PLASTICITY
DAMAGE
FRACTURE

9:00AM TO 5:00PM

TOBB ETU, Social Facilities Building, Room 3

THURSDAY
OCTOBER 25

Workshop on
"*Plasticity, Damage and Fracture of Engineering Materials*"

25 October 2018, TOBB University of Economics and Technology, Social Facilities Building, Room 3

The main limits in engineering design and production are plasticity, damage, and fracture. Ever increasing demand for materials with usually contradicting properties such as high strength and high ductility makes it vital to develop new approaches to these limits. In this workshop, recent theoretical, numerical and experimental work concerning plasticity aspects of damage, failure and fracture mechanics will be discussed.

This workshop is organized by Cihan Tekoğlu and Tuncay Yalçınkaya, with the financial support of TÜBİTAK, for the project no: 315M133.

Agenda

09:05 – 09:05	**Welcome** Murat Aktaş (TOBB ETU, Mechanical Engineering)
09:30 – 10:00	**Ductile Tearing of Metal Plates** Cihan Tekoğlu (TOBB ETU, Mechanical Engineering)
10:00 - 10:30	**A Comparison of Strain Localization Behavior in BCC, FCC, and HCP Metals** Mert Efe (METU, Metallurgical and Materials Engineering)
10:30 - 11:00	**Inter-Granular Cracking through Micro-Plasticity and Cohesive Zone Modeling** Tuncay Yalçınkaya (METU, Aerospace Engineering)
11:00 - 11:30	**Coffee Break**
11:30 - 12:00	**Experimental and Numerical Investigation of Elastic-Plastic Behavior of Additively Manufactured Lattice Materials** Recep Görgülüaslan (TOBB ETU, Mechanical Engineering)
12:00 - 12:30	**A Comparative Study on the Hyperelastic Constitutive Models for Rubber** Hüsnü Dal (METU, Mechanical Engineering)
12:00 - 12:30	**Effect of Welding Parameters on the Fatigue Strength of CMT Welded Lap Joints** Mehmet Okan Görtan (Hacettepe Univ., Mechanical Engineering)
12:30 - 14:00	**Lunch**
14:00 - 14:30	**Polymer Nanomechanics: Enhanced interfacial rigidity of 1D Thermoset Nanostructures** Hatice Duran (TOBB ETU, Materials Sci. & Nanotechnology)
14:30 - 15:00	**Computational Modeling of Durability Phenomena in Concrete** Serdar Göktepe (METU, Civil Engineering)
15:00 - 15:30	**Fiber/Matrix Interface Debonding in Steel-Fiber Composites** Barış Sabuncuoğlu (Hacettepe Univ., Mechanical Engineering)
15:30 - 16:00	**Coffee Break**
16:00 - 16:30	**Computation of Macroscopic Response of Multiphase Materials with Planar Interfaces** Ercan Gürses (METU, Aerospace Engineering)
16:30 - 17:00	**Static and Fatigue Failure Mechanisms in Curved Composite Laminates** Demirkan Çöker (METU, Aerospace Engineering)

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Ductile Tearing of Metal Plates

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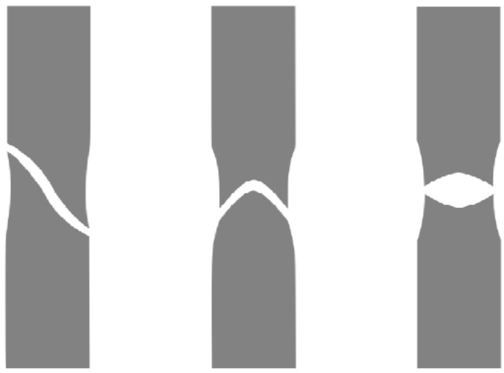
Abstract: This presentation compares the heterogeneous deformation behavior of selected alloys from materials having bcc, fcc, and hcp crystal structures. For this purpose, macro- and micro-scale deformation heterogeneities in a DC04 deep-drawing steel, a 6061-T6 aluminum alloy, and a AZ31 magnesium alloy are investigated under both uniaxial tension and biaxial stretching. Strain maps from the tests and microstructure and texture data are overlapped in order to identify the sources of the localizations. Three materials show remarkably different deformation behavior. Strain localizes into the grains with α fiber texture in the steel, with limited effects to the macro-scale formability. In 6061 aluminum alloy, strain localization to the grain boundaries is evident with possible risks of fracture initiation at these locations. Twinning activity controls the deformation in magnesium, where severe localizations to the tensile twins limit both the micro- and macro-scale formability. Both magnesium and aluminum alloys also show sensitivity to the strain path. The presentation will end with a suggestion of possible solutions to the heterogeneous deformation, and underline the material specific challenges and strategies.



