

**The Boeing Company
Engineering Test and Technology
Boeing Research and Technology**

**Continuous Lower Energy, Emissions, and Noise (CLEEN II) Structurally Efficient Wing
(SEW) Final Public Report**

**FAA/Boeing CLEEN II
Technology Demonstration Program**

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CLEEN II SEW Final Public Report

Overview

Boeing developed, built, and tested a next-generation wing structure that demonstrated significant improvements in structural efficiency. The demonstration showed a continuous weight reduction as compared to the 777-200 baseline. SEW technologies could potentially reduce fuel consumption up to 3.5% through weight reduction of the wing. SEW technologies contribute to the FAA's CLEEN II goal of reducing fuel burn.

The SEW Geometry corresponding to the Wing Component Test Article (WCTA) is shown in Figure 1.

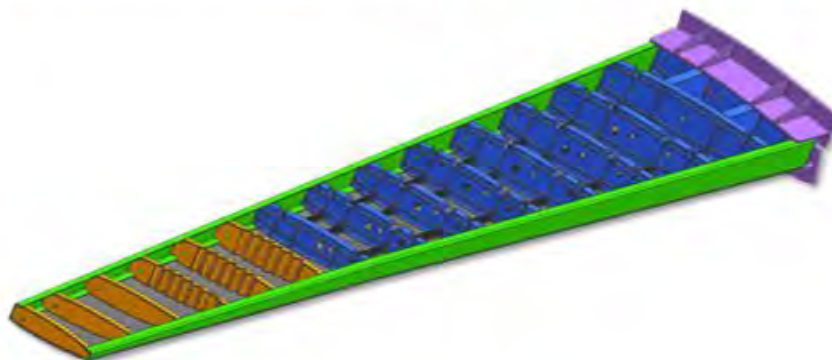


Figure 1 CLEEN II Structurally Efficient Wing (SEW)

The objective of the SEW Program was to demonstrate, through a disciplined building block test approach, a suite of material and structural technologies that contribute to the CLEEN II goal of

achieving fuel burn reductions by 2026. Cumulative anticipated benefits projected over twenty years are, Jet A fuel consumption savings of approximately 200 million tons and CO₂ production avoidance of approximately 660 million tons. The technologies, demonstrated in the WCTA, are summarized in Figure 2.

SEW CLEEN II Technology	Goal Impact	Benefits and Application
<ul style="list-style-type: none"> • Advancing manufacturing technologies • Advanced prepreg composites • Resin-infused stitched blade stringers • Resin-infused hat stringers • Advanced alloy metallic ribs • Resin-infused sine wave rib • Stamped thermoplastic ribs 	<p>Fuel burn reduction</p> <p>CO₂ Production Avoidance</p>	<p>Lower weight, higher performance wing</p>

All technologies contribute to the fuel consumption reduction goal by reducing structural weight and/or Drag

Figure 2 CLEEN II SEW Technologies

Technology Development

The major achievements for the SEW Program are summarized in Figure 3. The achievements track the graduation of SEW technologies from Technology Readiness Level (TRL) 3 to TRL 6.

- *Concept of Design Review (CoDR) Completed Early*
- *Preliminary Design Review (PDR) & Coupon Tests Completed (TRL4)*
- *Building Block Tests Completed (TRL5)*
- *Detail Design Review (DDR) Completed Early*
- *Tooling, Part & Test Fixture Fab Completed*
- *Test Readiness Review (TRR) Completed Early*
- *Full Scale Test Series Completed (TRL 6)*

Figure 3 SEW Major Achievements

The specific technologies included in the WCTA are described in Figure 4. The technologies were selected due to their potential for contributing to the FAA's CLEEN II goal of reducing fuel burn through weight reduction of the wing.

The upper skin was made from BMS8-276 composite material. Non-traditional laminates (NTLs) were incorporated to enable aeroelastic tailoring. Upper skin stringers were resin infused and precured prior to co-bonding to the upper skin. The vent stringer was fabricated from braided carbon fiber. The blade stringers were stitched and fabricated from non-crimp fabric.

The lower skin was made from IM+ composite material with higher stiffness compared to BMS8-276. NTLs were also incorporated into the lower skin. Lower skin stringers were also made with IM+ composite material and they were cocured with the lower skin.

The spars were also made from IM+ composite material. The aft spar included a co-cured splice with a kick in the span wise direction to capture realistic complexity representative of typical production designs.

Ribs in the inboard portion of the WCTA were made from Aluminum Lithium (Al-Li). That portion of the WCTA was designated as a wet fuel bay with requirements to sustain internal pressure loads. The pressure loads induce bending in rib flanges fastened to the skins. Laminated composite ribs would include an inherent interlaminar tension (ILT) weakness with increased weight. Therefore, metallic ribs, without the ILT weakness, were chosen.

