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PRSEUS Acoustic Panel Fabrication

Alex Velicki, Nicolette P.Yovanof, Jaime Baraja, Gopal Mathur, Patrick Thrash,
and Robert Pickell
The Boeing Company, Huntington Beach, California

November 2011

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FOREWORD

This document summarizes the work performed by Boeing Research & Technology, Huntington Beach, California under the Environmentally Responsible Aviation (ERA) Project to explore and document the feasibility, benefits, and technical risk of advanced vehicle configurations and enabling technologies that will reduce the impact of aviation on the environment. This report documents the work that was performed under a task order contract to design and fabricate a PRSEUS acoustic test panel. The panel was delivered to NASA-LaRC in April for final specimen preparation and acoustic testing in the Structural Acoustics Loads and Transmission (SALT) test facility. The ultimate goal of this activity is to assess the sound transmission characteristics of a PRSEUS panel subjected to a representative Hybrid Wing Body (HWB) operating environment.

The NASA technical monitor was Richard Silcox, Chief Engineer for Acoustics, Research Directorate, NASA-LaRC. Major contributions to the written report were made by Mr. Albert Allen of the NASA Structural Acoustics Branch by providing the testing and advanced concepts write-ups.

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TABLE OF CONTENTS

Introduction 1

1.0 Baseline Specimen Design 3
  1.1 Boundary Layer Calculation 3
  1.2 Acoustic Testing Approach 4
  1.3 PRSEUS Panel Design and Fabrication Background 5
  1.4 Specimen Design 6
  1.5 Panel Material Properties 10

2.0 Panel Fabrication 15
  2.1 Preform Assembly and Stitching 15
  2.2 Resin Infusion and Cure 17
  2.3 Edge Trim Machining 19
  2.4 Panel Dimensional Check 20
  2.5 Panel Adaptor Frame and Shim Fabrication 21

3.0 Test Specification Preparation 25
  3.1 Freely Hung Structural Vibration Testing 25
  3.2 In-situ Vibroacoustic Testing 28
  3.3 Testing Responsibilities and Contact Information 29

4.0 Advanced Concept Development 30
  4.1 Possible Areas of Study 30
  4.2 Proposed Future Work 32

5.0 Summary 33

Appendix – Specimen Design Drawings (5 pages) 35

LIST OF FIGURES

Figure 1. Overview of HWB PRSEUS Airframe Development Testing 1
Figure 2. Baseline Schedule and Work Statement 2
Figure 3. Aerodynamic BWB Baseline Configuration 3
Figure 4. Boundary Layer Thickness for the BWB-450-1L Configuration 4
Figure 5. Acoustic Testing Approach in SALT Facility 5
Figure 6. Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) 5
Figure 7. Stitched Dry Fabric Used to Create Self-Supporting Preform 6
Figure 8. Resin Infusion Approach and Cured Panel 6
Figure 9. PRSEUS Panel Materials Used for Multi-Bay Box Specimen 7
Figure 10. Test Panel Stringer and Frame Layout 7
Figure 11. Stringer Wrap Geometry 8
Figure 12. Nominal Panel Edge Geometry 8
Figure 13. Nominal Frame Geometry 9
Figure 14. Nominal Stitch Seam Locations in Frames and Stringers 9
Figure 15. Warp-Knit Fabric Arrangement 10
Figure 16. Stringer and Frame Details Inserted into Preform 15
Figure 17. Doubler and Skin Details Added Prior to Stitching 16
Figure 18. Single-sided Stitching Technique (Different Panel Shown) 16
Figure 19. Acoustic Panel During Resin Infusion 17
Figure 20. Completed Resin Infusion Operation 18
Figure 21. Cured Specimen Blank Prior to Edge Trim 18
Figure 22. Close-up of Cured IML Surface 19
Figure 23. Cured Specimen OML Surface 19
Figure 24. Specimen Edge Trim Machining at Vendor Facility 20
Figure 25. Panel OML Surface Displacement (inches) – Frames are Vertical 20
Figure 26. Adaptor Frame Detail 21
Figure 27. Adaptor Frame Geometry 22
Figure 28. Adaptor Frame Cross Section Geometry 22
Figure 29. Layer Shim Map 23
Figure 30. Shim Fabrication 24
Figure 31. SALT Facitily Layout 26
Figure 32. PRSEUS Test Panel FEM with Adaptor Frame (235,914 DoFs) 27
Figure 33. Statistical Energy Analysis (SEA) Model of PRSEUS Test Panel 28
Figure 34. Candidate Integral Acoustic Improvements Under Consideration 30
Figure 35. Specimen Drawing Sheet 1 of 5 35
Figure 36. Specimen Drawing Sheet 2 of 5 36
Figure 37. Specimen Drawing Sheet 3 of 5 37
Figure 38. Specimen Drawing Sheet 4 of 5 38
Figure 39. Specimen Drawing Sheet 5 of 5 39

LIST OF TABLES

Table 1. Panel Fabric Specifications 10
Table 2. Warp-Knit Fabric Stacking Architecture 11
Table 3. Laminate Stiffness 11
Table 4. Laminate Unnotched Strengths [ksi] 11
Table 5. Laminate CAI Strength for Exterior Members (100 ft-lb impact) 12
Table 6. Laminate CAI Strength for Interior Members (20 ft-lb impact) 12
Table 7. Rohacell Minimum Properties 12
Table 8. Rod Mechanical Properties 13
Table 9. Environmental Correction Ratios 14
Table 10. Frame Component Material Properties 23

ACRONYMS

BHD	Bulkhead
BWB	Blended Wing Body
CAI	Compression After Impact
CD	Cold Dry
CAPRI	Controlled Atmospheric Pressure Resin Infusion
CG	Center of Gravity
COLTS	Combined Loads Test System
D&DT	Durability and Damage Tolerance
FAR	Federal Aviation Regulations
FEM	Finite Element Model
H/W	Hot/Wet
HWB	Hybrid Wing Body
ICD	Interface Control Drawing
IML	Inner Moldline
IRAD	Independent Research and Development
KEAS	Knots Equivalent Airspeed
KIPS	Thousand Pounds
KSI	Thousand Pounds Per Square Inch
MLG	Main Landing Gear
MTOGW	Maximum Takeoff Gross Weight
MZFW	Maximum Zero Fuel Weight
NDE	Nondestructive Evaluation
NDI	Nondestructive Inspection
N_x	Axial Load in x-direction
N_{xy}	Shear Load in xy-plane
N_y	Axial Load in y-direction
OB	Outboard
OEW	Operator Empty Weight
OML	Outer Moldline
OHC	Open Hole Compression
OML	Outer Moldline
PRSEUS	Pultruded Rod Stitched Efficient Unitized Structure
PSI	Pounds per Square Inch
SALT	Structural Acoustics Loads and Transmission
SEA	Statistical Energy Analysis
SQ-IN	Square Inches
TBL	Turbulent Boundary Layer
VARTM	Vacuum-Assisted Resin Transfer Molding

INTRODUCTION

NASA has created the Environmentally Responsible Aviation (ERA) Project to explore and document the feasibility, benefits, and technical risk of advanced vehicle configurations and enabling technologies that will reduce the impact of aviation on the environment. A critical aspect of this pursuit is the development of a lighter, more robust airframe that will enable the introduction of unconventional aircraft configurations that have higher lift to drag ratios, reduced drag, and lower community noise. The primary structural concept being developed under the ERA program in the Airframe Technology element is the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) structural concept.

