Strength and Damage Tolerance of Adhesively Bonded Joints: Stress-Based and Fracture-Based Approaches

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Outline

- Introduction
- Bonded Joint Stress Analyses
  - in-plane shear loading
  - combined shear + tension loading
  - plastic strain-based ultimate load
  - variable bondline thickness
  - tension loading in general unbalanced single lap joint
- Damage Tolerance of Disbonded Joints – Buckling/Disbond Growth
  - experiments
  - models
- New Directions
Introduction – General Joint Loading

- in-plane shear + tension produces adhesive shear stress
Introduction
Damage Tolerance: Buckling/Disbond Growth

- compression causes buckling
- subsequent disbond growth possible
Introduction
Damage Tolerance: Buckling/Disbond Growth

- Stringer-Stiffened Panel
- Wing Assembly

Disbond
Overarching Objectives

- bridge knowledge gap between **coupon data** and **full scale structural performance**

- provide engineering and scientific community with advancements in:
  - the mechanics of bonded joints
  - damage tolerance design and analysis philosophy

- assist FAA and GA companies by providing research support
In-Plane Shear Loaded Lap Joint

- in-plane shear load transfer across joint produces $\tau_{xz}$ shear stress in adhesive

In-Plane Shear Loaded Doubler

- inherently 2D problem

\[ \nabla^2 \tau_{xy}^o - \lambda^2 \tau_{xy}^o + C_o = 0 \]

\[ \tau_{xz}^a = t_o \frac{\partial \tau_{xy}^o}{\partial y} \quad \tau_{yz}^a = t_o \frac{\partial \tau_{xy}^o}{\partial x} \]

- \( \tau_{yz} \) shear peaks along \( x = 0, a \)

- \( \tau_{xz} \) shear peaks along \( y = 0, b \) (not shown)

Combined Loading: Shear + Tension

Von-Mises Based Failure Envelope

Plastic Strain-Based Ultimate Load

- in-plane shear loading
- ductile adhesive joint carries greater load than elastic-limit design
- more conservative than Hart-Smith elastic-perfectly plastic model

![Shear Stress vs Shear Strain Graph](image)

adhesive test data from J. Tomblin, WSU

- Data
- Fitting Curve

![Graph](image)

- Hart-Smith model
- nonlinear model
- FEA predictions
- elastic-to-failure

Failure Prediction vs. Test Data

- box beam torsion lap shear coupon
- experiments conducted by Wichita State University (John Tomblin)

Variable Bondline Thickness (VBT)
VBT: Increased Stress Due to Bondline Thinning

Tension Loading of Unbalanced Single Lap

- closed-form stress analysis of generalized unbalanced joint

Joint Specs:
- glass/epoxy,
- overlap $2c = 25.4$ mm,
- $t_o = 2.49$ mm, $t_i = 2t_o$, $t_a = 0.33$ mm
Damage Tolerance of Disbonded Joints

- damage tolerance is safety concern
- thin flanges
  - typically 1 mm (0.04 in.)
  - susceptible to buckling + disbond growth
- disbond not easily detectable
- adhesive properties affect growth critically
  - processing of joint very important
Buckling/Debonding Experiments

Construction:
- glass/epoxy & carbon/epoxy face sheets
- 6.3 mm foam core
- two halves secondarily bonded with PTM&W ES6292 paste adhesive
Disbond Growth Model

- one-edge free flanges

- fracture-mechanics based
  - compute strain energy release rate

- assumed post-buckled mode shape

\[
\begin{align*}
  w(x,y) &= \frac{1}{2} \left[ c_1 (y-b) + c_2 (y-b)^2 + c_3 (y-b)^3 + \\
  &\quad c_4 (y-b)^4 + \ldots c_n (y-b)^n \right] \left( 1 - \cos \frac{2m\pi x}{a} \right)
\end{align*}
\]

\[m = 1:\]

\[m = 2:\]
Comparison of Model and Experiments

Glass/Epoxy $[0]_4$; $b^* = 25.4$ mm – 0.8 mm Flanges

$G_c = 578$ J/m$^2$

Disbond Length, $a$ (mm)

Applied Farfield Strain, $\varepsilon_0$
Non-Uniform Disbond Growth Front

Initial Disbond

Corner Growth

Panel Boundary

Sandwich

Bond Overlap
Strain Energy Release Rate Profile

- detailed view of $G$ along disbond front
- predicts corner disbond initiation
- comparison with VCCT/FEA as programmed by R. Kreuger

![Diagram of disbond front with detailed view of $G$ along edge, predicted disbond initiation, and comparison with VCCT/FEA model programmed by R. Kreuger.](image-url)
New Directions: Intrinsic Material Properties vs. Joint Behavior*

- Understand relationship between intrinsic material properties vs. “properties” inferred from structural (joint) behavior
  - **Intrinsic** material properties should be independent of joint configuration, e.g., bondline thickness, mode of loading
- Resolve differences observed from different test methods:
  - Tensile test dogbone
  - Napkin ring
  - Krieger Gage / ASTM 5656
- Use nonlinear analyses and correlation with tests to extract **true**, consistent, description of intrinsic material behavior

* this topic was raised at the ASTM Symposium on Joining and Repair of Composite Structures, March 2003, Kansas City, MO
New Directions: Bonded Joint Impact

Damage on 38.1 mm Overlap Joint Due to 40 J Impact;
(a) Impact Side; (b) Back Side,
(c) C-Scan Showing Disbond Area

basic guidance studies needed:
- characterize damage modes
- identify damage formation mechanisms
- determine governing parameters

advanced:
- model predictions
New Directions:
Shear Buckling and Disbonding

- investigate in-plane shear buckling and subsequent disbond growth
- leads into combined compression + shear loading
New Directions: Health Monitoring of Bonded Joints

- real time (or time interval based) monitoring of joint health
  - existing: ultrasonic scanning
    - common method for discrete interval inspection
  - real-time implementation difficult
    - electrical resistance
    - external or embedded sensors / crack gages / fiber optics
    - acoustic waves

- useful for internal, non-accessible locations
- correlate measurements with damage shape and location
  - input for damage tolerance prediction models
New Directions:
Full-Scale Behavior Prediction

Path to get from Coupons & Elements to Full Scale Component Level

1. Understand Experimental Data
2. Other Factors

Refined Models:
- Adhesive Plasticity, Peel Stress
- Failure Under Multiaxial Stress, Fracture Mechanics

Sandwich Construction: Halves Bonded Along Top and Bottom C-L

Vertical Load

Side Load at 25% Chord

Disbond in Joint Between Fuselage Halves

Sandwich Construction: Halves Bonded Along Top and Bottom C-L

develop predictive models: maintain balance between simplicity and complexity