Ribs in the outboard portion of the WCTA were made from composite material. That portion of the WCTA was designated as a dry bay without requirements to sustain internal pressure loads. Several

of the outboard ribs were stamp formed thermoplastic composite ribs. One of the outboard ribs was made of resin infused braided carbon fiber, similar to the vent stringer.

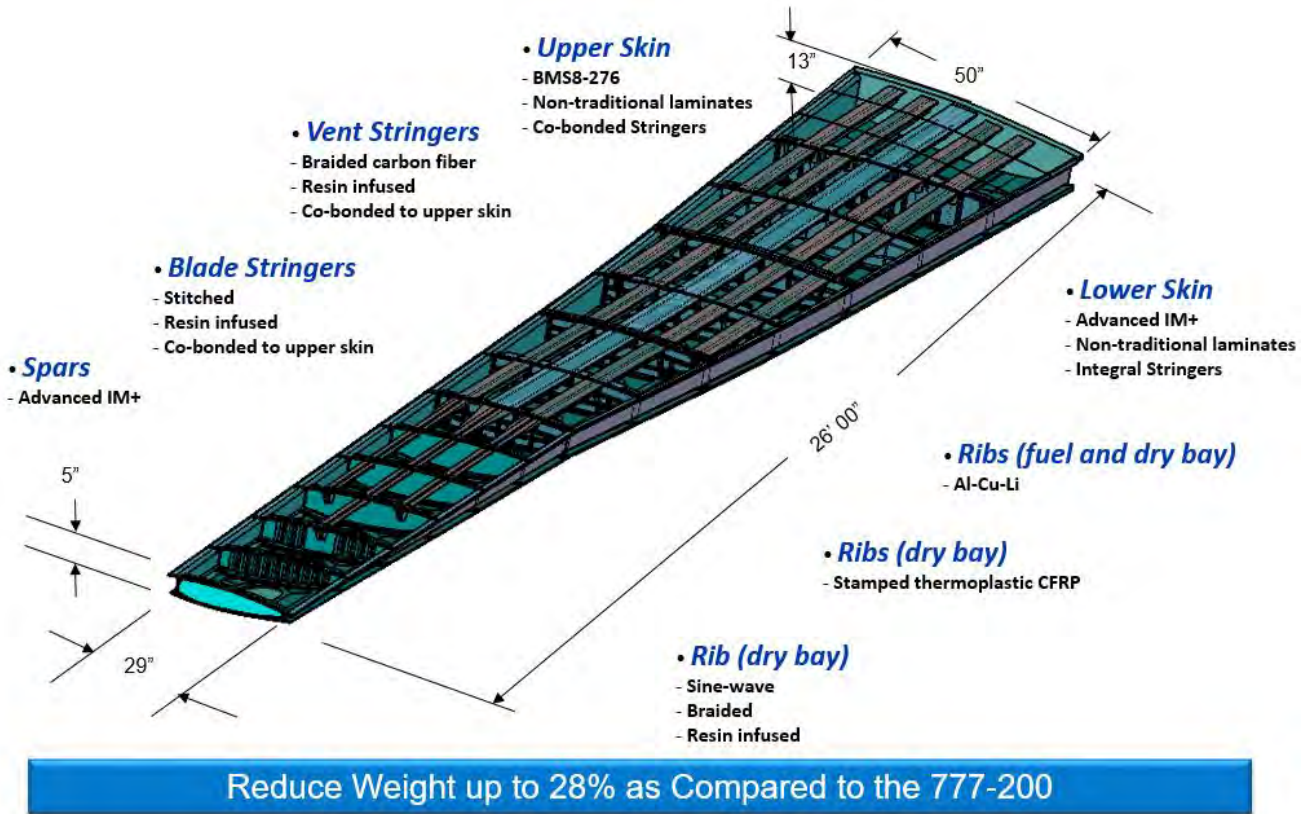


Figure 4 CLEEN II SEW Technology Demonstrations

The SEW Program Schedule is illustrated in Figure 5. It was accelerated to graduate technologies to TRL 6, including building block testing, a full scale static test, and a full scale residual strength test, in order to promote technology transition to future Boeing products. At the end of the program opportunities for additional large notch panel testing and NTL data correlation were leveraged to provide risk reduction in support of far term technology transition.