To improve structural performance and reduce fabrication costs beyond those achieved using conventional state-of-the-art composite fabrication techniques, the PRSEUS panel construction utilizes an integral one-piece design approach with cocured details that are joined together by stitching to provide exceptional out-of-plane strength and improved damage tolerance. Although the resulting structure has been shown to meet the demanding out-of-plane loading requirements of the Hybrid Wing Body (HWB) flat-sided pressure cabin design, there are concerns that the lighter, stiffer, cocured details of the PRSEUS structure could have higher sound transmission levels than those exhibited by conventional build-up structures flying today.

To address these concerns, and to establish a baseline set of acoustic characteristics for a PRSEUS panel, an acoustic test panel was designed, fabricated, and then delivered to NASA-LaRC for testing. The test panel design was based on the Hybrid Wing Body (HWB) minimum-gauge pressure cabin panel geometry established during the NASA NRA Phase I trade studies (Ref 1) and then structurally tested during the Phase II portion (Ref 2) of the program. An overview of the partially completed NRA/ERA PRSEUS specimen testing is shown Figure 1.

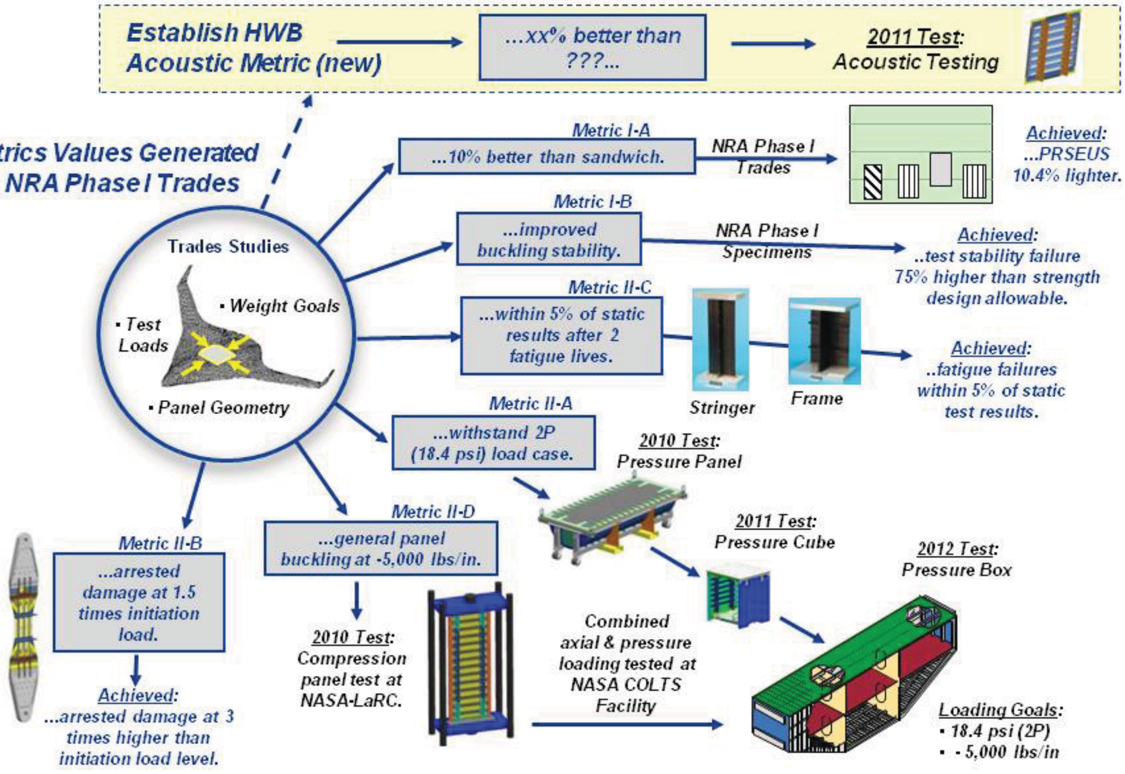
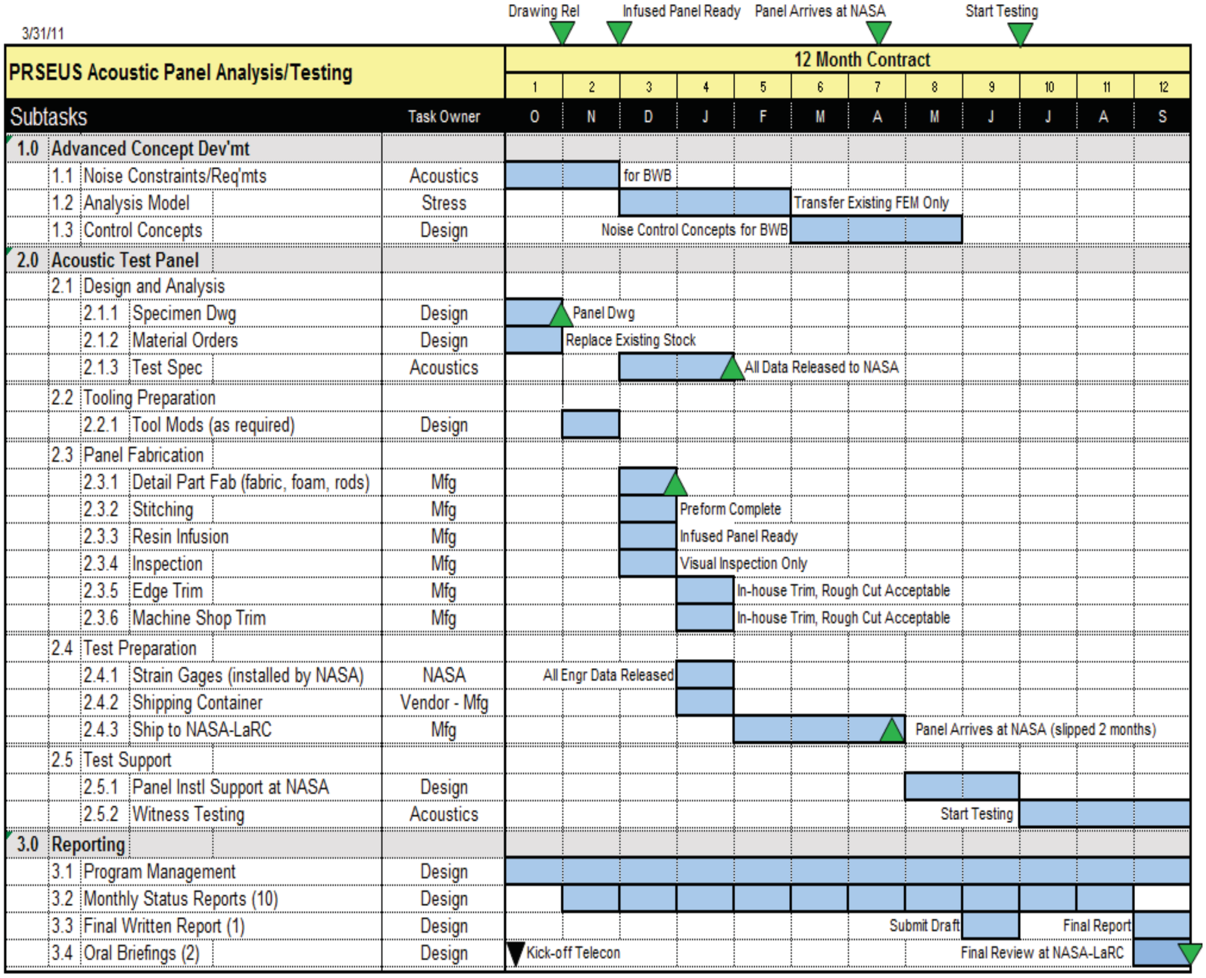


