DEVELOPMENT AND EVALUATION OF FRACTURE MECHANICS TEST METHODS FOR SANDWICH COMPOSITES

Andy Gill presenting for
Dr. Dan Adams

Department of Mechanical Engineering
University of Utah
Salt Lake City, UT
FAA Sponsored Project Information

- Principal Investigator: Dr. Dan Adams
- Graduate Student Researchers:
  - Chris Weaver
  - Andy Gill
  - Brad Kuramoto
  - Josh Bluth
- FAA Technical Monitor
  - Curt Davies
Fracture mechanics test methods for composites have reached a high level of maturity.

Less attention to sandwich composites:
- Focus on particular sandwich materials
- Focus on environmental effects
- No consensus on a suitable test configuration or specimen geometry for Mode I or Mode II fracture toughness testing
RESEARCH OBJECTIVE

- Develop fracture mechanics test methods for sandwich composites
  - Focus on facesheet core delamination
  - Both Mode I and Mode II
  - Suitable for ASTM standardization
RESEARCH APPROACH: THREE PHASE PROGRAM

- PHASE I: Identification and initial assessment of candidate test methodologies
- PHASE II: Selection and optimization of best suited Mode I and Mode II test methods
- PHASE III: Development of draft ASTM standards
PHASE I (REVIEW): Identification and initial assessment of candidate test methodologies

- Identify candidate Mode I and Mode II test methodologies
  - Literature review - Lead to five Mode I and eight Mode II configurations
  - Modifications from adhesive and composite laminate tests
  - Original concepts were also created

- Identification of materials and geometries currently in use for structural sandwich composites

- Assessment of candidate test configurations using finite element analysis

- Select promising configurations for mechanical testing
PHASE I CONTINUED
Identification and initial assessment of candidate test methodologies

- Three core materials (12-14 mm thickness)
  - Polyurethane foam core with density of 160 kg/m³ (10 lb/ft³)
  - Nomex honeycomb core
  - Aluminum honeycomb core

- Two facesheet materials (1.3-1.5 mm thickness each)
  - Woven carbon/epoxy, VARTM processed
  - Unidirectional carbon/epoxy, secondary bonding
PHASE I CONTINUED:

- Finite element analysis of initial test configurations
  - Evaluate fracture mode mixity (i.e. Mode I vs. Mode II)
  - Analyze stress state within specimen
  - Monitor crack opening after load application (Mode II)
  - Determine suitable loading geometries
  - Select promising Mode I and Mode II test configurations for mechanical testing
PHASE I CONTINUED:

- Finite element modeling
  - ANSYS 8.0 software
  - Two-dimensional, plane strain, geometrically nonlinear analyses
  - Crack path created with a row of overlapping nodes, coupled beyond crack tip
  - Crack closure method used to calculate energy release rates, $G_I$ and $G_{II}$
Identification of Mode I test configurations

- **Double Cantilever Beam (DCB)**
  - Significant Mode II component
  - Significant bending stresses in core
  - Crack “kinking” for Nomex honeycomb core
  - Specimen rotation due to off axis loading
  - Determined to be unsuitable for a standard test method

- **Modified DCB (MDCB)**
  - Significant Mode II component
  - Crack “kinking” for Nomex honeycomb core
  - Determined to be unsuitable for a standard test method
PHASE I MECHANICAL TEST RESULTS:

Mode I Investigation

✗ Single Cantilever Beam (SCB) with cantilever beam support
  - Significant Mode II component
  - Crack “kinking” for Nomex honeycomb core
  - Determined to be unsuitable for a standard test method

✗ Three Point Flexure (TPF)
  - Significant bending stresses in core
  - Extra machining operations required for specimen
  - Determined to be unsuitable for a standard test method
PHASE I MECHANICAL TEST RESULTS:

Mode I Investigation

- Plate-Supported SCB (MSCB)
  - Elimination of bending of sandwich specimen
  - Minimal Mode II component (less than 5%)
  - No significant bending stresses in core
  - No crack “kinking” observed
  - Appears to be suitable for a standard test method
PHASE I RESULTS:
Mode II Investigation