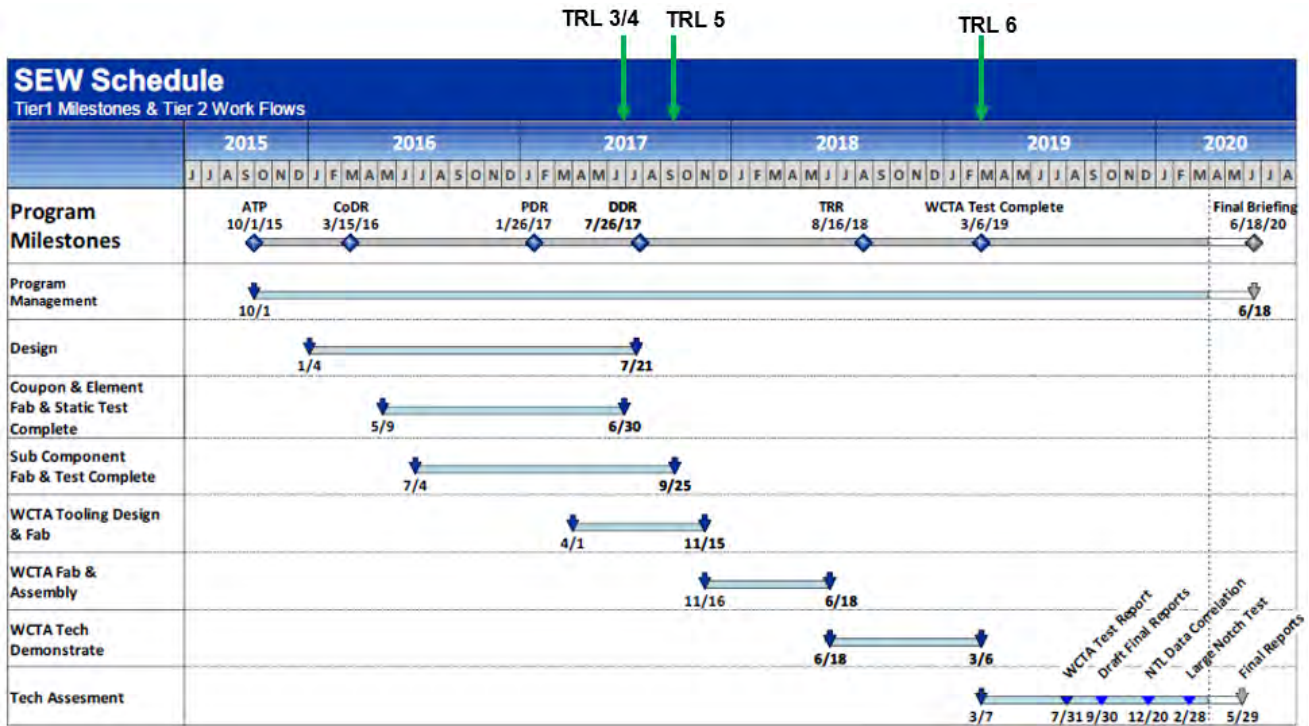


Figure 5 CLEEN II Boeing SEW – Accelerated Schedule

Early assembly preparation is illustrated in Figure 6. The assembly cell included a transport cart to control the position of the lower wing skin during assembly. Tooling was also located around the transport cart to control the position of the spars and ribs. Figure 6 also shows several of the components to be assembled. Those components are the upper skin with co-bonded blade and hat stringers, a resin infused sine-wave rib, and a thermoplastic rib.

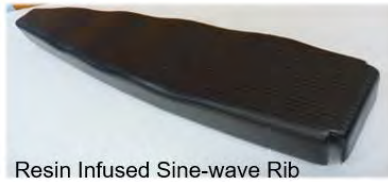


Figure 6 SEW WCTA Assembly Preparation

The full scale test of the WCTA was executed by the National Institute for Aviation Research (NIAR) at Wichita State University. The load introduction hardware included fore and aft framework around the WCTA as shown in Figure 7. Load was introduced through load pads at internal rib stations.



Figure 7 SEW WCTA Test

The WCTA was tested successfully to 177% Design Limit Load (DLL) at NIAR. Completion of this test established a TRL of 6 for SEW technologies, including composite material technologies at elevated temperature / wet conditions. Figure 8 shows the WCTA deflected state at 177% DLL.



Figure 8 SEW WCTA Test to 177% Design Limit Load

A residual strength test was performed after the test to 177% DLL to satisfy damage tolerance requirements. Damage was introduced into the WCTA as shown in Figure 9. The damage resided in the upper skin and front spar.



Figure 9 WCTA Residual Strength Test Configuration

The WCTA residual strength test was successfully completed. The area of the WCTA damaged prior to test was painted white for enhanced visualization. Figure 10 shows the overall deformation of the WCTA at failure as well as a close up of the damage in the upper wing skin.