FIGURE 1. OVERVIEW OF HWB PRSEUS AIRFRAME DEVELOPMENT TESTING

The primary objective of this task order contract was to design and fabricate an acoustic test specimen that would be delivered to NASA-LaRC to support a NASA-funded test program. In parallel with this testing, some initial conceptual investigations were completed to assess the manufacturing feasibility of changing specific panel design parameters that could improve the acoustic signature without adding substantial weight to the panel. Techniques such as integral damping and hybrid materials in the skin were conceptually assessed, along with some other alternatives that could potentially reduce sound transmission through PRSEUS structures. The overall work statement of this 12-month project is summarized below in Figure 2.



3/31/11

Drawing Rel · Infused Panel Ready · Panel Arrives at NASA · Start Testing

PRSEUS Acoustic Panel Analysis/Testing — 12 Month Contract

	Subtasks	Task Owner	1 O	2 N	3 D	4 J	5 F	6 M	7 A	8 M	9 J	10 J	11 A	12 S	Notes
1.0	**Advanced Concept Dev'mt**														
1.1	Noise Constraints/Req'mts	Acoustics	■	■											for BWB
1.2	Analysis Model	Stress			■	■	■								Transfer Existing FEM Only
1.3	Control Concepts	Design						■	■	■					Noise Control Concepts for BWB
2.0	**Acoustic Test Panel**														
2.1	Design and Analysis														
2.1.1	Specimen Dwg	Design	■												Panel Dwg
2.1.2	Material Orders	Design	■												Replace Existing Stock
2.1.3	Test Spec	Acoustics			■	■									All Data Released to NASA
2.2	Tooling Preparation														
2.2.1	Tool Mods (as required)	Design		■											
2.3	Panel Fabrication														
2.3.1	Detail Part Fab (fabric, foam, rods)	Mfg			■										
2.3.2	Stitching	Mfg			■										Preform Complete
2.3.3	Resin Infusion	Mfg			■										Infused Panel Ready
2.3.4	Inspection	Mfg			■										Visual Inspection Only
2.3.5	Edge Trim	Mfg				■									In-house Trim, Rough Cut Acceptable
2.3.6	Machine Shop Trim	Mfg				■									In-house Trim, Rough Cut Acceptable
2.4	Test Preparation														
2.4.1	Strain Gages (installed by NASA)	NASA				■									All Engr Data Released
2.4.2	Shipping Container	Vendor - Mfg				■									
2.4.3	Ship to NASA-LaRC	Mfg					■	■	■						Panel Arrives at NASA (slipped 2 months)
2.5	Test Support														
2.5.1	Panel Instl Support at NASA	Design								■	■				
2.5.2	Witness Testing	Acoustics										■	■	■	Start Testing
3.0	**Reporting**														
3.1	Program Management	Design	■	■	■	■	■	■	■	■	■	■	■	■	
3.2	Monthly Status Reports (10)	Design		■	■	■	■	■	■	■	■	■	■		
3.3	Final Written Report (1)	Design									■			■	Submit Draft; Final Report
3.4	Oral Briefings (2)	Design	▼											■	Kick-off Telecon; Final Review at NASA-LaRC

FIGURE 2. BASELINE SCHEDULE AND WORK STATEMENT

In parallel with the concept development activities, the specimen fabrication tasks were completed and resulted in the delivery of a 4-ft by 4-ft PRSEUS test panel to the NASA-LaRC Structural Acoustic Loads Transmission (SALT) test facility in mid April 2011. The completion of this milestone represented the majority of the work plan, leaving only the final reporting and test coordination activities to close out the task order contract.

At this early stage in the development of the PRSEUS structural concept, the acoustic studies are emphasizing experimentation in order to quantify a baseline set of noise and vibration parameters that can be used to quantitatively measure the baseline, as well as calibrate the analytical methods that will ultimately be required to assess future candidate improvements to the baseline panel construction.

1.0 BASELINE SPECIMEN DESIGN

Gathering a consistent set of design guidelines for the acoustic specimen was complicated slightly by the fact that several different HWB baseline configurations are being concurrently studied within NASA and Boeing at any given point in time. Although nearly all of the structures data was derived using the 408,000-lbs MTOW BWB-5-200G planform (Ref 1), the aerodynamic studies were primarily focused on the larger 867,000 to 940,000-lbs MTOW BWB-450 baseline airplane. Normally such large differences in MTOW would lead to substantially different structural gauges and panel geometries, but in this case, the critical acoustic regions are typically concentrated in the thinnest or minimum-gauge regions of the cabin. For a conventional tube-and-wing aircraft the minimum-gauge panel regions are strongly influenced by the fuselage radius, which is more or less, dictated by the specific payload/MTOW of the design. This is different for the flat-sided HWB panels, which are primarily sized by the internal pressure, or 2P loading condition, making it much less sensitive to vehicle size or weight. As such, the minimum-gauge panel geometries derived from the BWB-5-200G configuration can easily be combined with the aerodynamic properties derived for the BWB-450 configuration to generate a consistent set of test parameters needed for conducting an initial acoustic assessment.

1.1 Boundary Layer Calculation

The higher MTOW BWB-450-1L planform (Figure 3) was used to derive the boundary layer thickness for the acoustic analyses and testing activities. (Note: The “1L” nomenclature designation is for configuration control and denotes a minor planform change for a particular study.)

