\pm30]_6$	$R_\tau = 0.1$	constant

legend: +: +45°

–: –45°

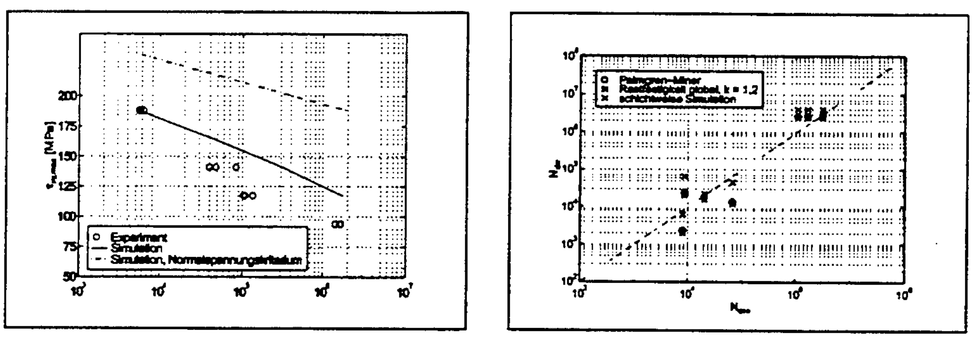
$$R_\sigma = \frac{\sigma_{1(2),\,min}}{\sigma_{1(2),\,max}} \quad , \qquad R_\tau = \frac{\tau_{xy,\,min}}{\tau_{xy,\,max}}$$



(a) cross-ply

(b) orthotropic

Comparison between experiment and life prediction for constant amplitude fatigue loaded CFRP



(c) constant amplitude

(d) quasi-random

Comparison between experiment and life prediction for torsion fatigue loaded GFRP

Fatigue Life Prediction and Truncation During Spectrum Loading

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Abstract

When certifying aircraft-composite structures, safe operation has to be demonstrated for the structures service life. This requires fatigue testing with a realistic load spectra, for several service lives, with load enhancement factors, or with both. Fatigue testing for several service lives takes a great deal of time and is consequently expensive. One way to reduce the fatigue-testing time and thereby the cost is by truncation of load cycles in the load spectra. Before this can be done safely a good understanding of the fatigue-life limiting damage mechanisms has to be reached. Delamination growth is often the fatigue-life limiting damage mechanism. Therefore, it is important to understand how truncation of a load spectra will affect delamination growth. It is common that the load spectra an aircraft is subjected to during its service life changes due to, for example, changed missions distribution. Therefore, it is important to have methods to estimate the change in fatigue life for different spectra. Since different structural components in an aircraft are subjected to different spectra it would be useful if the fatigue life for an arbitrary spectra could be estimated from constant amplitude fatigue curves. The models developed here are based on Paris law for delamination growth. Recently a model for predicting the constants in Paris law for different mixed mode ratios and R-values were developed. The possibilities for truncating load spectra will be studied by integrating Paris law for different levels of truncation of realistic load spectra. The amount of crack growth for different load cycles in the load spectra will also be calculated and the effect of threshold value for delamination growth will be discussed. The obtained results will be compared with experimental results in the literature. The change in fatigue life due to changes in a load spectra will be calculated by integrating Paris law. During these calculations it will be assumed that failure of the specimen will be due to a load cycle with the same magnitude in the two spectra. Obtained results will be compared to experimental results in the literature. A model will also be developed to predict the fatigue life of an arbitrary load spectra when constant amplitude fatigue curves are available for different R-values.

Fatigue fracture and life prediction of fibre-reinforced materials for petroleum equipment

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INTRODUCTION

In general, fibre-reinforced materials (FRM) present a combination of high-strong reinforced elements and matrix that have sufficient high degree of deformability. The distruction of reinforced element or damage of border of division is accompanied by allocation of stress so that damage is located in relatively small volume.

RESULTS AND DISCUSSION

The FRM application is espessially perspective in petroleum industry. FRM may be used for example as body of fibreglass sucker rod (SR). The coupling of sucker rod body with steel head is the weakest point in this case. The damage is located in head at highcycle loading. It is explained by the fact that at the compressing of the end of fibreglass rod the matrix and external fibres are deformed and damaged.

During the test on highcycle fatigue the FRM showed the following characteristic peculiarity: at the higher load the sample usually works a small number of cycles and the place of destruction is the delamination in the certain section (parts of samples are not separated one from another - they are connected together due to reinforced elements - fibreglass; at the same time the matrix is destructed). In the case of the lower loads sample works large number of cycles until failure and the place of destruction is more clearly observed (parts of samples are completly separated one from another). The section of destruction is situated on the distance of 20-30 mm from the head of the sucker rod.

The samples were destructed so because Wöhler's curves for epoxy matrix and glass (or bazalt) reinforced fibre have the different slope on inclined part in semilogarithmic system of coordinates. At the high stress the matrix is destructed quickly, and the fibres keep together. Then one can observe the delamination of rods, but the samples are not devided in separate partes. At the low stress the matrix and reinforced elements are destructed approximately at the same time. In this case the place of destruction is more local, the sample is divided in two parts.

Above mentioned may be refered to samples of big and small diameters. For example, the test of fibreglass SR ∅22 mm and fibrebazalt rods ∅7 mm was performed. Samples were loaded by stress of 130 and 160 MPa for fibrebazalt and 50 and 130 MPa for fibreglass. The peculiarity of FRM testing is so that the experimental points have significant dispersion (compared to the metal sample - more than 3 times larger). The curves of fatigue for different probability of nondestruction were built.

Such dispersion of points is explaned by the fact that the crack in composite materials is developed according to other laws, than that in homogenous materials. In FRM exists double heterogenity: together with heterogenity inside of components exists the heterogenity of adhesion matrix to reinforced elements. Therefore we may suppose, that the stability of properties in FRM may be obtained by better technology during production by increacing the adhesion level between composite phases.

During industrial implementation the producer of FRM is interested in prediction of the life term of the product in predetermined conditions. But FRM is characterised by very large interval of dispersion of strength properties. If we analize the process of destruction of the FRM products, we may reach same conclusions about stabilization of their caracteristics.

It is well known that composite materials are damaged beginning from different places of initiation where the first crack may appear:

- 1) in matrix;
- 2) in fibres;
- 3) by separation fibre from matrix.

In the cases 1) and 2) we can influence by increasing material quality and high technology. In the case 3) the influence is more difficult, because the role of technology in this case is several times higher than that in the two previous because the quality of material, the state of fibre surface, and adhesion of matrix to fibre play important role. The factor of correct position of fibre in the construction of product also plays an essential role.

Evidentally, even if we strictly keep to the technology of manufacturing the material we will still have the dispersion of characteristic higher than that of steel materials. Third factor plays great role in this case. In order to eliminate it we can make the border of division sensitive to tangential stresses and rigid to normal. In case of fibreglass rupture this place may be smaller concentrator of stresses than for usual phase of surface. Also it will make smaller influence on the fibre in case of crack propagation in the matrix.

So the role of first two factors will increase. The rise of technology of producing FRM component influences the degree of strength characteristics dispersion of material with opposite dependence.

In order to make the border of division sensitive to tangential tension and hard to normal we must cover the fibre by special materials which have adhesive properties.

Static tests of FRM sucker rods showed that the destruction was located in places of fixation and had a form of shifts. The body of rod was not damaged, but the area of shift was significantly bigger than that of rod's body. These tests show that damage of the matrix and the border fibre-matrix elements are predominant points of FRM destruction, but at the same time fibres stay the base of strength.