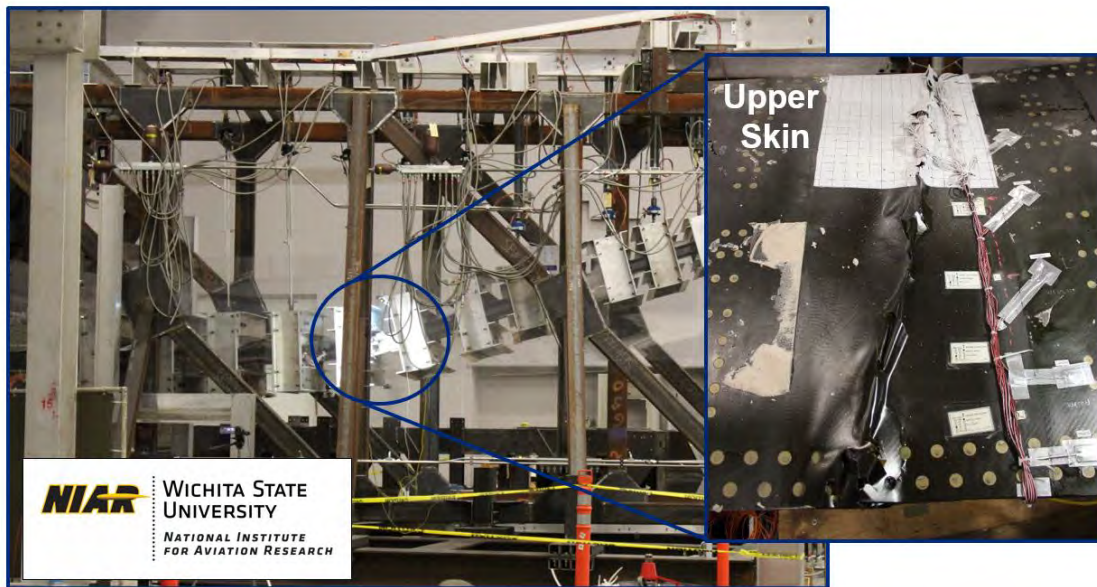


Figure 10 SEW WCTA Residual Strength Test

The WCTA residual strength test results indicated excellent correlation of test data and analysis. Figure 11 shows crack growth versus load data. Video and strain gage test data are shown as blue and orange respectively. Finite Element Model (FEM) analysis data are shown as green.

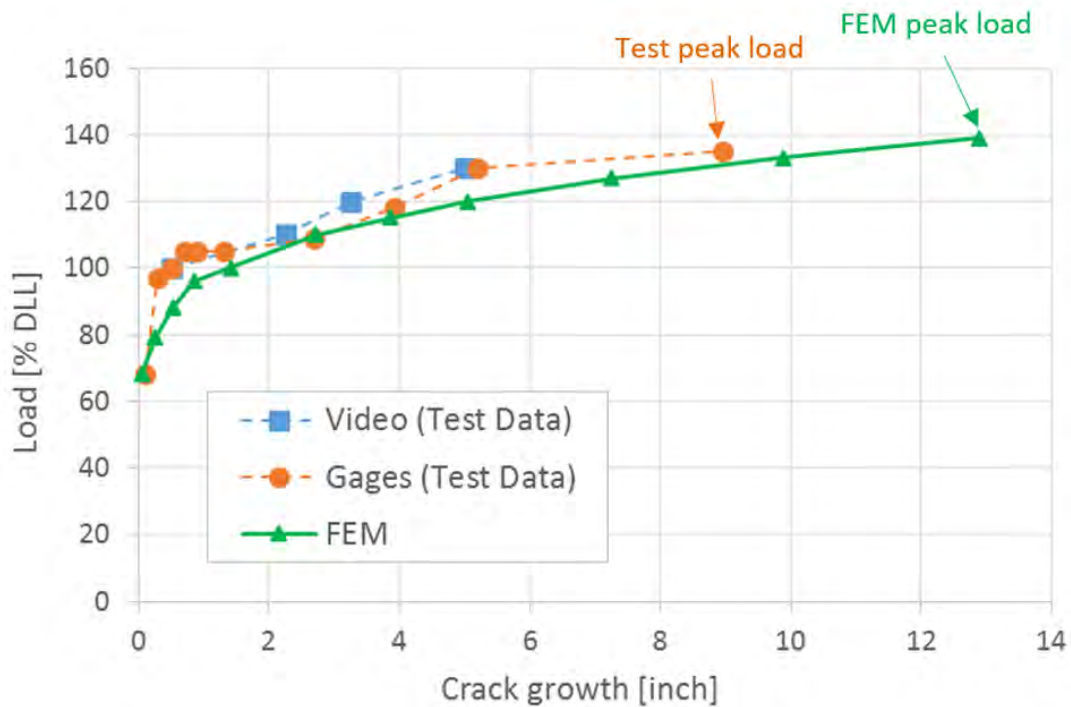


Figure 11 Residual Strength Test Analysis

The WCTA residual strength FEM behavior exhibited excellent correlation with test article behavior as illustrated in Figure 12. Damage propagation shown as red pixels in the FEM correlated well with actual damage observed in the upper skin and front spar.