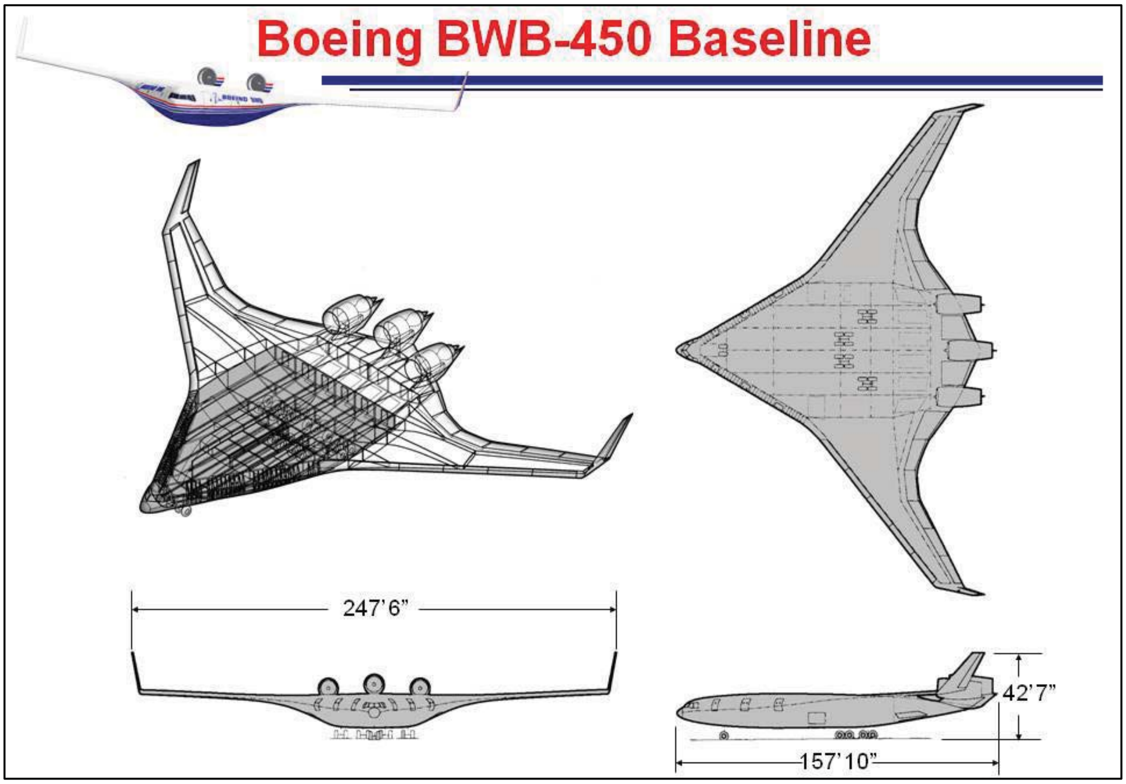


FIGURE 3. AERODYNAMIC BWB BASELINE CONFIGURATION

Boundary layer thickness δ and displacement thickness δ* results along fuselage length were calculated using CFD methods and are plotted in Figure 4 using the following flow parameters: $M_\infty = 0.85$, Re = 170,380, $T_\infty = 394°R$.

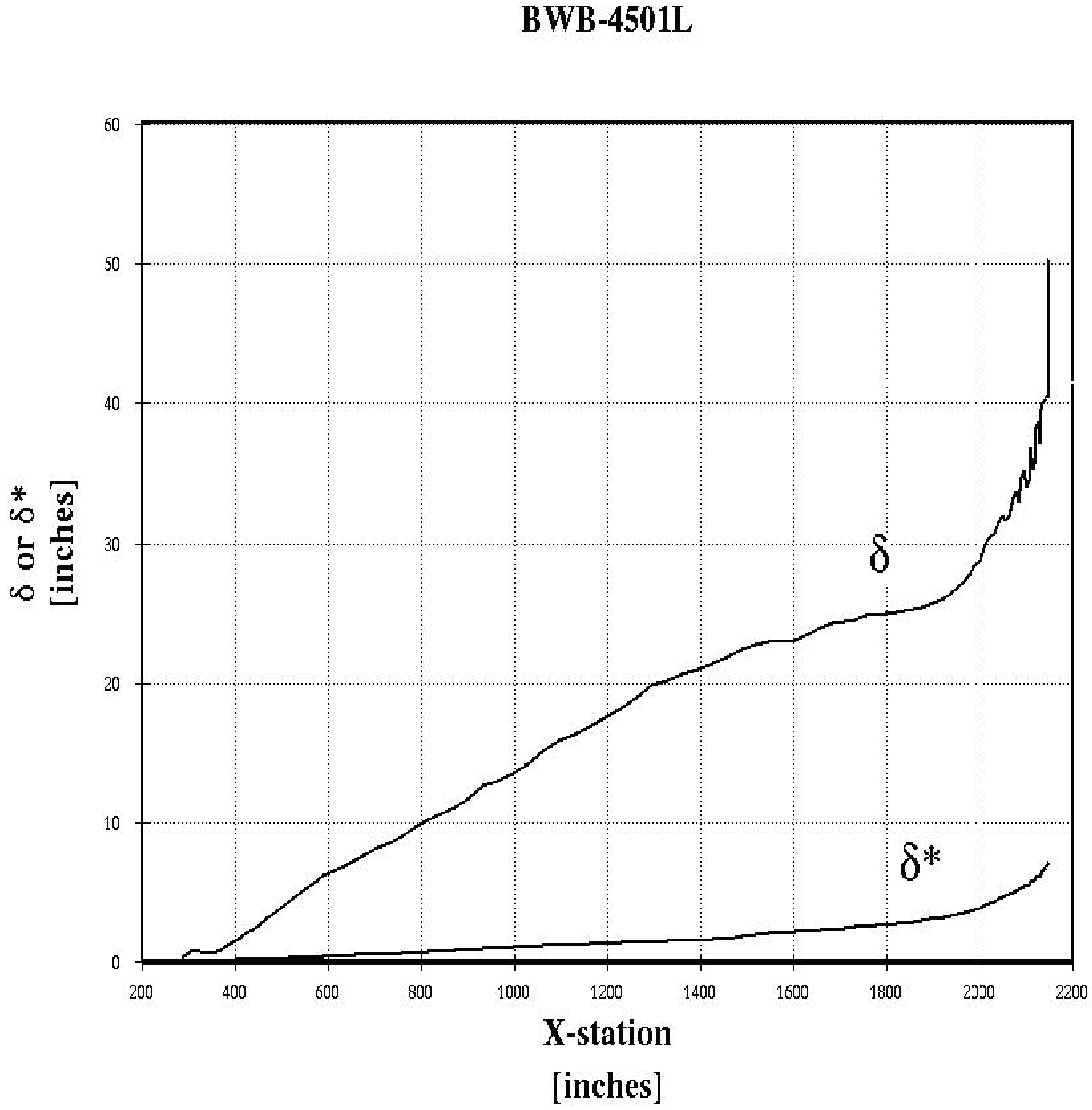


FIGURE 4. BOUNDARY LAYER THICKNESS FOR THE BWB-450-1L CONFIGURATION

1.2 Acoustic Testing Approach

The nominal 4-ft by 4-ft test frame opening in the SALT test facility was selected as the design envelope for the acoustic specimen (Figure 5). Diffuse acoustic field transmission loss and point excited radiated sound power measurements will be made while the panel is installed in the SALT test facility window. These results will then be compared with known structures concepts.