(a) (b) (c)

Fig. 1: (a) Slanted, (b) cup-cone, and (c) cup-cup crack morpholgy (see e.g. (El-Naaman ve Nielsen, 2013).

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Acknowledgements

C. Tekoğlu, H. Duran and K. L. Nielsen gratefully acknowledge the financial support by TÜBİTAK (project no: 315M133).

A Comparison of Strain Localization Behavior in BCC, FCC, and HCP Metals

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Abstract: The aim of this study is to investigate the effects of microstructure on the crack morphologies in ductile metals(see Fig. 1). In metals and metal alloys, cracks propagate predominantly by the growth and coalescence of voids nucleated by the second phase particles whose size are in the order of μm. The fundamental hypothesis of this study is that, not only the volume fraction, but also the average size and spatial distribution of these particles/voids would affect crack propagation. In order to test this hypothesis, both numeric and experimental studies are performed. These studies verified the hypothesis, and the results showed that, small and remotely distributed particles lead to cup-cup crack propagation, while large and closely spaced particles favor slanted or cup-cone crack propagation. The effects of average size and spatial distribution of particles/voids on the crack morphology is more pronounced for metals with an intermediate level of strain hardening.

Inter-granular Cracking Through Micro-plasticity and Cohesive Zone Modeling

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Abstract: Even though inter-granular fracture phenomenon is generally regarded as a macroscopically brittle mechanism, there are various cases where the fracture occurs at the grain boundaries with considerable plastic deformation at the macroscopic scale. There are several microstructural reasons for grain boundaries to host crack initiation. They can interact with impurities and defects, can provide preferential location for precipitation, can behave as a source of dislocations and can impede the movement of dislocations as well. The understanding of the crack initiation and propagation at the grain boundaries requires the analysis of the grain boundary orientation and the orientation mismatch between the neighboring grains and the related the stress concentration, which is only possible through the combination of micromechanical plasticity and fracture mechanics. For this reason, the current work studies the evolution of plasticity in three dimensional Voronoi based microstructures through a strain gradient crystal plasticity framework (see e.g. Yalcinkaya et al. (2011), Yalcinkaya et al. (2012), Yalcinkaya (2017)) and incorporates a potential based cohesive zone model (see Park et al. (2009), Cerrone et al. (2014)) at the grain boundaries for the crack initiation and propagation. The numerical examples consider the effect of the orientation distribution, orientation of grains and the grain boundary conditions on the inter-granular fracture behavior of micron-sized specimens.

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Experimental and Numerical Investigation of Elastic-Plastic Behavior of Additively Manufactured Lattice Structures

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Abstract: Lattice structures, which consist of interconnected strut members in micro- and millimeter scales, recently gained popularity to attain a lightweight structure while maintaining the high specific mechanical properties such as strength and energy absorption due to the advancements in additive manufacturing (AM) techniques. However, the irregularities and uncertainties, introduced by the AM techniques on the geometry and material of the lattice structures, result in differences between the simulated behavior and the manufactured behavior of the lattice structures. In this study, the plastic behavior and energy absorption of various lattice structure designs of a crush box geometry are investigated experimentally under compression. It has been observed that the crush box designs with lattice structures provide much higher energy absorption compared to a hollow crush box with square profile. The nonlinear material behavior of the AM-fabricated specimens is characterized based on the experiments and used in the nonlinear finite element analysis (FEA) of the experimented designs. Results indicate that a close prediction can be made by the nonlinear FEA compared to the experimental results, but further investigation is needed to effectively account for the microscale uncertainties in the FEA of the lattice structures.