Identification of Mode II test configuration

- Three-point End Notch Flexure (3ENF)
- Mixed Mode Bending (MMB)
- End Load Split (ELS)
- Four-point delamination test
- Cracked Sandwich Beam (CSB) with hinge
- Modified CSB
- Facesheet delamination test
- DCB with uneven bending moments
- Three-point cantilever
- Double sandwich test
PHASE I RESULTS:
Mode II Investigation

- Challenges in developing a suitable Mode II test
  - Maintaining Mode II dominated crack growth with increasing crack lengths
  - Obtaining crack opening during loading
  - Obtaining stable crack growth along facesheet/core interface
  - Only two of the ten investigated test configurations produced any form of interlaminar stable crack growth
    - Modified CSB (MCSB)
    - Mixed Mode Bending (MMB)
  - Seven test configurations experienced crack “kinking”, the other unstable
PHASE I MECHANICAL TEST RESULTS:

Mode II Investigation

- Mixed Mode Bending (MMB)
  - Crack opening as delamination propagates for foam core
  - Possible to achieve high percentage Mode II (>90%) using short lever arm lengths
  - Semi-stable crack growth for foam core
  - Crack “kinking” for Nomex honeycomb core
  - Core crushing for aluminum honeycomb core

Not well suited for a standard Mode II test method
PHASE I MECHANICAL TEST RESULTS:

**Mode I Investigation**

- Modified Cracked Sandwich Beam with Hinge
  - Creates crack opening as delamination propagates
  - High percentage Mode II (>80%) for all materials investigated
  - Semi-stable crack growth along facesheet/core interface

Appears to be suitable for a standard Mode II test method

---

![Diagram of modified cracked sandwich beam with hinge](image-url)
PHASE II ACTIVITIES: Further Development of Mode I and Mode II Test Methods

- Sensitivity study – determination of acceptable range of specimen parameters
- Development of suitable test fixturing
- Development of suitable test procedures
- Development of suitable data analysis methods
SENSITIVITY STUDIES:
Determination of Acceptable Ranges of Specimen Parameters

- Facesheet parameters
  - Thickness, flexural stiffness, flexural strength

- Core parameters
  - Thickness, density, stiffness, strength

- Specimen and delamination geometry
CURRENT FOCUS:
Mode I Sensitivity Study

- Use of plate-supported Single Cantilever Beam (SCB) test
- Focus on two parameters of concern
  - Sandwich core material
  - Facesheet thickness
- Investigate mode mixity for range of delamination lengths
MODE I SENSITIVITY STUDY: Effect of Core Material on %Mode I

- Mode I dominant over range of cores considered
- Minimal variability among materials and crack lengths
- Test appears suitable for a wide range of common core materials
MODE I SENSITIVITY STUDY: Effect of Facesheet Thickness

Woven carbon/epoxy facesheets, polyurethane foam core

- Mode I dominant over range of facesheet thicknesses considered
CURRENT FOCUS: Mode I Test Fixture Development

- Ability to test 1 in. to 3 in. wide sandwich specimens
- Edge clamp restraints to lower panel support
- Translating fixture base
CURRENT FOCUS: Mode II Sensitivity Study

- Use of Modified Cracked Sandwich Beam
- Determination of acceptable range of specimen parameters
  - Core thickness, stiffness
  - Facesheet flexural stiffness
- Investigate mode mixity and crack opening for range of delamination lengths
MODE II SENSITIVITY STUDY: Effect of Core Material

- Varying the cores in plane modulus has little affect on % Mode II
  - Foam, Nomex, and aluminum honeycomb all remained above 90%

- Failure of test decided when there is core/face-sheet interaction

- In plane modulus of core affects crack length at which interaction begins

- Use trend line to develop MCSB core material test limits
CURRENT FOCUS: Mode II Test Fixture Development

- Modified three-point flexure configuration
- Emphasis on minimizing specialized specimen preparation-core removal
- Proposed design would support top face sheet without need of core removal
UPCOMING ACTIVITIES: Further Development of Mode I and Mode II Test Methods

- Sensitivity study – determination of acceptable range of specimen parameters
  - Computational simulations to determine limits
  - Experimental validation of limits
- Fabrication and evaluation of test fixturing
- Development of suitable test procedures
- Development of suitable data analysis methods
Thank You For Your Time
Any Questions