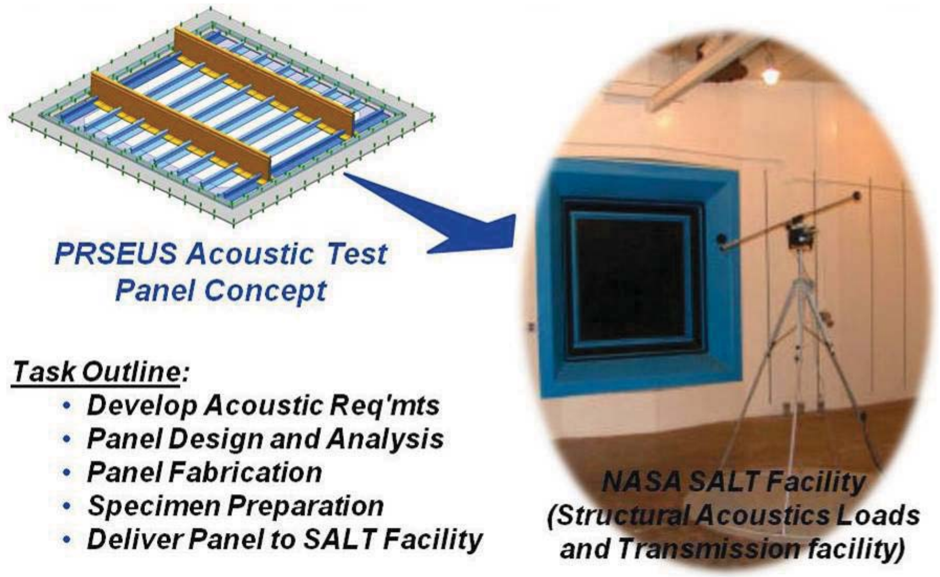


FIGURE 5. ACOUSTIC TESTING APPROACH IN SALT FACILITY

Vibration tests will be conducted in two different boundary conditions: a) free-free, and b) semi-clamped condition - around all panel edges when mounted in the TL suite window. A laser vibrometer may be used to scan the normal velocity response on the surface of the panel subject to point force shaker excitation.

1.3 PRSEUS Panel Design and Fabrication Background

The highly integrated collection of dry warp-knit fabric, pre-cured rods, and foam-core materials are assembled and then stitched together to create a PRSEUS panel (Figure 6). Load path continuity at the stringer-frame intersection is maintained in both directions. The 0-degree fiber dominated pultruded rod increases local strength/stability of the stringer section while simultaneously shifting the neutral axis away from the skin to further enhance the overall panel bending capability. Frame elements are placed directly on the IML skin surface and are designed to take advantage of carbon fiber tailoring by placing bending and shear-conducive lay-ups where they are most effective. The stitching is used to suppress out-of-plane failure modes, which enables a higher degree of tailoring than would be possible using conventional laminated materials.

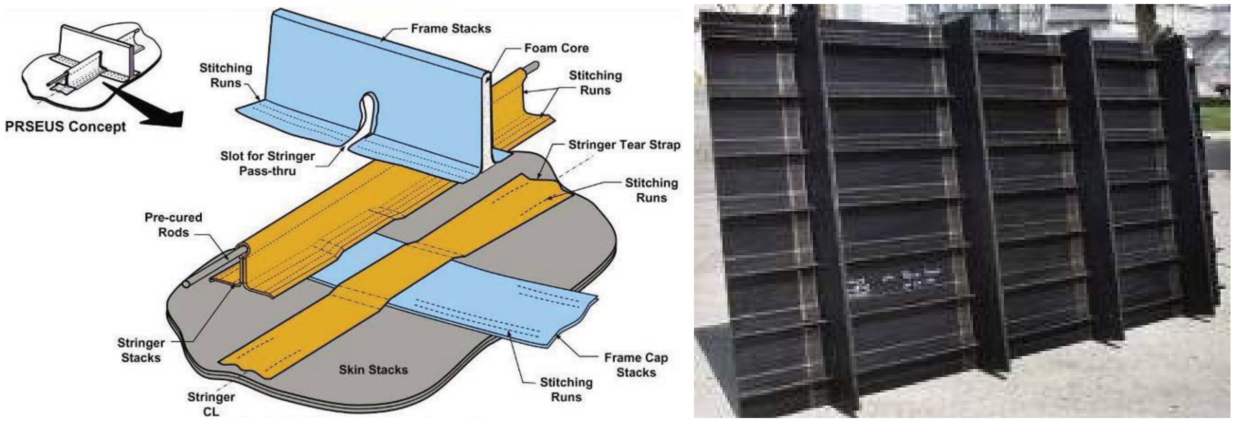


FIGURE 6. PULTRUDED ROD STITCHED EFFICIENT UNITIZED STRUCTURE (PRSEUS)

In addition to enhanced structural performance, the PRSEUS fabrication approach is also ideally suited to the compound curvatures found on the HWB airframe. The self-supporting stitched preform assembly feature that can be fabricated without exacting tolerances and then accurately net molded in a single oven-cure operation using high-precision outer moldline (OML) tooling (Figure 7). Since all of the materials in the stitched assembly are dry, there are no out-time, or autoclave limitations as in prepreg systems, which can restrict the size of an assembly as it must be cured within a limited processing envelope.

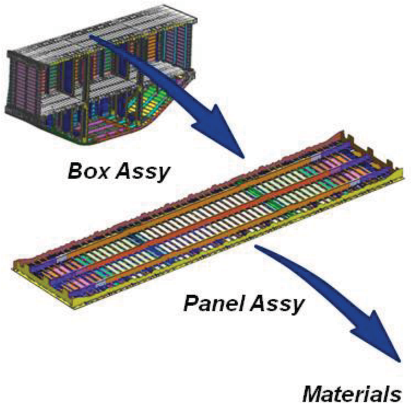
FIGURE 7. STITCHED DRY FABRIC USED TO CREATE SELF-SUPPORTING PREFORM

Resin infusion is accomplished using a soft-tooled fabrication method where the bagging film conforms to the inner moldline (IML) surface of the preform geometry and seals against a rigid OML tool, thus eliminating costly internal tooling that would normally be required to form net-molded details (Figure 8). The manufacture of multiple PRSEUS panels (Ref 1 and 2) proved that the essential feature of this concept – the self-supporting preform that eliminates interior mold tooling – is feasible for the near-flat geometry of the HWB airframe. This task order will use these same techniques to fabricate the acoustic test panel.

FIGURE 8. RESIN INFUSION APPROACH AND CURED PANEL

1.4 Specimen Design

The acoustic specimen was designed using the same materials, features, dimensions, and processing parameters as were used in the prior testing efforts (Ref 1 and 2). The material callouts were also consistent with the Multi-Bay Pressure Box specimen (Figure 9). The nominal 6-inch stringer and 24-inch frame pitch used for the acoustic test panel were selected to match existing toolsets to minimize fabrication costs. (Figure 10)



- Carbon Fiber Fabric:
  - DMS 2436 Type 1, Class 72, Grade A
    - Cured thickness= .052
    - Each stack has 7 plies in a +45, -45, 0, 90, 0, -45, +45 pattern
    - Percentage of fiber by area weight is (45/43/12) using a (0/45/90) nomenclature
  - DMS 2436 Type 1, Class 75/78, Grade A
    - Cured thickness= .0157
    - Each stack has 2 plies in a +45, -45 or, -45, +45 pattern
  - DMS 2436 Type 1, Class 76/77, Grade A
    - Cured thickness= .0157
    - Each stack has 2 plies in a 0, 90 or, 90, 0 pattern
  - DMS 2288 Type 1, Class 2, Grade A
    - Cured thickness= .0055
    - Pre Preg epoxy tape
  - DMS 2288 Type 2, Class 2, Grade B
    - Cured thickness= .0075
    - Plan weave pre preg epoxy cloth
- Epoxy Resin: DMS 2479 Type 2, Class 1 (VRM-34)
- Stitching: 1600 denier Vectran Thread DMS 2443
  - One-Sided stitching is used on all stitching except stringer web
    - Stitching penetrations are 5 per inch
    - Uses RS535 End Effector
  - Two-Sided stitching is used on stringer web
    - Stitching penetrations are 8 per inch
    - Bobbin uses Vectran 400 denier thread
- Pultruded Carbon Rod
  - Carbon fiber with epoxy resin
  - .375" Small tear drop
- Fame Core material:
  - Rohacell 110WF foam
  - Thickness = .50"
  - Fiberglass/ epoxy core at the joints
- Fillets: Woven Standard Modules Carbon Fibers
  - Stringer: 0.15" radius
  - Integral Tee: 0.345" radius
  - Integral Cap: 0.50" radius