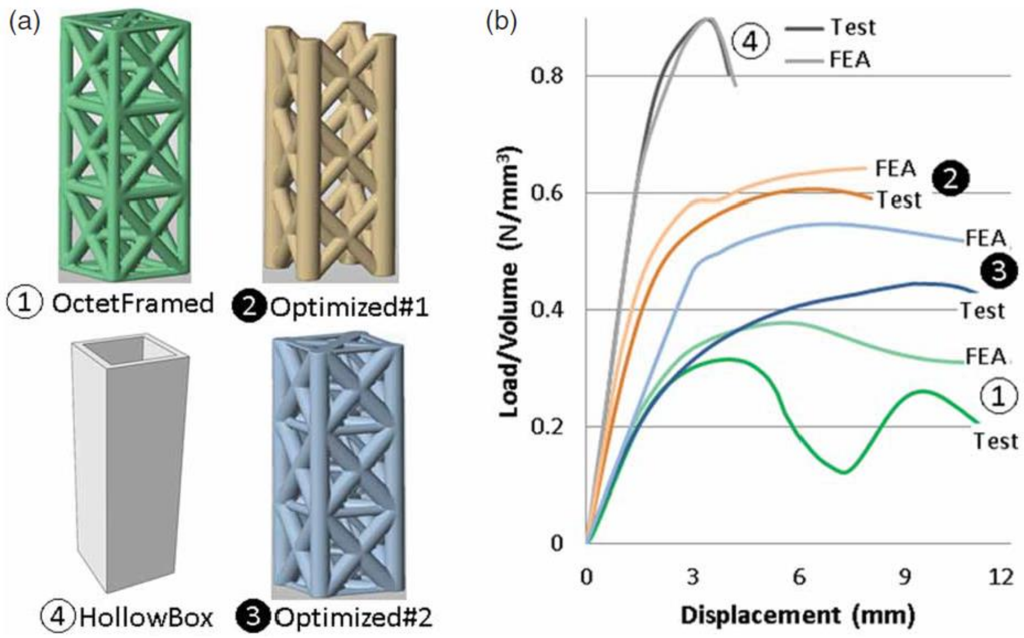

Fig. 1: a) Crush box designs with lattice structures and hollow box, b) FEA and experiment results of these structures in compression.

A Comparative Study on the Hyperelastic Constitutive Models for Rubber

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Abstract: This paper presents a novel approach for comparison of constitutive models for rubber. Model parameters are identified by simultaneous fitting of a given data of a set of homogeneous experiments (uniaxial tension, equibiaxial tension, and pure shear, **Figure 1**) by multiobjective optimization. Using these parameters, fitting error can be calculated. In this study, however, quality of fit parameter, which represents the amount of error normalized by the data, is calculated for unbiased comparison of models. 40 different constitutive models for rubber-like materials from the literature are compared based on their quality of fit values [1]. Among these models, micro-sphere [2] and Alexander's model [3] gives the best results for simultaneous fitting. However, some models work in low or moderate stretch levels. The stretch values up to which a model performs reasonably good (in terms of quality of fit) is called validity range. It allows ranged comparison of models and provides insight for model selection in engineering practice. Quality of fit values, validity ranges and errors are presented for all 40 models.