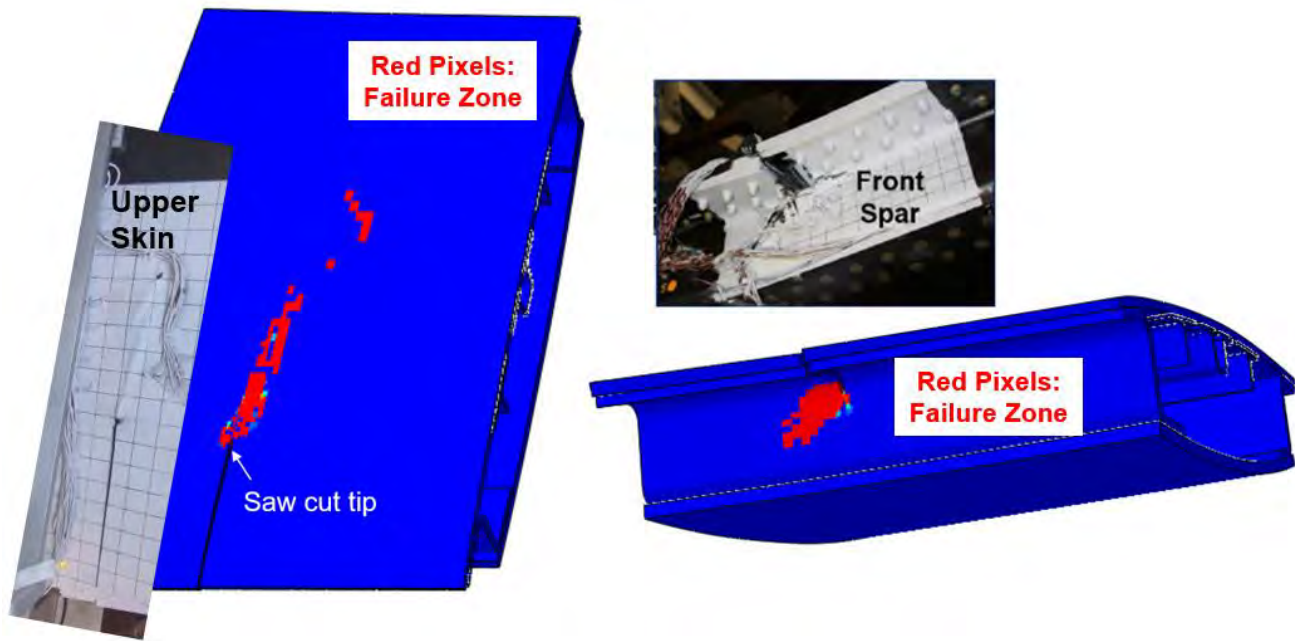


Figure 12 Residual Strength Model Behavior

Summary

The SEW WCTA demonstrated technologies encompassing more efficient materials, laminate definition, and wing box structural configuration. The building block test results support the transition of SEW technologies to commercial transport and military applications. Highlights from the SEW Program include:

- The building-block test approach on SEW developed the selected technologies along the TRL scale, resulting in a TRL 6 demonstration with the completion of the Wing Component Test Article (WCTA) full scale test series.
- SEW contributes to the FAA's CLEEN II goal of reducing fuel burn.
- SEW technologies could potentially reduce fuel consumption up to 3.5% through weight reduction on future commercial transport wing.
- FAA & Industry benefit from continued CLEEN program investment and collaboration.
- The SEW building block development program, which culminated in the WCTA test activity, collectively demonstrated feasibility of numerous structural technologies, some of which could be considered for future commercial airplane development programs.

Acronyms

ATP	Authority to Proceed
CoDR	Concept Design Review
DDR	Detailed Design Review
DLL	Design Limit Load
FEM	Finite Element Model
NIAR	National Institute for Aviation Research
PDR	Preliminary Design Review
SEW	Structurally Efficient Wing
TRL	Technology Readiness Level
TRR	Test Readiness Review
WCTA	Wing Component Test Article