FIGURE 9. PRSEUS PANEL MATERIALS USED FOR MULTI-BAY BOX SPECIMEN

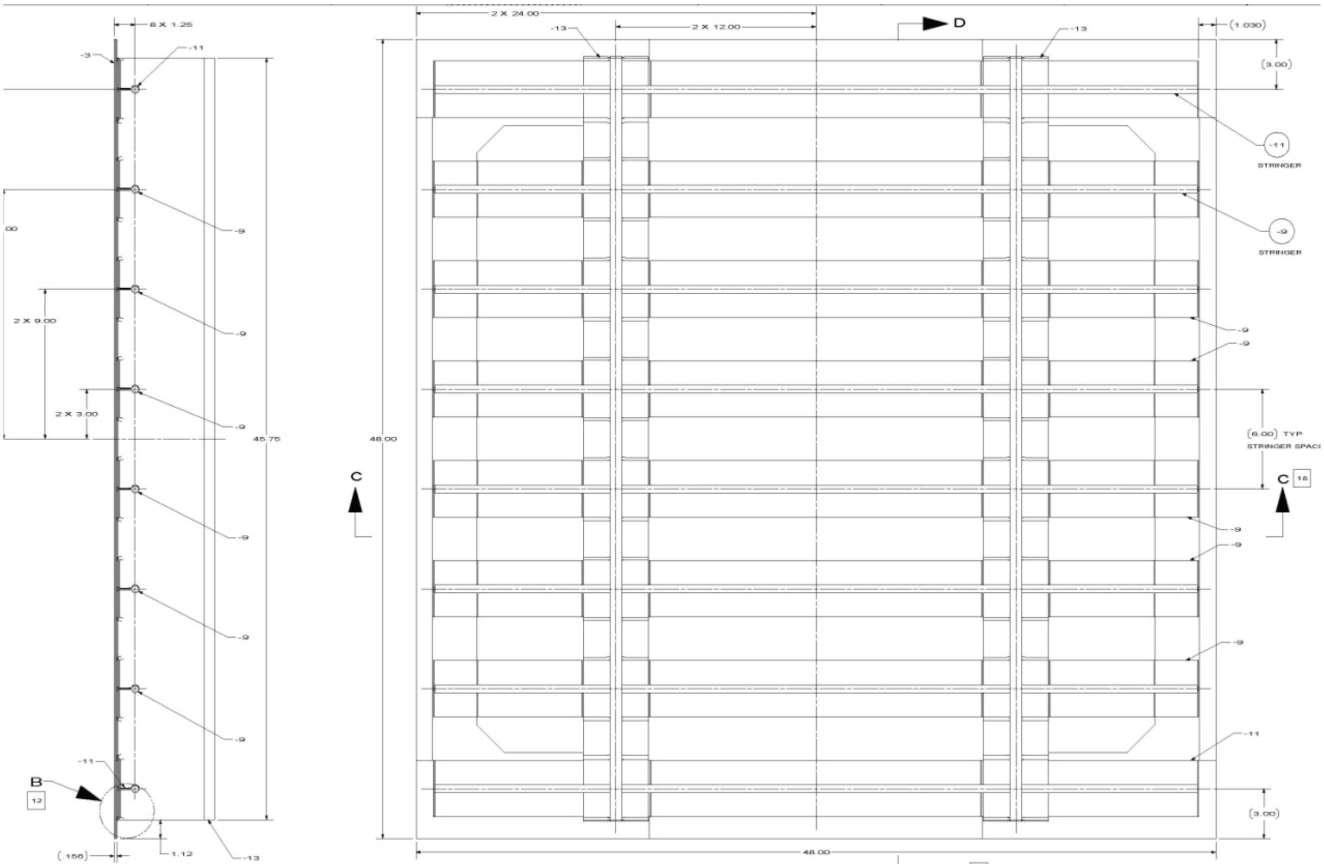


FIGURE 10. TEST PANEL STRINGER AND FRAME LAYOUT

The wider stringer flange base (3.37 dimension in Figure 11) was used to maintain continuity with the Phase II tooling and second-generation stitching head end effector. This flange width and stitch seam spacing differs from the newer improved narrower design used for the Multi-Bay Box specimen which is enabled by the third generation stitching head improvements.

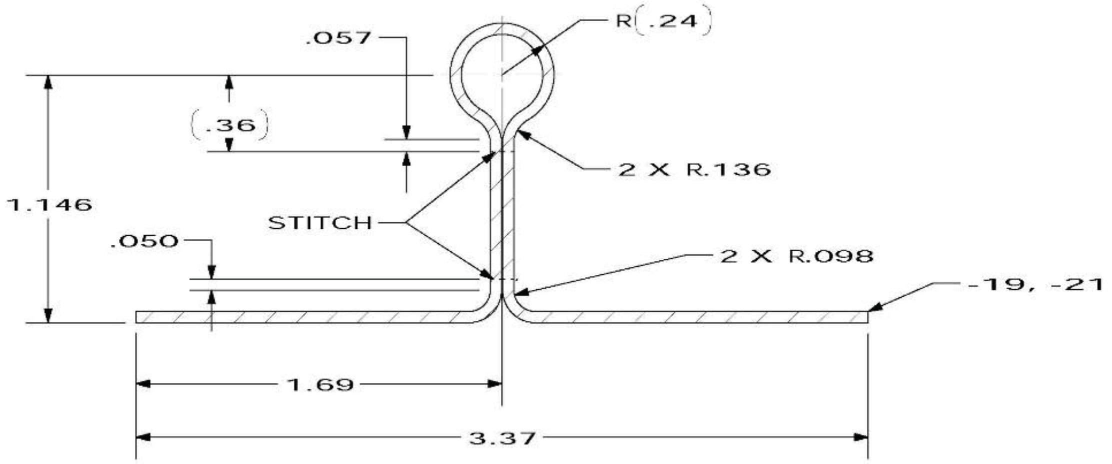


FIGURE 11. STRINGER WRAP GEOMETRY

The nominal skin gauge is .052-inch thick (1 stack) in the center region of the panel. Filler stack pieces (Figure 12) were added around the periphery of the panel to create a common three-stack land (.156 inch) that was later ground flat on the IML side to create a uniform surface for clamp-up within the test frame. The principle material axis for the skin is aligned perpendicular to the stringers to minimize pressure pillowing during pressurization.