The tests of oil equipment products made from FRM used the method of acoustic emission. This method was applied in static and fatigue tests of fibreglass rods ∅22 mm With its help the source of acoustic signal emission and the approximation of failure by size intensity and amplitude of acoustic signal were determined.

The influence of agressive environments on FRM properties was studied.

The regressive equations of mechanical behaviour of fibreglass samples were determined after exposition in 10% solution of HCl and in oil emulsion.

For solution HCl: $\sigma_B = 95,8466 - 0,014t$

For oil emulsion: $\sigma_B = 99,3953 - 0,0009t$,

where t - exposition time in agressive environment, hours;

σ_B - tensile strength, MPa.

The new concept of FRM damage is formulated which is based on the energy absorption in interphase borders.

CONCLUSION.

In order to predict the fatigue failure of fibreglass SR it is necessary to apply the results of fatigue tests with different probability of non-destrucrion.

The method of acoustic emission permits to determine fatigue life and static failure of SR. Aging time of 12-24 months decreases approximately to 10-15% the tensile strength and fatigue limit of fibreglass sucker rods.

Prediction of Probability Distribution of Fatigue Life of Poly-Ether-Ether-Ketone Composite under VAL

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Abstract: The fatigue formula,i.e., eqn(1), developed for the fatigue crack initiation life of metallic notched elements was checked to be used to fit the fatigue life test data.

$$N_f = C_f[\Delta\sigma_{eqv}^{2/1+n} - (\Delta\sigma_{eqv})_{th}^{2/1+n}]^{-2}$$

$$\Delta\sigma_{eqv} = \sqrt{\frac{1}{2(1-R)}}K_t\Delta S$$

where K_t is the stress concentration factor; R and ΔS are the stress ratio and nominal stress range; C_f, $(\Delta\sigma_{eqv})_{th}$ are, respectively, the fatigue resistant coefficient and the fatigue threshold; $\Delta\sigma_{eqv}$ may be referred to as the equivalent stress amplitude. when $\Delta\sigma_{eqv} \leqslant (\Delta\sigma_{eqv})_{th}$, there will be no fatigue damage and the fatigue life tends to be infinite. Therefore, $(\Delta\sigma_{eqv})_{th}$ can be taken as the criterion for omitting the small loads in life prediction. Using the above fatigue formula to fit the fatigue test data in literature, one can obtain the expression for the fatigue life of poly-ether-ether-ketone composite.

Using the fatigue formula of poly-ether-ether-ketone composite and Miner's rule for cumulative fatigue damage, the log-mean fatigue life of the above composite under variable amplitude loading(VAL) can be predicted, and the predicted fatigue life was checked with test results. Furthermore, the probability distribution of the fatigue life of the above composite under VAL can be predicted by using the Mier's rule and the so-called *P-S-N* curves or the fatigue life with given survivability under constant amplitude loading. The predicted probability distribution of the fatigue life of poly-ether-ether-ketone composite is in fairly good agreement with test results under two-level loading in literature.

Development and calculation of polymeric reinforced rod's joints with metallic bandages

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Introduction

Oil wells' sucker rods experience great working loads during a pumping cycle, that's why it's of great importance to create a reliable connection of fiberglass sucker rod body with steel head. The first of all it's necessary to determine the local interaction of cylinder shell tube or rod (composite material) with rigid bodies.

Methods and Procedures

Adhesive and mechanical methods of metallic bandages joints with reinforced plastic rods are analysed. Strength equality of such joints could be achieved by covering areas increase of two connected elements .This leads to large material capacity. Actual coupling construction differs among manufacturers and in existing joints the ratio strength of plastic rod/strength of coupling equals to 7:4 for adhesive and 5:2 for mechanical methods (obtained by multilateral compression).

Discussion

If the adhesive joint doesn't decrease the strength of coupling the compressive methods changes it, because the bandage's deformation results in the damage appearence on the rod surface.

During the stretch an adhesive joint breaks in the adhesive surfaces and mechanical one - in the rod's body. But the coupling obtained by compression are more productive, profitable and cheaper. These joints work very good under the cyclic loading and don't cruch when the compressive load is imposed on the rod. When the bending stresses are applied to the coupling the rod's body is broken in both cases.

These types of joints were improved by means of new developed technology of rod connection with steel bandage and by constructive changes of the coupling elements. Calculated ratio of strength equality achives values 7:5...7:6. The characteristics of fatigue resistence under bending loads rise to up 30-50%.

New mathematical models of contact stresses in coupling were proposed and they were simulated by computer programs.

The numerical analysis of contact stresses for different cases (influence of geometrical and physical-mechanical joints parameteres, different kinds of contact interactions) was performed.

The full-size fatigue tests of fiberglass sucker rods under the bending and axial loading approved the reliability and strength of joints. The curves of Wohler were obtained with different degree of probability.

Session 6: Woven Materials

Effect of Environmental Moisture on Fatigue Properties of CFRP Reinforced by Plain Woven Carbon Fiber

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ABSTRACT

The effect of environmental moisture in air on the fatigue damage of CFRP was examined. Carbon fabric / epoxy laminates was used for the materials of the specimen. The conditions of testing humidity were 85, 40 and 0%(perfect dry), respectively. The testing chamber was filled up with pure nitrogen gas (N_2) in order to attain the perfect dry condition for the specimen while the cyclic tensile loading was being applied. The internal damage and fracture surface ware observed, and the microscopic fatigue mechanisms under high or dry humidity were also discussed. The fatigue lives under several cyclic stress revels were evaluated by comparing the difference of that under the perfect dry or high humidity condition.

The fatigue lives were significantly improved under the perfect dry condition, compared with those at 85 and 40% humidity. It was clearly found that the internal fatigue damage progression of the CFRP was strongly affected by the environmental moisture, even if the humidity was low.

A model for the fatigue damage progression, in which the moisture affected the interfacial strength between carbon fibers and epoxy resin, was proposed. An engineering technique reducing the fatigue testing time, was suggested by conducting the test at high humidity conditions.

Keywords: Environmental moisture, Fatigue damage, Nitrogen gas, Humidity. Carbon fabric / epoxy laminates, Cyclic tensile loading

Mechanics of Woven Composite Behavior

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Fiber bundles consisting of thousands of individual filaments can be interlaced to create a variety of woven mats. Figure 1 illustrates some of the possibilities. These mats can then be stacked and perhaps stitched to create a preform. The preform is infiltrated with resin and the part is cured to obtain a composite part. Composites fabricated in this way are potentially less expensive due to reduced part count and near net shape fabrication. They are also potentially more damage tolerant due to the interlaced structure.

In recent years a variety of analyses have been developed to predict effective moduli. These range from enhanced laminate theory models to full three-dimensional finite element models. Figure 2 shows typical variation of effective properties with waviness. As one might expect, loss of stiffness with increased waviness depends on the weave type. Three dimensional analysis has shown that the microstress distribution is complex even for simple loading, such as the uniaxial loading case in Figure 3. There have also been attempts to predict damage initiation and growth. Perhaps because of the geometric complexity, the emphasis has been more on describing the analysis formulation and demonstrating typical results than explaining the mechanics of textile behavior. Accordingly, the objective of this paper is to describe the mechanics of constituent interaction that determines effective stiffnesses, Poisson's ratios, and microstress distributions. There are a number of questions to be addressed. Some of the specific questions to be addressed include

- How important are the following in determining the sensitivity of axial stiffness to waviness?
  - Reduction of tow stiffness due to rotation
  - Lengthened load path
  - Shear lag
- What is the effect of waviness on transverse Poisson's ratio and why?
- What constituent properties determine the sensitivity of the moduli to waviness?
- What is the sensitivity of maximum stresses and the volume distribution of the stresses to mesh refinement?
- What is the effect of weave type on stress concentration?
- What properties are predicted well using modified laminate theory?
- How significant are geometric nonlinear effects in tension and compression for undamaged material?

