Residual Strength Characterization of Unitized Structures Fabricated Using Different Manufacturing Technologies

B.R. Seshadri  
National Institute of Aerospace

S.W. Smith  
NASA Langley Research Center

W.M. Johnston  
Lockheed Martin Engineering and Sciences Corporation

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• Built-up and Integral Structures

• Development of Prediction Methodology for Integral Structures Fabricated using different Manufacturing Procedures

• Testing Facility

• Fracture Parameters Definition

• Crack Branching in Integral Structures

• Results and Discussion

• Concluding Remarks
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
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
As part of earlier aging aircraft program, 40-inch and 12-inch wide built-up stiffened and unstiffened panels with and without multi-site-damages (MSDs) were successfully analyzed for residual strength using CTOA concept.

As part of aircraft-structural integrity program (ASIP), large curved built-up panels were analyzed for residual strength under pressure loading.

40-inch wide flat integrally stiffened thin panels with initial crack were analyzed for residual strength.

48-inch wide curved integrally stiffened panel was analyzed for residual strength under the combination pressure and tensile loading.

20-inch wide integrally stiffened Alcoa thick panels were analyzed for residual strength.

C(T) and M(T) specimens of various thicknesses and materials have been successfully tested and analyzed using CTOA concept.
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
W = 24.0 in.
B = 0.190 in.
da = 0.05 in. 2c_i = 4.0 in.

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

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 (2ci = 4.0 in.)
- 4.8 deg.
- 4.8 deg., hc = 0.15 in.

Slant fracture, Failure load (2ci = 6.0 in.)
- 4.4 deg.
- 4.4 deg., hc = 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.

2ci = 4.0 in.
2ci = 6.0 in.
Load Crack Extension data for 24-inch Wide Built-up Panel

Panel-1

- STAGS, 4.6 deg., $h_c = 0.15$ in.
- 2219 - T81
  - $W = 24.0$ in.
  - $B = 0.190$ in.
  - $d_a = 0.05$ in.
  - $2c_i = 4.0$ in.

Panel-2

- STAGS, 4.6 deg., $h_c = 0.15$ in.
- 2219 - T81
  - $W = 24.0$ in.
  - $B = 0.190$ in.
  - $d_a = 0.05$ in.
  - $2c_i = 6.9$ in.
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.

Intact integral
Test-1
Test-2

ZIP3D, 4.6 deg.

Failure load

Load, kips

Crack Extension, Δc, in
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.
2c_i = 6.0 in.

ZIP3D, 4.6 deg.

Failure load
Intact integral

Test-1
- Front
- Back

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

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

**ZIP3D, 4.6 deg.**

**Test-1**
- Front: ○
- Back: □

**Test-2**
- Front: ●
- Back: ■

**Failure load**

0.19"
0.15"
4.3"
0.75"
12"
12"

W = 24.0 in.
B = 0.290 in.
$2c_i = 6.0$ in.
da = 0.05 in.
Schematics of Friction Stir Welding Process

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

Load, kips

Crack Extension, Δc, in

Test-1
- Front
- Back

Test-2
- Front
- Back

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

ZIP3D, 4.6 deg.

Failure load

Test-1
Test-2

Intact integral
Concluding Remarks

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

• The panels will be reevaluated for residual strength after obtaining the residual stress field and stress-strain curve for the heat effected zone material.

• The analysis methodology demonstrated potential for use in future design of integrally stiffened aerospace structures.