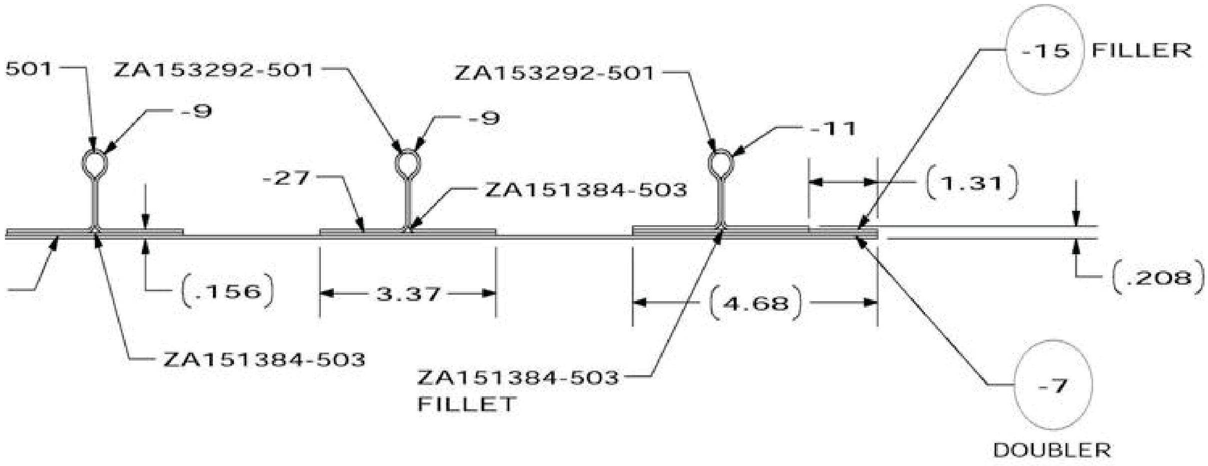


FIGURE 12. NOMINAL PANEL EDGE GEOMETRY

The frames are a two-stack arrangement with the principle material axis aligned along the length of the frame. A Rohacell closed-cell foam detail with machined features is used as the core element of the sandwich-like frame design (Figure 13). Fiberglass inserts were not needed, or used, for the core ends since the frames are not bolted or restrained by the test fixture.

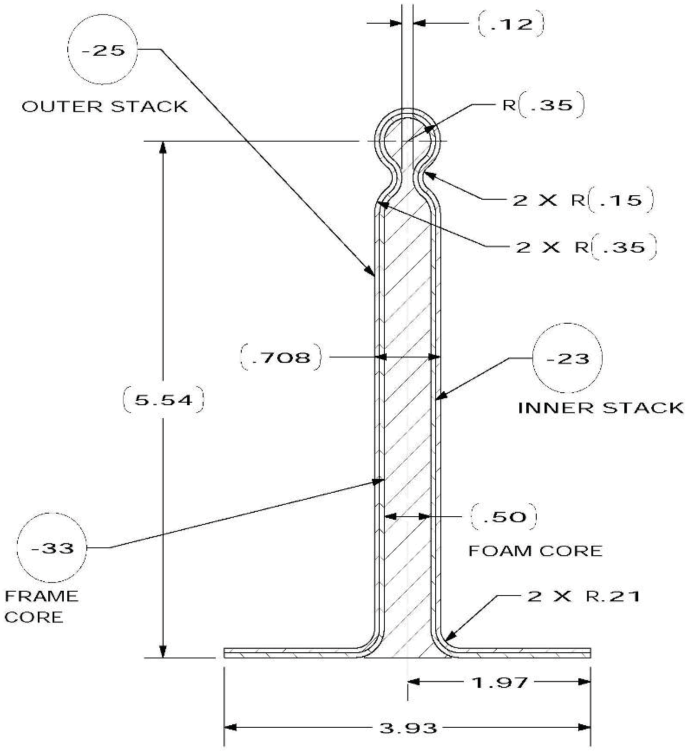


FIGURE 13. NOMINAL FRAME GEOMETRY

Conventional single-sided double-row stitching was used to attach the frame and stringer details. Stitch placement along the fillets and flange edges (Figure 14) is primarily dictated by the fixed needle penetration geometry of the stitching end effector, but also changes slightly as the overall stack thickness varies.

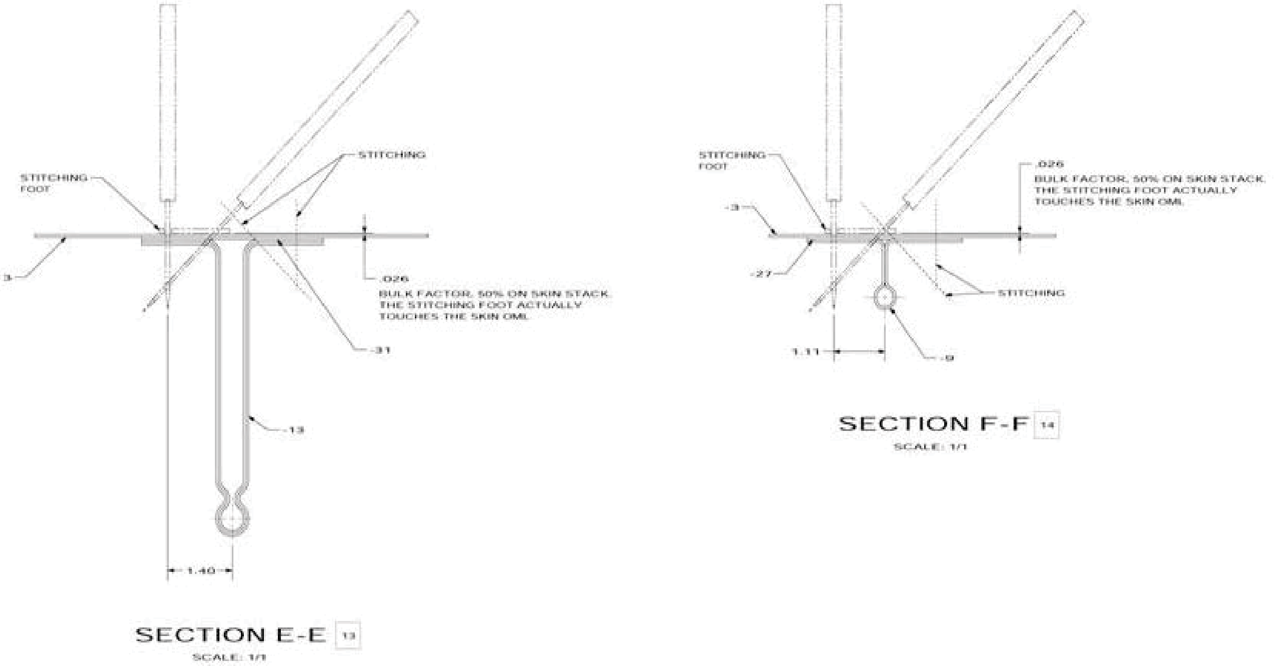


FIGURE 14. NOMINAL STITCH SEAM LOCATIONS IN FRAMES AND STRINGERS

1.5 Panel Material Properties

Material properties and design values were derived from the test data developed by the ACT Composite Wing program (Refs 3 and 4). The fiber system was generally based on medium-performance AS-4 fibers, with some selective usage of IM-7 fibers to improve tensile performance. The acoustic test panel utilized the Class 72 Type I warp-knit fabric arrangement which is comprised exclusively of AS-4 (or equivalent intermediate modulus fibers). Further acoustic optimization studies should consider changes to the warp-knit fabric architecture (Figure 15) by modifying or adding mixed fibers, embedded elements, and/or interlayer damping features. The inclusion of such features, introduced during the warp knitting operation, would have little effect on the overall material costs.