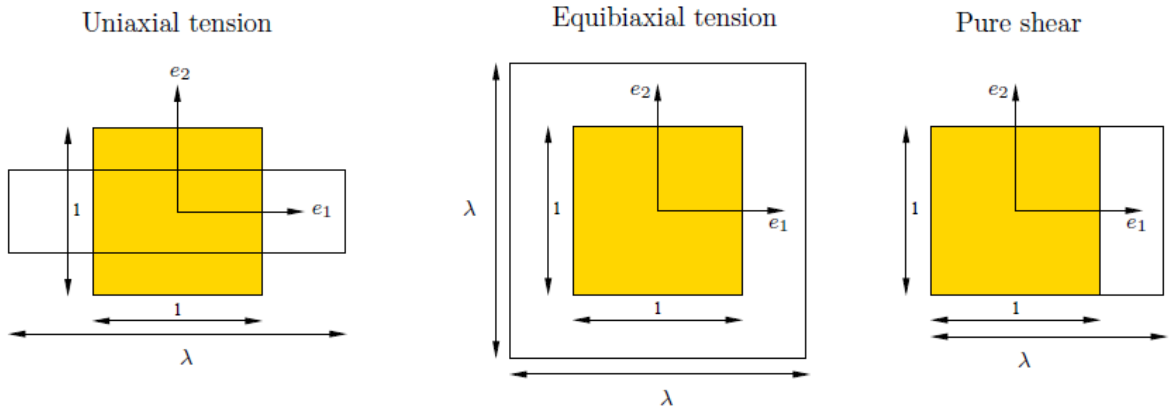

Fig. 1: The homogeneous deformation states of a unit-cube element.

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Effect of Welding Parameters on the Fatigue Strength of CMT Welded Lap Joints

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Abstract: Sheet metal suspension arms are usually manufactured by stamping of blanks and welding of those to a final product. Thanks to their low weight and high fatigue strength, these are widely used in passenger cars where weight is of high importance. However, due to the characteristics of suspension systems, suspension arms are subjected to dynamic loading which may cause fatigue failure. In the current study, effects of end current during cold metal transfer (CMT) welding of steel sheets on weld profile and fatigue strength of joints are investigated. For that purpose, a lap joint sample has been designed. Samples have been robotic CMT welded with different end current parameters. The effect of aforementioned parameters on weld profile has been investigated on the weld cross section. Moreover, fatigue strength of the weld joints has been determined using axial testing.

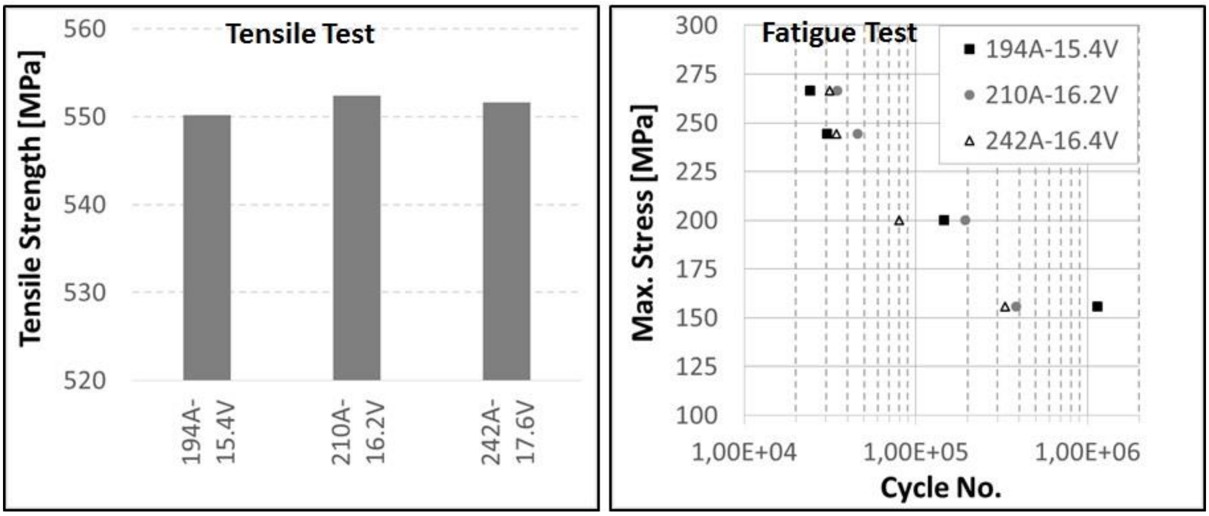

Fig. 1: Tensile and fatigue test results of investigated CMT welded specimens.