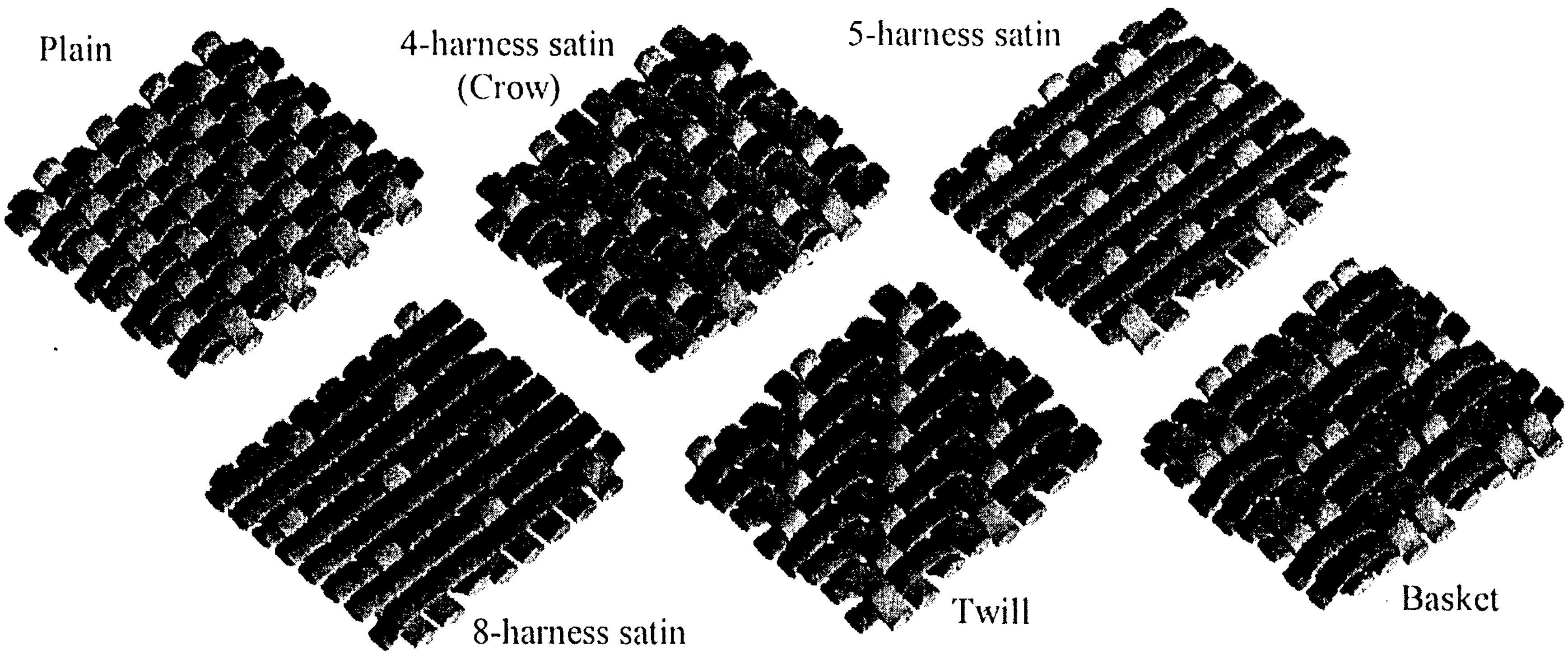

Figure 1 Schematics of weave architecture.

