Residual Strength Characterization of Unitized Structures Fabricated Using Different Manufacturing Technologies

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Built-up and Integral Structures

• Built-up structure
  – Expensive & time intensive manufacturing & assembly
  – Difficult to inspect
  – Sites for crack initiation

• Integral Structure
  – Reduced assembly
  – Reduced initiation sites
  – Damage containment features
  – Effected by residual stress

**Integral types:**
- Machined (forged/extruded then machined to final form)
- Near net shape
- Joined

1 foot
Different Manufacturing Procedures Analyzed

24-inch wide integrally stiffened panel

Objective: Need robust analytical method to characterize these varying configurations.
Testing Facility

300 kip test facility

A typical panel test setup
Prediction Methodology

Coupon data utilized to predict the residual strength

Calibrated critical crack tip opening angle (CTOA) from coupon tests used in ZIP3D and STAGS analysis
Fracture Parameters Definition:

Crack Tip Opening Angle, $\Psi_c$ (CTOA)

- $\delta_c$ - Opening displacement
- $\Psi_c$ - Measured at a fixed distance $d$ behind the moving crack tip

$$\Psi_c = 2 \tan^{-1}\left(\frac{\delta_c}{2d}\right)$$

- $\Psi_c$ is a function of material and thickness

Plane strain core height, $h_c$
1. Develop CTOA vs. thickness relationship using mechanical test specimen data.

2. Analyze each section of an integrally stiffened panel using the appropriate CTOA.

Variation in critical CTOA with specimen thickness

Crack extends through sections of various thicknesses in the integrally stiffened panel
Crack Branching in Integral Structures

- Effects of crack tip plasticity, three dimensional constraints around a crack tip addressed.
- Crack branching process - not well understood.
- Crack growth in reinforced sections – not been fully realized.
Different Stages in Crack Branching

Crack growth simulation

STAGE 1

STAGE 2

STAGE 3

STAGE 4

General scenario

Lead crack branching into multiple integrals of various thickness
Load Crack Extension data for 24-inch Wide Unstiffened M(T) Panel

**Panel-1**

- **2219 - T81**
- **ZIP3D, 4.8 deg.**
- **STAGS, 4.8 deg., h_c = 0.15 in.**
- Front crack length
- Back crack length

- **Failure load**

**Panel-2**

- **2219 - T81**
- **ZIP3D, 4.4 deg.**
- **STAGS, 4.4 deg., h_c = 0.15 in.**
- Front crack length
- Back crack length

- **Failure load**

**V- fracture**

**Slant fracture**
Load Crack Extension data for 24-inch Wide Unstiffened M(T) Panel

V-fracture, Failure load (2c_i = 4.0 in.)
- 4.8 deg.
- 4.8 deg., h_c = 0.15 in.

Slant fracture, Failure load (2c_i = 6.0 in.)
- 4.4 deg.
- 4.4 deg., h_c = 0.15 in.

2219 - T81
W = 24.0 in.
B = 0.190 in.
da = 0.05 in.

Critical CTOA value for residual strength prediction 4.6 deg.
- 2c_i = 4.0 in.
- 2c_i = 6.0 in.
Load Crack Extension data for 24-inch Wide Built-up Panel

Panel-1

- 2219 - T81
- W = 24.0 in.
- B = 0.190 in.
- da = 0.05 in.
- 2c_i = 4.0 in.

Panel-2

- 2219 - T81
- W = 24.0 in.
- B = 0.190 in.
- da = 0.05 in.
- 2c_i = 6.9 in.

STAGS, 4.6 deg., h_c = 0.15 in.

Failure load

Front crack length
Back crack length

Intact stiffener

Rivet

Load, kips

Crack Extension, Δc, in

0 1 2 3 4 5

0 40 80 120 160

0 1 2 3 4

0 40 80 120 160

0.15"
0.75"
4.3"
2.0"
0.19"
Load Crack Extension data for 24-inch Wide Integrally Machined Panel

2219 - T81

- \( W = 24.0 \) in.
- \( B = 0.190 \) in.
- \( da = 0.05 \) in.

\( 2c_i = 6.0 \) in.

ZIP3D, 4.6 deg.

Test-1
- Front
- Back

Test-2
- Front
- Back
Load Crack Extension data for 24-inch Wide Free Form Panel

2219-T81
W = 24.0 in.
B = 0.190 in.
da = 0.05 in.
2ci = 6.0 in.

ZIP3D, 4.6 deg.

Test-1
○ Front
□ Back

Test-2
● Front
■ Back

Failure load
Intact integral
Load Crack Extension data for 24-inch Wide Extruded Panel

Crack Extension, Δc, in

Failure load

2219 - T81
W = 24.0 in.
B = 0.290 in.
2c_i = 6.0 in.
da = 0.05 in.

ZIP3D, 4.6 deg.

Intact integral

Test-1
- Front
- Back

Test-2
- Front
- Back

Test-1
Test-2

Load, kips

0 40 80 120 160 200 240

Crack Extension, Δc, in

0 1 2 3 4

Load Crack Extension data for 24-inch Wide Extruded Panel

Crack Extension, Δc, in

Failure load

2219 - T81
W = 24.0 in.
B = 0.290 in.
2c_i = 6.0 in.
da = 0.05 in.

ZIP3D, 4.6 deg.

Intact integral

Test-1
- Front
- Back

Test-2
- Front
- Back

Test-1
Test-2

Load, kips

0 40 80 120 160 200 240

Crack Extension, Δc, in

0 1 2 3 4
Schematic of Friction Stir Welding Process

HAZ – Heat affected zone
TMAZ – Thermomechanically affected zone

Residual Stress Distribution in Friction Stir Welded Aluminum alloy
ZIP3D Finite Element Model of 24-inch Wide FSW Residual Strength Panel

Analysis accounts for:

- Multiple materials
- Residual stress effects due to FSW
- Crack Branching into Integral
- Variation in thickness
- Plasticity effects
Load Crack Extension data for 24-inch Wide FSW Panel

2219 - T81
W = 24.0 in.
B = 0.190 in.
da = 0.05 in.
2c_i = 6.0 in.

ZIP3D, 4.6 deg.

Test-1
- Front
- Back

Test-2
- Front
- Back

Failure load

Intact integral
• The prediction methodology estimated the residual strength of both built-up and integrally machined 24-inch wide panels within 5.0 % of test.

• The analysis predicted the residual strength of FSW and EBF3 panels within 10 % of test data.
  – The panels will be reevaluated for residual strength after obtaining the residual stress field and stress-strain curve for the heat effected zone and deposited material.

• The analysis results indicate a robust prediction methodology based on CTOA concept is able to characterize varying integral configurations fabricated using different manufacturing procedures.