Polymer Nanomechanics: Enhanced Interfacial Rigidity of 1D Thermoset Nanostructures

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Abstract: Plastic deformation of polymers is a complex phenomena, involving both the crystalline and amorphous phases. In this talk, the strength, toughness and their interconnection will be addressed with particular emphasis on cavitation, crystal plasticity and plastic deformation of crystalline and amorphous phase, which leads to high molecular orientation of both phases. We will focus on and compare two extreme cases; mechanical deformation of i) intrinsically crystalline polymer nanofibers (Fig.1a) and ii) nanoconfinement induced crystallization of amorphous polymers (Fig.1b). Understanding the influence of hard confining interfaces on the physical and mechanical properties of thermosets is central to the rational design and performance optimization of thermoset resins. Polycyanurate networks (PCNs), which form random networks in the bulk, are representative of an important class of thermosetting materials. We showed that free surfaces of PCNs exhibit rigidity enhanced by one order of magnitude (quantified by Young's modulus) if they are initially synthesized in the presence of hard confining interfaces, such as the pore walls of nanoporous anodic aluminum oxide (AAO). The mechanical properties (i.e. Young's modulus) of single PCNs were tested using Nanointendation Atomic force microscopy measurements. Young's modulus of nanorods were 22 GPa[1]. Strikingly, this value is one order of magnitude higher than that of bulk polymer (3.46 GPa)[2]. An impressive increase of the Young's modulus of polymeric nanorods was correlated with interface induced molecular orientation of aromatic groups, taking advantage of carbon–carbon bonds strength.

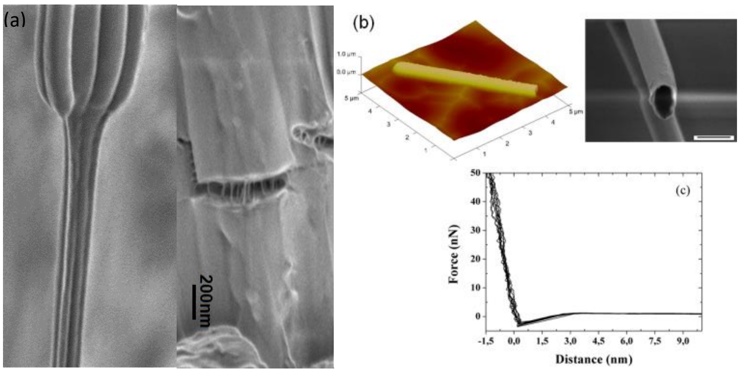

Fig. 1: (a) SEM image of crystalline polymer (b) AFM/SEM images of a single PCN and (c) Force-distance curves performed on PCN during cantilever's approach and retract scans.

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Computational Modeling of Durability Phenomena in Concrete

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Abstract: In this contribution, coupled constitutive models furnished by robust computational framework are developed to address the durability problems that arise due to the uneven chemical heating through hydration in mass concrete [4] and the non-uniform shrinkage by means of the reduction in relative humidity [5]. In the case of mass concrete structures such as dams, the coupling between the hydration reaction, temperature evolution, and deformation at early ages may lead to cracking. In many hydraulic and building structures, located in a region with high temperature variations between day and night, the humidity diffusion leading to a highly heterogeneous shrinkage strain distribution is observed. The parameters governing shrinkage can be classified in three groups: (i) environmental parameters (relative humidity, temperature, rate of moisture loss, duration of moisture loss), (ii) geometry of the concrete element (surface area to volume ratio, thickness), (iii) cementitious paste parameters (water-cementitious material ratio, amount and composition of the cementitious material, degree of hydration). Hence, the proposed approaches account for the chemo-thermo-mechanical coupling to investigate the cross effects between the evolution of temperature due to hydration and stresses through the deformation in mass concrete for the former problem. While the latter class of problems are tackled by the coupled hygro-thermo-mechanical models incorporating shrinkage-induced stress concentrations either in hardening or hardened concrete within the framework of Reactive Porous Media [1] based on the coupled problem of Darcy-Biot-type fluid transport. These coupled models are further supplemented by the Phase Field models [2], [3] to predict the crack initiation and propagation under the considered coupled effects.