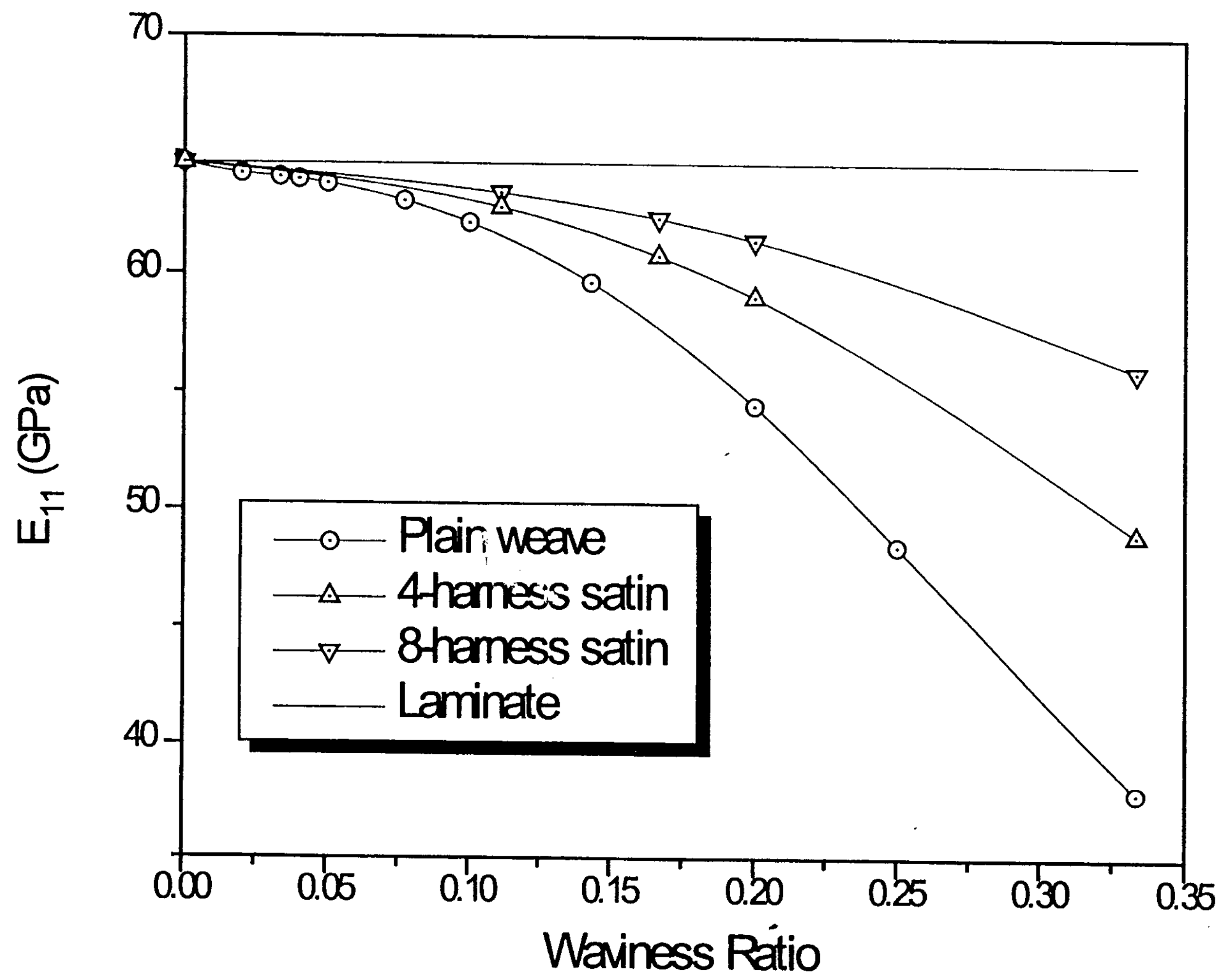

Figure 2 Variation of in-plane modulus with waviness

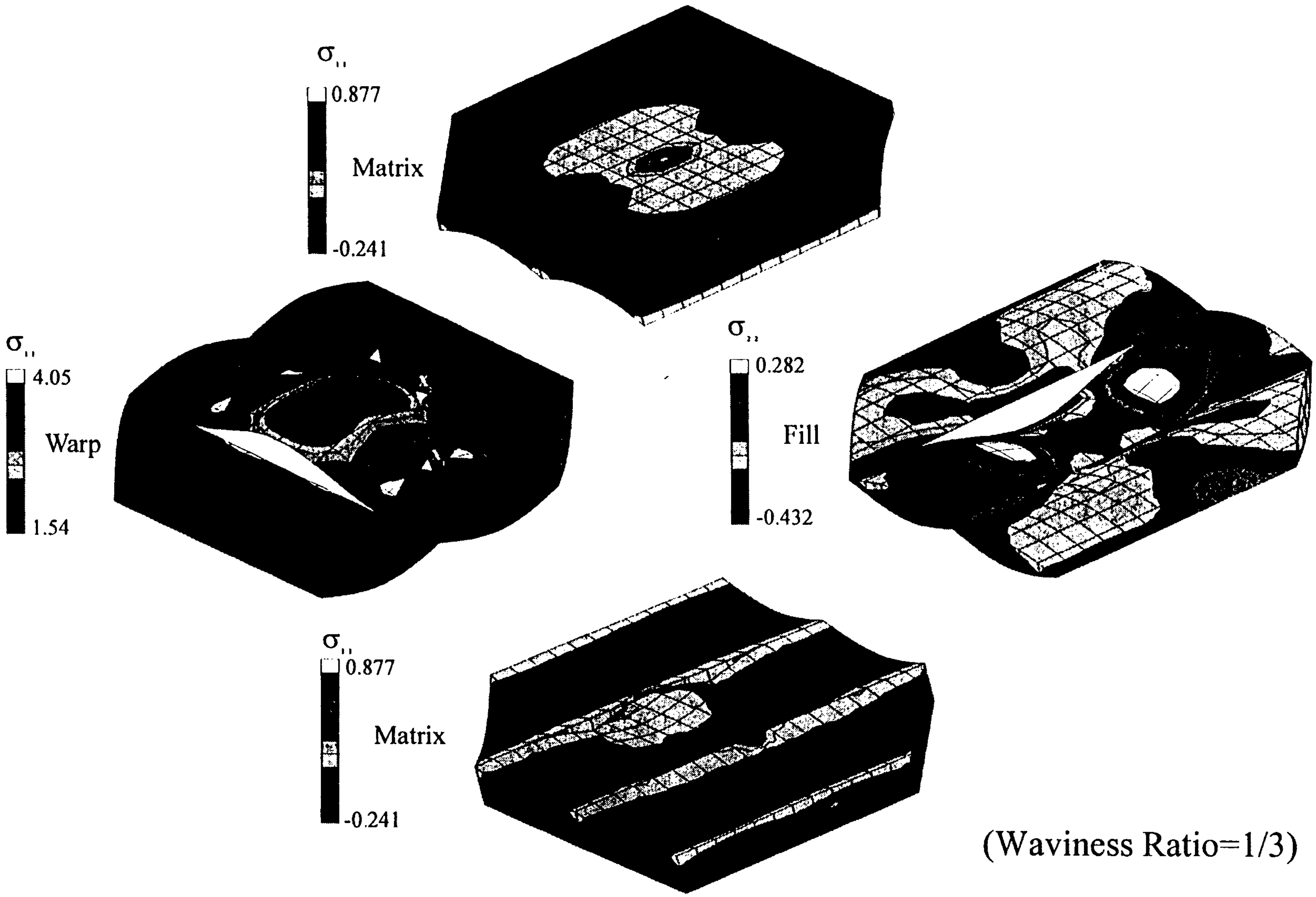

Figure 3 Stress distribution for 8-harness satin weave under uniaxialload.

Long-term Behaviour of Filament Wound CFRP Rolls for Paper Machine Application

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ABSTRACT

One of the most challenging tasks of composite design is to predict reliably the long-term behaviour. However, due to the lack of proper models and experimental data the designer is often faced with an impossible task.

These components are subjected to high cycle rotational bending fatigue up to $5 \cdot 10^9$ load cycles often combined with environmental spectra including moisture, high temperatures and corrosive agents. Therefore, the objective of this work is to investigate the high cycle fatigue behaviour of CFRP under ambient and wet conditions.

To investigate the fatigue behaviour on a test rig tube specimens as shown in figure 1 were manufactured.

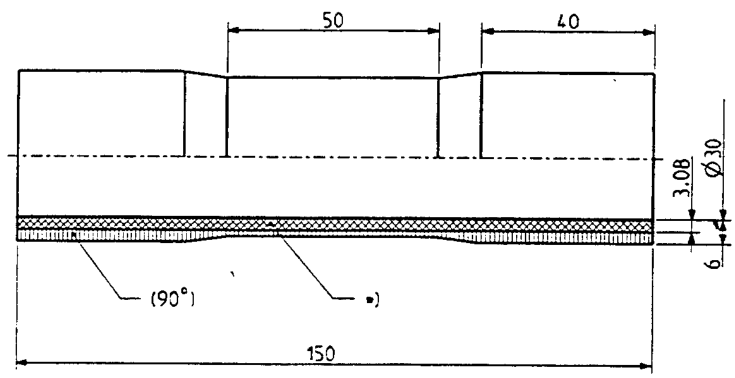

Fig. 1: Tube specimen configuration

This specimen configuration was choosen to exclude edge delamination during the fatigue experiment, to avoid the need of anti-buckling guides and to manufacture the specimens on the same devices as the paper machine rolls.

The tubes were fabricated from HTS 5631 carbon fires with CY 179 resin. The stacking sequence is [37/-37/83/40/-40/9/-9/-16/16/-35/35/83/-38/38] and fits the smallest unit of the lay-up of the rolls in the application. An additional glass ply is on the outer surface of the carbon tube in order to have a comparable surface as in real paper machine rolls which is important for the investigation of the long-term behaviour under the influence of moisture. To have a comparable stress state fatigue loading of the specimens is fully reveresed (R=-1) under load control with a constant sinusoidal waveform. To shorten the testing time the frequency was increased from 5 Hz and the influence of the test frequency on the surface temperature of the specimen was investigated. Due to the capability of the servohydraulic actuators the test frequency was limited to 20 Hz, but with this frequency just 10^7 cycles can be tested in a reasonable testing time. Therefore, the fatigue data have to be extrapolated up to $5 \cdot 10^9$ cycles. The extrapolation will only succeed if the fatigue damage mechanisms do not depend on the stress level. Furthermore, the damage mechanisms in the laminate are investigated by means of micrographs. Stiffness reduction is monitored by stroke measurements.

