Effect of damage on performance of composite structures – applications to static and fatigue strength predictions

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Outline

• static
  – open hole
  – BVID

• fatigue
  – constant amplitude
  – B-Basis curve
  – “Goodman diagram”
  – truncation level determination
Sandwich with rampdown

Section cut through center of specimen
Effect of damage type on compression strength

![Graph showing the effect of damage type on compression strength. The graph compares undamaged and damaged strengths for different sizes of holes (0.25 diameter hole, BVID 21"x21", BVID 6"x6").](image)

Implication for cutoff strains

Size effect
Strength/Weight ratio for various materials and layups (sandwich under compression)

![Graph showing failure stress/panel weight (psi/lb) for various conditions: undamaged, 0.25" hole, BVID+ for each sample.](image-url)
Strength/Weight ratio for different materials and layup (sandwich under shear)

Normalized to 2ply, 3pcf HFT 250 cure

0.25" hole ↔ BVID
BVID versus 0.25” hole
(sandwich compression or shear)

• Statistically indistinguishable
• Can use 0.25” hole as a simpler test
• Can use hole analysis instead of more complicated impact damage analysis
• Subject to spot checking by tests (may be material dependent)
Cutoff strains

- Small coupon data are conservative
- Different cutoff strain values depending on application

*Implementation may require tailoring!*
Modeling impact damage

- Area of reduced stiffness (modulus retention ratio concept)
- Lekhnitskii-based stress analysis for laminate with inclusion – constant stiffness in the damaged region
- Linear variation of stiffness in the damaged region – limited test input required
- ND tests to measure in-plane stiffness of damaged region very worthwhile
Sandwich CAI – Analysis versus test

Unnotched strength (psi)

CAI (psi)

Damaged region has constant stiffness
Improved CAI analysis

The approach [1] treats the site with impact damage as an inclusion of different stiffness.

The variation of the stiffness inside the damaged region as a function of the radial distance \( r \) (no dependence on \( \theta \)),

\[
E = E_0 + E_1 \frac{r}{R}
\]

![Diagram showing the variation of stiffness with distance](image)

- Far field stiffness
- Puncture (hole) at center of damage site
- Damage site

\( R \) and \( R_i \) are the radii of the damage site and its inner boundary, respectively.
• calculate average stiffness in damage region
• divide by far-field stiffness (modulus retention ratio)
• compute SCF:

\[
SCF = 1 - (1 - \lambda) \frac{1 + \left( \frac{E_{12}}{E_{11}} \right) \sqrt{2 \left( 1 + \frac{E_{11}}{E_{12}} - \nu_{12} \right) + \frac{E_{11}}{G_{12}} + \frac{E_{11}}{E_{12}} - \nu_{12} \right)} \sqrt{E_{22}}}{1 + \lambda \left( 1 + \frac{E_{22}}{E_{11}} \right) \sqrt{2 \left( \frac{E_{11}}{E_{22}} - \nu_{12} \right) + \frac{E_{11}}{G_{12}} + \frac{E_{11}}{E_{12}} - \nu_{12} \right) \sqrt{E_{22}} - \frac{1}{E_{11}}}}
\]

• calculate CAI strength:

\[
\sigma_{CAI} = \frac{\sigma_u}{SCF}
\]

Ideally, should create a model that predicts E,o, E1 using NDI data. If not available, constants E,o and E1 can be back-calculated from one specimen and applied to other energy levels. R is measured from one specimen; Ri, if non-zero, assuming linear variation of Eo/(Eo+E1) and the same test specimen
CAI predictions versus test – improved model

Stiffness in damaged region = avg of linearly varying stiffness

![Graph showing experimental CAI strength versus prediction with improved model]
Fatigue analysis
(sandwich or monolithic structure)

• Probability of failure $p$ during each cycle
• Probability of failure $P$ after $n$ cycles
• Maximizing $P$ as a function of cycles gives a prediction for the cycles to failure
• $p$ ? In simplest approach assume $p =$ const
• Obtain $p$ from static test data (statistical distribution for static strength gives $p$)
Fatigue analysis

• R ratio dependence
• Statistical distribution dependence (normal versus 2-parameter Weibull)
• Sensitivity to statistical parameters (scatter)
Fatigue analysis based on the probability of failure

\[ P = Np(1 - p)^{(N-1)} \]
Cycles to failure

\[ N_c = -\frac{1}{\ln(1 - p)} \]

\[ p = 1 - 0.5\left[1 - \left[1 + (A + BZ_p)^C\right]^D + \left[1 + (A - BZ_p)^C\right]^D\right] \]

\[ Z_p = \frac{|\sigma_{\text{max}} - X_m|}{s} \]

Normal distribution

\[ A = 0.644693 \]
\[ B = 0.161984 \]
\[ C = 4.874 \]
\[ D = -6.158 \]

\[ \sigma_{\text{max}} = \beta \left( \frac{1}{N_f} \right)^\left( \frac{1}{\alpha} \right) \]

2 par Weibull with
\[ \alpha \] shape parameter and
\[ \beta \] scale parameter
Unidirectional AS4/3501-6 with R=0.
Tension-tension fatigue for $[(\pm 45/02)2]s$ T800/5245

![Graph showing stress (GPa) vs. cycles for different R values.

- Black squares with 'test [35]'
- White squares with 'present'

Lines indicate different R values: R=0.1 and R=0.5. The graph shows a decrease in stress with increasing cycles.}
Tension-compression fatigue (R=-1) for [(±45/02)2]s T800/5245
Compresion-compression fatigue ($R = 10$) for $[(\pm 45/02)2]s$ T800/5245
Tension-Torsion case (tension=torsion and R=0) for woven glass fabric
Onset of delamination load for skin/stiffener configuration (R=0.1, IM6/3501-6 material)
Onset of edge delamination for [352/-352/02/902]s AS4/PEEK (R=0.1)
Onset of delamination for quasi-isotropic glass/epoxy (R=0.1)
Tension-compression fatigue (R=-1) of [02/±45/02/±45/90]s BMI laminate
Tension-Compression (R=-1.66) failure of T300/914 bolted joints
Fatigue predictions for sandwich specimens with BVID

Compr. strain (microstrain)

Cycles
Applications

- Fatigue life prediction under constant amplitude
- Determination of B- (or A-) Basis life curve
- “Goodman” diagrams
- Truncation levels for testing
- Extension to spectrum loading
Determination of B-Basis life

- compare to Northrop report value of 13
"Goodman" diagram
Truncation level determination

- weak dependence on R
- 0.3-0.4 for 1 million cycles
Reminder

• still need to account for environment, material scatter (if not explicitly included in equations)
Conclusions

• 0.25” holes and BVID damage for sandwich are equivalent (compression and shear)
• predictions for CAI for sandwich with BVID
• determination of cycles to failure under constant amplitude
• application to:
  – B-Basis life determination
  – Goodman diagrams
  – truncation levels
Caveats

• Hole to Impact equivalence is a function of
  – specimen size
  – maybe material(?)

• Determination of fatigue curves requires further improvements:
  – Non constant value of p (track damage creation and growth)
  – Improved methodology for R-dependence

• “Analysis without testing is almost as bad as testing without analysis”