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Fiber/Matrix Interface Debonding in Steel-Fiber Composites

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Abstract: Steel fiber composites have recently become available as a remedy to the low ductile behavior of composites made of conventional fibers such as glass and carbon. Due to the high stiffness contrast between polymer matrix and these steel fibers, they are open to high stress concentrations under transverse loading [1]. The two main failure modes in transverse loading are the crack formation in the matrix and the fiber /matrix debonding. In this study, the latter one was analyzed for steel fibers with a representative volume element and the definition of cohesive surfaces (Fig.1). Inıtially the behavior was compared with the conventional composite types. Then the effects of the material parameters, the surface coating of steel fibers were investigated. The results revealed the importance of surface coating to prevent the debonding behavior. The cross-section of fibers and the strength of interface were determined to be the major contributors of the early fiber/matrix debonding whereas the stress concentrations do not change this behavior significantly. There was also an interesting result that a slight decrease in the evolution of maximum principle stress was captured as soon as debonding starts.

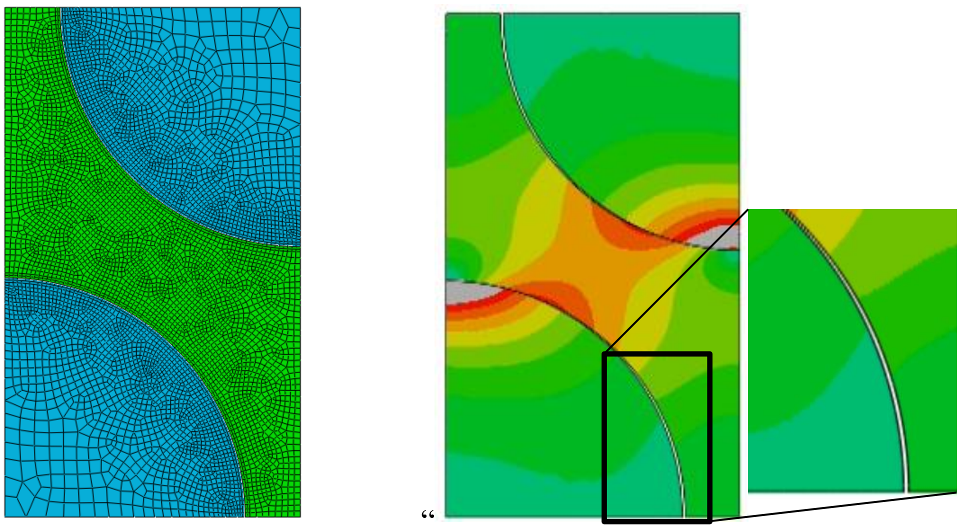

Fig. 1: (a) Finite element mesh of the unit cell; (b) debonding of matrix from fibers.

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Computation of Macroscopic Response of Multiphase Materials with Planar Interfaces

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Abstract: Apparent mechanical properties strongly depend on the structure and morphology of a material, since these regulate the micro-mechanisms that operate during the deformation. Therefore, morphology is an important factor that should be considered in micromechanical models. To this end, a method that could be employed to construct micromechanically based models for different morphologies is proposed. In the proposed method, a geometry representing the microstructure is discretized into arbitrary number of regions where each region is in contact with either one or two regions. Similar to the lamination theory [1], a planar interface lies between two neighboring regions, and deformation gradient field of each region is assumed to be uniform. It is well-known that in rank-1 laminates there exists a single interface where both force equilibrium and deformation continuity are present. In the proposed method, there are multiple interfaces at the same scale, but the force equilibrium and the deformation continuity are not satisfied simultaneously on these interfaces. Instead, one of these physical requirements is replaced with an energetically motivated condition that minimizes an energy expression. However, as the number of regions increases and the consecutive interfaces approach each other, the neglected condition is better satisfied, since the energetically motivated condition approaches to the neglected physically motivated condition. In classical lamination theory, it is well-known that the Hill–Mandel condition is satisfied. In the proposed method, it can be shown by relaxing the force equilibrium or the deformation continuity (or both) that the Hill–Mandel condition is trivially satisfied as well.