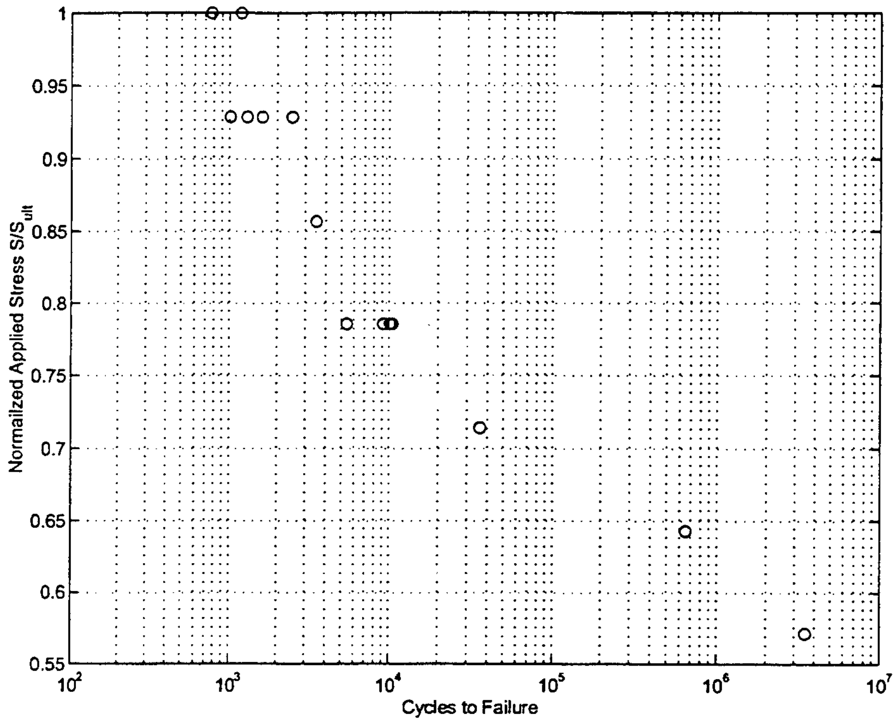

Fig. 2: S-N curve for CFRP tube specimens

Session 7: Modeling

A study of fuzzy fatigue reliability of submarine pipeline spans under vortex induced vibration

LUO YANSHENG* LI YUQI and FANG HUACAN**

Abstract

In case span present, the vortex shedding will occur because of the interaction between span/soil/sea water, and will induce the vibration of span due to the left and drag forces which accompany with. The vibration will be main factor that induced fatigue failure of submarine pipelines, and some affected factors not only present randomness but also fuzziness. As result of that, the fuzzy reliability must be considered.

In general, these hydrodynamic factors C_L, C_D and C_M are obtained by a lot of experiments, and these data are dispersion. Therefore, it's values are given by some codes (for example: DNV and API) in width range. The arbitrary is unavoidable in selection of these factors by different engineers, when calculating induce forces, and the fuzziness is existed.

The character of soil in seabed is also uncertainty. The fuzziness in choosing mechanics parameters as rigidity and damping factors of soil must be considered. Based on the fuzzy reasoning , a fuzzy model are presented for select these fuzzy factors as follow

$$B'(v) = \bigvee_{i=1}^{m}[\lambda_i \wedge B_i(v)], \quad \forall v \in V \quad \cdots\cdots\cdots\cdots\cdots \quad (1)$$

Where $B'(v)$ is fuzzy conclusion, each λ_i is true value between rule sets and fact sets, each $B_i(v)$ is a reasoning conclusion correspond to the condition factor according to the reasoning rule.

As Miner's accumulative theory, while the accumulative fatigue damage of a structure equals to 1, it will be failure. In fact, it is proved by practice that the threshold is not precise enough. Defining it as a fuzzy range is reasonable, and the safety grade can be expressed by membership function as follow

$$\mu_{\tilde{B}}(\tilde{D}) = \begin{cases} 1 & \tilde{D} \le a \\ \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{b-a}(\tilde{D} - \frac{a+b}{2}) & a < \tilde{D} < b \\ 0 & \tilde{D} \le \tilde{\sigma} \end{cases} \quad \cdots\cdots\cdots\cdots\cdots \quad (2)$$

Where $\mu_{\tilde{B}}(\tilde{D})$ is safety grade under fuzzy fatigue accumulative damage $\tilde{D}$, a and b are factors of a safety region, which can be obtained by experiments.

All above, the vibration system of submarine pipeline span is fuzzy, and the induced forces presented fuzziness too. Therefore, the vibration response of pipeline span presents fuzziness certainly. Considering the randomness and fuzziness, the reliability of span will be fuzzy reliability. Consequently, the reliability of span vibration system can be defined as a probability of that fuzzy safety law be satisfied, which can be determined by follow

$$\tilde{P}_S = P(\tilde{\Theta}) = P\{D(\tilde{S}_a, t) \subset \tilde{B}, \quad \forall t \in T\} \quad \cdots\cdots\cdots\cdots\cdots \quad (3)$$

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Life Prediction of a Woven Continuous Fiber Ceramic Composite System .

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Hot-section components in high temperature engineering applications like gas turbine engines are primarily made from actively cooled superalloys. Currently there is a drive in the turbine industry to increase inlet temperatures, to reduce material densities, and to eliminate component cooling. One class of materials with the necessary high temperature properties and low density desired is engineering ceramics. Monolithic ceramic, however, suffer from two major reliability issues. These are sensitivity to processing and low fracture toughness. This last item, can lead to catastrophic failure and severely restricts ceramics from use in aerospace or land based turbine engine applications. To overcome this problem, the continuous fiber reinforced ceramic composite (CFCC) was developed.

A damage evolution model for composite materials is presented as well as its specialization to a woven enhanced SiC/SiC composite system. Application of the model to high temperature tensile fatigue and rupture life predictions are also presented. A comparison of predicted to experimental behavior is then made.

NUMERICAL MODELLING OF FIBER REINFORCED CONCRETE FATIGUE IN BENDING

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A numerical model for the analysis of concrete under fatigue loading is presented. It is based on the visco-plastic theory by replacing the time-dependent behavior by a cycle-dependent behavior. The analysis is performed in a two step procedure. Initially, loads are monotonically increased until they reached their maximum level of the cyclic process, which is done with a standard non-linear analysis. Then, with the loads fixed at the maximum level, the cycles are applied to the structure and a cycle-dependent analysis is executed.

Two individual load surfaces are used to define the direction of flow: one for concrete in compression and the other for concrete in tension and tension-compression. Hardening/softening of these surfaces is governed by two independent hardening parameters.

Since a large number of cycles have to be modeled the consideration of the complete stress-strain history it is not advantageous because it is very time consuming and, in general, only the overall evolution is needed. Thus, the constitutive model considers the increase of deformation in each cycle. The total deformation is separated into an elastic deformation and into a permanent deformation. The evolution of the deformations is governed by a power law that is function of the state of stress and of the hardening parameter.

The monotonic stress-strain envelope is used as the envelope for the cyclic process. Thus, a deformational criterion to assess the fatigue life of concrete is used. When the deformations reach the softening branch of the monotonic stress-strain curve, the material is not able to support any more cycles with the same amplitude.

A series of fatigue tests on steel fiber reinforced concrete under flexural fatigue loading are used to assess the model performance. The model is capable of simulating individual tests and of establishing stress level versus fatigue life curves.

THE USE OF A CHARACTERISTIC DAMAGE VARIABLE IN THE STUDY OF TRANSVERSE CRACKING DEVELOPMENT UNDER FATIGUE LOADING IN CROSS-PLY LAMINATES

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In aeronautical industry, designers need to estimate the performances of structural parts made of composite materials with brittle polymer matrix. Under uniaxial fatigue loading, the first damage mode consists of a progressive matrix cracking in the off-axis plies. These first cracks can often be allowed, but their development must be carefully followed, as they affect the initiation of other harmful damages (delaminations, fibre breakages) that can lead to the ultimate failure of the composite structure.

A two-dimensional shear-lag analysis, assuming parabolic displacement in cracked layers, and taking into account residual thermal stresses, has been developed in order to model the progressive matrix cracking [1, 2]. A general governing equation has been derived for $(0_m/90_n)_s$ laminates that involves only in-plane stresses in both layers, based on equilibrium, continuity and boundary conditions. The analytical form of this equation has led us to introduce a new parameter : an adimensional characteristic damage variable, d_a, that depends on the crack density, on the uncracked ply stiffness properties, and on the stacking sequence through the layer thicknesses. Analytical expressions of the elastic constants and of the strain energy release rate are then obtained as functions of the characteristic damage variable. It appears that the decrease in the strain energy release rate G with progressive cracking can be represented through a single curve (whatever the material, the cross-ply stacking sequence, the maximum applied stress are) :

$$\frac{G}{G_{max}} = \tanh\left(\frac{1}{d_a}\right) - \frac{1}{d_a}\left(1 - \tanh^2\left(\frac{1}{d_a}\right)\right)$$

where G_{max} is the value of the strain energy release rate corresponding to matrix cracking onset.

The preceeding characteristic damage variable is then used for making the most of the numerous experimental studies that have already been carried out in our laboratory, through fatigue tests on various stacking sequences of cross-ply carbon/epoxy lmiantes, and for different applied stress levels. The growth rate of characteristic damage variable, $\frac{dd_a}{dN}$, is plotted against $\left(N - N_{fpf}\right)$ (N : actual cycle number ; N_{fpf} : first ply failure cycle number). All the results belong in a single power-law curve, whose interpolated equation can be easily integrated. The initiation stage (corresponding to the integration constant) has been previously studied [2]. Predictions concerning 90° crack propagation and saturation can then be obtained in any $(0_m / 90_n)_s$ cross-ply laminate and any cyclic loading level.

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RELATION CAIN RUPTURE AND CHAIN SLIPPAGE IN CREEP DEFORMATION OF AN ORIENTED LINEAR CRYSTALLINE POLYMER

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The interrelationship between the elementary creep processes of the crystalline polymers-slippage through crystallite and ruptures of passage molecular chains is adduced. The biphase model of a linear highoriented crystalline polymer of fibrillary microstructure with alternating amorphous and crystalline regions type of linear polyethylene is considered. As well as for inorganic solids at constructions of the creep molecular model is used of the crowdion Frenkel-Kontorova's for mechanically stimulation of linear chain slippage.

According to of the molecular model in polymer sample creep the leading elementary process is mechanically stimulation of thermofluctuation slippage of passage macromolecules. It is valid for flexible chain polymers at least.

The system of nonlinear kinetic equations for the description of creep process has been written. The creep processes are complexely dependent on load, conformation structure, concentration of end-groups, entanglements and cross -links, molecular mass distribution and on other molecular and supermolecular parametrs of polymer sample.

Session 8: Hybrid Systems

Fatigue Characteristics of Hybrid Composites with Nonwoven Tissue

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The mechanical characteristics of hybrid composites with nonwoven tissue are to investigate under tensile static and tension-tension fatigue loading. Static test and fatigue test of [+45/-45] symmetric angle-ply laminated CFRP using a unidirectional fiber reinforced and hybrid composites with nonwoven tissue are carrying out. Inserting nonwoven carbon tissue between layers makes the hybrid angle-ply laminates. Two different lay-ups are studying, namely [+45/-45]3s normal, [+45//-45]3s hybrid. The symbol (//) means that nonwoven carbon tissue is inserted at the interface. The specimens are cut and polish according to ASTM standard and curing by autoclave. In the static test, a new estimation method is proposed for stiffness of hybrid composites with nonwoven carbon tissue. This method is two-dimensional rule of mixtures of the most resemblance method involved with one-dimensional rule of mixtures. The estimate results for new method are compare with experiments and one-dimensional rule of mixtures. The in-plane shear relation can be obtained from the only uni-axial tensile test results of the [+45/-45] symmetric angle-ply laminates of CFRP. Chord shear modulus and offset shear strength of standard specimen is compared with those with nonwoven carbon tissue. In the fatigue test, to investigate fatigue failure process of hybrid composites with nonwoven carbon tissue. Fatigue life and residual strength of hybrid composites under different fatigue stress amplitudes is evaluated and compared with CFRP. The damage and failure mechanisms of the hybrid composites are discussed by a microscope and replica method.

Key Words: CFRP, Hybrid Composites, Fatigue Characteristics, Nonwoven Carbon Tissue, Two-dimensional rule of mixtures

Thermal Fatigue Failure Induced by Delamination in Thermal Barrier Coating

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ABSTRACT The paper presents the experimental and theoretical investigation on the thermal fatigue failure induced by delamination in thermal barrier coating system. Laser heating method was used to simulate the operating state of TBC (thermal barrier coating) system. The non-destructive evaluation such as acoustic emission (AE) detect was used to study the evolution of TBC system damage. Micro-observation and AE detect both revealed that fatigue crack was in two forms: surface crack and interface delamination. It was found that interface delamination took place in the period of cooling or heating. Heating or cooling rate and temperature gradient had an important effect on interface delamination cracking propagation. A theoretical model on interface delamination cracking in TBC system at operating state is proposed. In the model, a membrane stress P and a bending moment M are designated the thermal loads of the thermal stress and temperature gradient in TBC system. In this case, the coupled effect of plastic deformation, creep of ceramic coating as well as thermal growth oxidation (TGO) and temperature gradient in TBC system was considered in the model. The thermal stress intensity factors (TSIFs) in non-FGM (functional gradient material) thermal barrier coating system is analytical obtained. The numerical results of TSIFs reveal some same results as obtained in experimental test.

Key words: Thermal fatigue failure, Delamination, Thermal barrier coating

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A FUZZY SET APPROACH TO INTRALAMINAR CRACKS SIMULATION PROBLEMS

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Abstract

Fatigue damage of composite materials subjected to repeated loading is a complicated physical process which is difficult to accurately describe and model. The properties and behaviour of composites are greately influenced and controlled by the geometric and constitutive details of microvolumes of materials and interfacial effects in the region of damage events. Commonly, those micromechanics effects are described in a pure stochastic manner in order to simulate the development of the fatigue damage process – see e.g. Ref. [1]. However, it is well-known in advance that a damage response of composite materials is rather of a non-stochastic nature since this is just a nature of the micromechanical material parametrs characterizing composites. In such a case the fuzzy set approach seems to be better and more natural approach to model different (dependent on technology) variability of material parameters – see e.g. Ref. [2]. The simplicity of the implementation of the fuzzy-set approach in conjunction with finite element analysis is in addition the fundamental advantage over the probabilistic approach.

The objective of the present study is to investigate the ranges of variation of crack densities in the response of cyclically loaded $[0_n, 90_m]_S$ laminates associated with pre-selected variations (fuzziness) in the material micromechanical material parameters. As the fuzzy parameters three quantities have been introduced: (i) the flaw size a, (ii) the flaw position x and the distance S of the flaw considered to the neighbouring cracks. Variability of the above – mentioned parameters is introduced by specifying a membership function that plays a role of the possibility distribution in the classical stochastic approach. The membership functions are assumed to be triangular. The response quantity in the form of the strain energy release rate is a function of the parameters : a, x and S, and therefore is treated as a fuzzy function. In this way it is possible to construct possibility distributions by using the vertex method to numerically implement the extension principle – see Ref. [3]. In the vertex method the membership functions of all fuzzy parameters are discretised using several α-cuts. For a given α-cut the corresponding output quantity – the strain energy release rate (denoted by G) is obtained in the form of the interval, corresponding in this sense to the scatter of the experimental data. For each α-cut the lower and upper bounds of the interval are built as the minimum and the maximum of the response function for the binary combinations of the input fuzzy quantities.

For each vertex the numerical finite element analysis of the crack development simulation is divided into the following steps: (i) a search of the first largest flaw and calculation of the shear-lag effect, (ii) a search of the next flaws that yields the most energetic strain energy release rate G. Subsequent cracks are determined and the process goes until it is not energetically possible to find any more cracks or other failure modes such as

delaminations, fiber break etc. become to be active. The numerical simulation have been carried out for $[0_n, 90_m]_S$ laminates made of GFRP and subjected to cyclic tension-compression. The results of the numerical computations are also compared and verified with the experimental data.