Using the proposed method, we model the disk-like spherulite morphology that is observed in thin film samples of semi-crystalline polymers. The disk-like spherulite is composed of alternating amorphous and crystalline phases. The crystal plasticity with orthotropic elasticity and the isotropic 8-chain rubber elasticity constitutive models are employed in the regions that belong to these phases. Results under different deformation modes are compared with a FE model [2] that also models the disk-like spherulite morphology with identical constitutive models and material parameters.

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Static and Fatigue Failure Mechanisms in Curved Composite Laminates

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Abstract: Results of an experimental study on the damage progression in curved CFRP composite laminates under static and fatigue loadings are presented in this paper. Two different cross-ply laminate thicknesses are examined with grouped plies to elucidate the failure mechanisms: thick $[0_3/90_3/0_3/90_3/0_3]_s$ and thin $[0_3/90_3/0_3]_s$. A new test fixture is designed to apply moment/axial combined loading to curved specimens and DIC method is used to obtain the strain distribution in the curved region until failure. Our major finding is that under fatigue loading, the failure location and mechanism are different from that under static loading. Fatigue failure is observed to form in the group of 90° plies where the radial stress is maximum whereas static failure is observed to form in the group of 90° plies where the combined radial, tangential and shear stresses attain a maximum value, in the form of Tsai-Wu failure criterion. For fatigue failure, micro-cracks existing in the maximum radial stress location in the group of 90° layers grow under cyclic loading and coalesce into one major matrix crack which reaches the 0/90 interface gradually to continue as a delamination. On the other hand, static failure initiates inside the group of 90° layers with a dominant crack growing dynamically and jumps to the 0/90 interface near the arms abruptly with a 40-50° angle to continue as a delamination. With the damage mechanisms in cross-ply cornered laminates identified clearly, design improvements can be suggested for structures using composite curved beams that are more durable and operate for a longer lifetime.

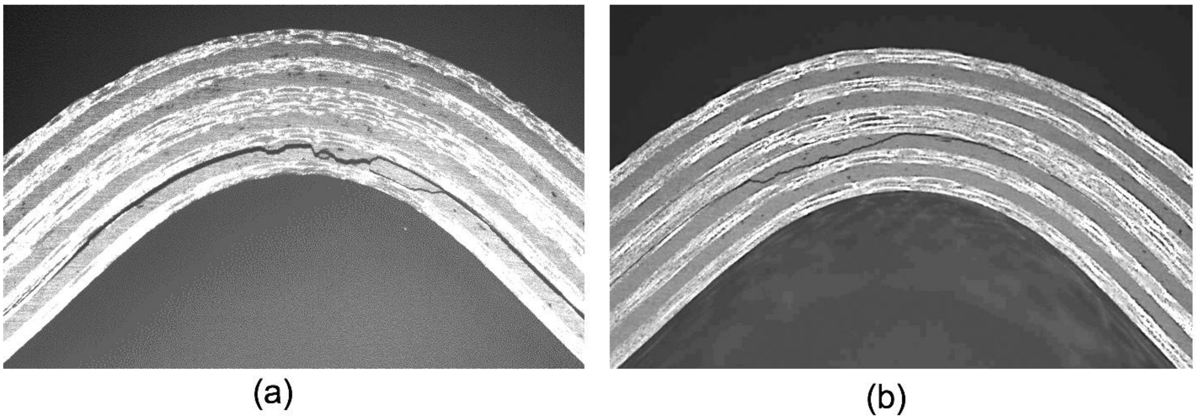

Fig. 1: Micrographs of the curved laminate along the thickness direction showing the failure (a) in the first 90 ply group under static loading, (b) in the second 90 ply group under fatigue loading.

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