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INVESTIGATION OF SOME CRACK-RESISTANCE OF COMPOSITE FOAMED THERMOPLASTICS(CFT) UNDER ACTION OF DIFFERENT FACTORS OF FATIGUE

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The crack-resistance and strength of fatigue of some samples for analysis and articles of CFT depends mainly of the strength of fatigue of their thermoplastic matrix. In this connection in details was investigated the strngth of fatigue for different thermoplatic matrices: polyethilene high density(PEHD), polypropylene(PP) and polyamide(PA) at room and higher temperatures, under action of media with increased chemical activity, and statical and cyclyc mechanical loadings.

It was estblshed that the complicated state under pressure with fatigue intensifv processes of tenderness. Under active state of chemical medium, high density polyetylene(HDPE) and PP matrices of CFT are very steady.With increasing of temperature and especiially under applied state of tensions, the resistance of the investigated compositions of the tension is considerably decresed with the samples moulded conventionaly under pressure(CMP) for difference of analogycal by consistaance but received from condition by method of the injection moulding with gas counter pressure(MIMGCP). In this point the crack-resistance and destruction due to fatigue of CFT is in connection to bigger level with the processes of reversivity flexibility and flowbility of thermoplastical matrix in local zones of the interfase medium at the structural element "thermoplastical matrix - filler - gas-bubbles", i.e. in the zones of pre-destruction, borning and development of microcracks by fatigue [1÷3] .

On the base of sample's scheme, the position for consideration of the reversible plastic flowing was former, on the lakation of this flowing in narrow strips comming out from the top of the microcrack. Graphically the schemes of the defformational state under pressure on the top of the treating, microcrack borne in CFT samples with maximum and minimum grate level of tension in the determined cycle of fatigue. This models treatment serve for a basic for analysing of experimental structures of CFT according to MIMGCP and CMP, subject to the cycling, testing for fatigue. As wellas using this model gives chance for analysis to unequal load cycling and treatment of mutual influence was on the base first of all from the speciality of the plastic defformation with CFT - MIMGCP samples and to the changes in tae levels for closing of the treated cracks by the changes of the amplitude of loading(incidently or in the determined spectre).

Using this method it allows to be comprised huge number considerable factors, pre-determining crack-resistence by fatigue in correlation with composition components technological parameters of processing and purpusely structure formation with the products of CFT by MIMGCP.

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"Meeting US Navy Ship Requirements with Composite Materials, Past, Present and Future"

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Abstract for the Keynote Address at:
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The US Navy Surface ships being designed and constructed for service in the next century need to meet very demanding warfighting requirements. In addition to being more effective warfighting platforms, they will need to meet significantly reduced acquisition cost, life cycle cost, and manning requirements. Taking advantage of cutting edge research and development advancements over the last decade, the Navy acquisition community is turning to the technology of composite materials to meet these demanding, and sometimes conflicting requirements. The Naval engineering community has recognized that composite materials play a significant role in the system engineering integration necessary to meet emerging requirements.

This presentation highlights the requirements that guide the use of composite materials for ship applications, shows how composite materials have been used to meet these requirements in the past, and describes how they are being considered to meet the demanding requirements of tomorrows ships. The US Navy pioneered the use of composite materials for small craft in the 1940's, and now uses composites in submarine bow domes, the MHC class of mine warfare ships, and for miscellaneous machinery, equipment, and secondary structures. As composites make their way into the future fleet, we see the topsides of the surface Navy changing significantly with the introduction of the Advanced Enclosed Mast Sensor (AEM/S) System onboard the USS Arthur D Radford and the USS San Antonio class of amphibious ships.

As composites continue to demonstrate their value in ship design, the true integration of this exciting technology into the ship system engineering process also grows. Leveraging the design options that composites provide will allow the Navy shipbuilding community to achieve reduced acquisition costs, reduced life cycle costs, reduced manning, and in increased system integration objectives.

Session 9: Analysis Methods

Fatigue Damage Evolution in Composites – A New Way Forward in Modeling

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ABSTRACT

A reliable and cost-effective fatigue life prediction methodology for composite structures requires a physically based modeling of fatigue damage evolution. An undesirable alternative is an empirical approach. A major obstacle to developing mechanistic models for composites is the complexity of the fatigue damage mechanisms, both in their geometry and the details of the evolution process. It is the contention of this author that overcoming this obstacle requires insightful simplification that allows the use of well-developed mechanics modeling tools without compromising the essential physical nature of the fatigue process. This paper will present a way forward in this direction.

The general concept concerning modeling of an irreversible mechanism in fatigue of composites by dissipative work conducted by tractions on growing surfaces will be described. The implementation of this concept will be illustrated by considering progressive transverse cracking in cross ply laminates under cyclic tension. The predicted crack density evolution, which agrees well with experimental data, will be used in a life prediction scheme to generate fatigue life diagrams. An alternative modeling based on extension of the fracture mechanics approach for fatigue crack growth will be discussed and arguments will be presented as to why it cannot provide a predictive capability.

A MESO-MECHANICAL ANALYSIS FOR FATIGUE DAMAGE OF LAMINATE COMPOSITES

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Homogenizing and analyzing the local damage at meso-scale of laminates under cyclic loading, this investigation establishes a new approach to fatigue life prediction for laminate composites. According to the global response of the laminate in stiffness reduction, the damage is classified as localized damage: progressive transverse cracking and global damage including longitudinal cracking, delamination and fibre fracture.

The lamina undergoing transverse cracking is simulated as a homogeneous mesodomain with unidirectional deteriorated stiffness, termed an effective lamina. The meso damage factor of the effective lamina is defined by the change of in-situ transverse elastic modulus of the transverse ply

$$D_2^{ms} = \frac{E_2(0) - E_2^{ms}(\rho)}{E_2(0)}$$

It is found that the meso damage factor is a function of crack density and the transverse ply thickness. The effective lamina represents an in-situ load-carrying capability of the cracked transverse ply, and the stresses in the effective lamina and the critical lamina are obtained by using the classic lamina theory.

By means of the meso damage factor at the stage of crack saturation, or CDS, the redistributed stress in the critical lamina can be evaluated. The applied stress which results in a critical redistributed stress in the constrained ply at CDS equal to the conditional fatigue limit of unidirectional longitudinal ply is rationalized as the conditional fatigue limit of the laminates. The fatigue life of the transverse laminate is predicted based on the redistributed stress in the 0 ply and the S-N curve of the unidirectional longitudinal ply. For example, a conservative prediction of the fatigue life of laminates can be obtained by integrating the following equation

$$\frac{dD}{dN} = \alpha \frac{t}{t_1}[\sigma_1(CDS)]^n$$

in which α and n are constants determined by S-N curves of 0 unidirectional ply. The fatigue test results of cross-ply laminates of glass fibre/epoxy-resin with different thickness is presented. The theoretical prediction shows a good consistency with the experimental data.

On the sequence effect in block amplitude loading of cross-ply composite laminates

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ABSTRACT

The Palmgren-Miner sum has shown to be inexact in many cases for various composite materials. Several empiric models have been conceived to account for this discrepancy, as well as the effect of block sequence. The approach taken here is based on the underlying mechanisms. A carbon fiber/epoxy cross-ply laminate was used as a model material. In general, composites show both initiatory and progressive mechanisms under fatigue loading. The former is active at high static stresses, whereas the latter predominates at lower amplitudes where they are given sufficient time to propagate. Initiatory mechanisms give rise to damage from the progressive mechanisms can start, and conversely the progressive mechanisms continually alter the local stress state which result in new damage caused by the initiation controlled mechanisms. In a cross-ply laminate, the initiatory mechanism is the formation of transverse cracks, and the progressive mechanism is mainly delamination growth initiated from the transverse cracks. In an experimental investigation, the interaction of these mechanisms has shown why a sequence of high-low amplitude level results in shorter lifetimes than a low-high order. This seems to be a common behavior for many other composite materials, which can be mechanistically explained by a similar kind of interaction. Advantages and drawbacks of the mechanistic approach compared with the Palmgren-Miner class of empiric rules are also discussed.

MICROMECHANICAL ANALYSIS OF DELAYED FIBER FRACTURE IN UNIDIRECTIONNAL GRFP SUBMITTED TO FATIGUE IN WET ENVIRONMENTS.

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ABSTRACT

The fatigue behavior of unidirectional glass/epoxy composites under bending or tensile loading is known to be dominated by the delayed fracture of the fiber reinforcement. The latter process is largely driven by the sub-critical growth of cracks from surface defects under the combined effects of stress and moisture. Often refereed as stress corrosion cracking (SCC), these mechanisms are strongly dependent upon the changes in the surrounding physico-chemical environment of the glass fibers. During moisture exposure, the diffusion of water at the fibre/matrix interface and the resulting degradation of the interphase can thus result in a strong changes in the fatigue endurance of the material.

In this study, a quantitative micro-mechanical analysis of these fiber failure processes has been carried out during the first stages of the fatigue life, i.e. before the appearance of a macroscopic damage. The objective was to investigate the potential of a SCC based model to predict the damage accumulation within the material under the combined effects of stress and water ageing. An *in situ* detection of fiber breaks has been carried out in an UD Glass/epoxy composite subjected to bending loading. In such a configuration, most of the first damage in terms of fiber breaks is located under the loading nose, where it can be detected using an optical microscope coupled to quantitative image analysis. In a first stage, the changes in the density of broken fibers has been quantified as a function of time under static fatigue loading (R=1) in a water environment at different temperatures. From these data, the relevant parameters describing the in-situ SCC behavior of the glass fibers have been derived. Quantitative relationships have also been established between the stiffness losses and the accumulation of the micro-defects. Using these results, the potential and the limitations of the extrapolation of the static fatigue data to dynamic fatigue at various frequency and R ratio are considered. The difference between the prediction of the SCC model and the observed behavior are interpreted by taking into account stress transfer processes at the degraded interfaces.

Session 10: Applications

Strength and Fatigue of Filament Wound Composites for Flywheel Batteries

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ABSTRACT

Fiber reinforced polymer composites are leading material candidates for high-speed flywheel energy storage batteries. The main advantages of high-speed flywheels over competing technologies such as electrochemical batteries are the potentially higher energy and power densities (per unit weight) inherent to composites and the longer cycle life enabled by the recent development of efficient, affordable magnetic bearings. The composite portions of flywheels, generally made by wet filament winding, consist of rings or cylinders connected to a hub/shaft assembly or magnetically suspended with a shaftless "inside-out" motor/bearing system. A flywheel battery may spend most of its service lifetime idling at full speed with only a few discharge/recharge cycles in an uninterruptible power supply application or it may be intentionally deep cycled numerous times per day in a peak-shaving application. Hence, creep and fatigue are both important durability issues. Failure of such high-speed machinery must be well understood for safety reasons.

Insofar as new proprietary material systems and manufacturing methods are constantly being introduced and our ability to predict failure of composites from first principals is still rudimentary, composite rotor durability studies need to be carried out with materials, shapes, manufacturing routes, loading histories, and operating environments as close as possible to reality. However, the time-honored build/test approach has proven to be difficult to carry out because of (a) the difficulty of failing the composite portion of a rotor before some other component (such as the hub or shaft) fails and (b) the high cost of long-term spin tests in heavily armored test cells. Coupon-level, accelerated test methods that capture the most important effects of the actual load history and operating environment therefore need to be identified to assist in prototype design.

The objective of this article is to review the available information concerning the strength and fatigue behaviors of representative materials for filament wound composite flywheel rotors. The author and his co-workers at the Pennsylvania State University have recently produced some of this information. Ongoing questions and issues regarding precursor materials, manufacturing route, fiber alignment, operating environment, coupon design, and test method are included. Comparisons between data on representative flywheel rotor materials and the more abundant data on cut-and-laid prepreg material systems are made in several instances.

On Probabilistic Treatment of Fatigue Concepts for Composite Materials

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The main idea behind the article is to present an application of the three alternative methods of description of well-established deterministic fatigue theories for composites when material properties and external loads are treated as random. The fundamental concepts in composite fatigue as Palmgren-Miner's or Paris-Erdogan models as well as most recent theories in this field are presented in the context of first two probabilistic moments, i.e. expected values and variances of damage function. Considering different forms and complexity of various damage functions proposed until now, the three following techniques of randomization are proposed: analytical approach (integration over random spaces), stochastic perturbation method (in both analytical and computational context) with general restrictions to up to the second order approach and, finally, Monte-Carlo simulation computational methodologies.

It should be underlined that the main purpose of these research is to show how to obtain probabilistic versions of different composites fatigue models without any comparison of these theories in the context of engineering computations or practical applicability to various composites. The general motivation is first of all random nature of fatigue processes both in homogeneous and heterogeneous materials and structures and, on the other hand, the results of experimental work given by statistical estimators of material parameters and constants. At the same time, successful transcription of the theory by theory in terms of random spaces application does not seem sensible - using some common general methods engineers, researchers and practitioners will be able to do that by themselves; the same conclusion is obtained taking into account the total number of different fatigue models in composites.

Having any probabilistic theory of fatigue it is possible to analyze stochastic sensitivity of damage function with respect to expected values and standard deviations of its arguments what can be useful in further evaluation of different fatigue models and various experimental techniques. Finally, decisive for such a formulation is capability of stochastic fatigue life prediction of composite structures considering their reliability in different engineering applications.

Some references:

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Low Cycle Fatigue Behavior of Polymer Matrix Composites

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Abstract

Last decade is marked by the transition in the use of advanced composite materials which has expanded from the aerospace and defense applications into wider commercial arena. Today composites are used in power generation industry, automotive industry and transportation, construction industry and civil engineering, biomedical engineering and various consumer goods. In service, similarly to other materials, advanced composites age, suffer physical or chemical degradation, and accumulate micromechanical damage. Reliable life prediction for the in-service fatigue life of structures made of composites is of paramount importance for the efficient design and safety.

Low cycle fatigue (LCF) conditions occur when composite structures are subjected to severe fatigue loading and harsh environment which lead to high material degradation rates. The LCF life and mechanical performance of composites depend on their fatigue damage tolerance and the rates of property degradation under cyclic or pulse loads. The LCF conditions are often associated with high levels of loading which may be as high as 90% of the ultimate strength.

In this paper, the LCF behavior of a unidirectional glass fiber/epoxy matrix composite is investigated. The S-N curves are obtained for the LCF life assessment. LCF characterization is carried out to identify the key physical phenomena occurring during LCF processes and to determine their unique characteristics. LCF damage mechanisms in unidirectional PMCs subjected to tension-tension fatigue are examined for axial fatigue loading. Fatigue damage mechanisms, evolution patterns of damage and damage accumulation processes are singled out and thoroughly analyzed as the key mechanical phenomena contributing to the property degradation under fatigue conditions.

Analysis of experimental data indicates that finite strain rate and stress ratio effects are significant under LCF conditions. Higher stress ratios are shown to affect the fatigue life of specimens tested. A phenomenological fatigue model is suggested to described LCF and high-cycle fatigue (HCF) behavior. Damage accumulation processes and fatigue life predictions are discussed.