FIGURE 15. WARP-KNIT FABRIC ARRANGEMENT

The panel material properties are largely based on the results of material testing performed in support of the ACT wing program (Ref 3). Although the current version of the materials properties database is limited in scope and only encompasses a simplified set of baseline material properties proposed for use in development activities, it will continuously be updated to reflect the future design, testing, and analysis needs as additional test data becomes available (Table 1).

TABLE 1. PANEL FABRIC SPECIFICATIONS

Skin and Tear Straps	DMS-2436D, TYPE 1, CLASS 72
Stringer Wrap	DMS-2436D, TYPE 1, CLASS 72
Frame Wrap	DMS-2436D, TYPE 1, CLASS 72
Edge Doublers	DMS-2436D, TYPE 1, CLASS 72

Type 1 laminates consist of AS4 fibers only and have a fiber pattern of (44.9/42.9/12.2) and per the stacking sequence shown in Table 2. The laminate stiffness for Type I laminates is listed in Table 3, while the laminate strengths for thin gauge samples are listed in Table 4. The stitching angle for these laminates is in the X direction (0-deg fiber direction).

TABLE 2. WARP-KNIT FABRIC STACKING ARCHITECTURE

Ply Number	Orientation	FAW-Class 72
1	+45	153
2	-45	153
3	0	320
4	90	173
5	0	320
6	-45	153
7	45	132

TABLE 3. LAMINATE STIFFNESS

	Tension				Compression			
	E_x (msi)	E_y (msi)	G_{xy} (msi)	ν_{xy}	E_x (msi)	E_y (msi)	G_{xy} (msi)	ν_{xy}
Type 1 Class 72	10.25	5.07	2.48	0.403	9.23	4.66	2.26	0.397

TABLE 4. LAMINATE UNNOTCHED STRENGTHS [KSI]

Laminate	B-Allowable stress				
	F_{tx}	F_{cx}	F_{ty}	F_{cy}	F_s
Type 1 Class 72	105.1	79.2	46.5	37.9	29.9

The compression strength design values are typically governed by the compression-after-impact (CAI) values which are a function of the number of stacks and the non-detectable damage levels that are used. For the external components, the impact energy limits were 100 ft-lb, while internal components were limited to 20 ft-lb impacts. Table 5 and Table 6 specify the allowable CAI strength for the Class 72 Type I laminate as a function of material thickness. (Ref 4)

TABLE 5. LAMINATE CAI STRENGTH FOR EXTERIOR MEMBERS (100 FT-LB IMPACT)

Stacks	Thickness [in]	Stress, longitudinal [ksi]	Stress, transverse [ksi]
2	.110	38.8	19.6
3	.165	38.8	19.6
4	.220	38.8	19.6
5	.275	38.8	19.6

TABLE 6. LAMINATE CAI STRENGTH FOR INTERIOR MEMBERS (20 FT-LB IMPACT)

Stacks	Thickness [in]	Stress, longitudinal [ksi]	Stress, transverse [ksi]
2	.110	37.9	22.2
3	.165	42.0	24.6
4	.220	47.6	27.9
5	.275	53.3	31.2

Core Material Properties - Rohacell 110 WF foam was used in the frame. Table 7 lists the minimum stiffness and strength properties for Rohacell foam at RT.

TABLE 7. ROHACELL MINIMUM PROPERTIES

Rohacell	Density lbs/ft^3	Compressive Strength psi	Tension Modulus psi	Shear Strength psi	Shear Modulus psi	Tensile Strength psi
110 WF	6.24	407	21000	294	7950	441

Rod Material Properties - The rods were fabricated using a compression molding technique with a Toray unidirectional T800/3900-2B fiber/resin system. Since only a limited test database exists for the rods using this manufacturing approach, a representative set of mechanical properties (Table 8) was generated for the molded rods used in the PRSEUS panels. Since this data was compiled from material supplier literature, it is only intended to be used for preliminary development activities and should be replaced with actual test data at the earliest opportunity.

TABLE 8. ROD MECHANICAL PROPERTIES

Laminate Mechanical Properties	Test Condition	Minimum Average
Tension		
Ultimate Strength, ksi	RT	390
Modulus, Msi	RT	22.0
Ultimate Strain, percent	RT	1.68
Notched Tension, Ultimate Strength, ksi	RT 180°F	67.5 62.0
Notched Compression, Ultimate Strength, ksi	RT 180°F	42.0 35.0
Compression		
Ultimate Strength, ksi	RT 180°F	200 176.2
Modulus, Msi	RT -75°F	18.2 18.2
Comp After Impact, Ult Strength, ksi, 270 in-lb	RT	40.5
Compression Interlaminar Shear, Ult Strength, ksi	RT 180°F	9.00 7.50

Environmental K nockdowns - All reported strength values in this document are for RTD condition. When environmental conditions are to be considered in the analysis, these RTD strength value should be multiplied by the appropriate R_{env} ratio listed in Table 9. (Ref 3)

TABLE 9. ENVIRONMENTAL CORRECTION RATIOS

Failure Mode	Material	Parameter .	Cond.	Ratio
Unnotched tension	All	F_t	CD	0.933
Unnotched compression	All	F_c	HW	0.601
Tension after impact	All	ε_{tai}	CD	0.933
Compression after impact	All	ε_{cai}	HW	0.919
Hole net-section tension	Warp/knit	ε_{uht}	CD	0.954
Hole net-section tension	Braided	ε_{uht}	CD	0.819
Hole net-section compression	AS4 Warp/knit	ε_{uhc}	HW	0.823
Hole net-section compression	IM7 Warp/knit	ε_{uhc}	HW	0.814
Hole net-section compression	Braided	ε_{uhc}	HW	0.768
Hole bearing initial yield	Warp/knit	F_{bri}	HW	0.779
Hole bearing initial yield	Braided	F_{bri}	HW	0.809
Hole bearing yield	Warp/knit	F_{bry}	HW	0.776
Hole bearing yield	Braided	F_{bry}	HW	0.842
Hole bearing ultimate	Warp/knit	F_{bru}	HW	0.863
Hole bearing ultimate	Braided	F_{bru}	HW	0.908
Fastener pull-through yield	All	F_{pty}	HW	0.771
Fastener pull-through ultimate	All	F_{ptu}	HW	0.882

2.0 PANEL FABRICATION

One 4-ft by 4-ft specimen was fabricated under this task order contract. The stitching and cure tooling shown in the photographs was procured under a prior NASA NRA Phase II task contract (NNL07AA48C, Project No. 4200208122) and loaned to this task order.

2.1 Preform Assembly and Stitching

Although the acoustic test panel was designed to accommodate an existing toolset, some modifications were made to the stitching frame tooling to make room for the additional stack build-ups around the panel edges. Once these changes were made, the specimen fabrication proceeded as planned without any problems or deviations during any aspect of the build process. Each step in the preform build-up – from the initial material trimming on the Gerber flatbed plotter, to the stringer and frame detail placement (Figure 16), to the tear strap and skin lay down, to the final stitching operation to complete the preform assembly (Figure 17) – was completed as planned.

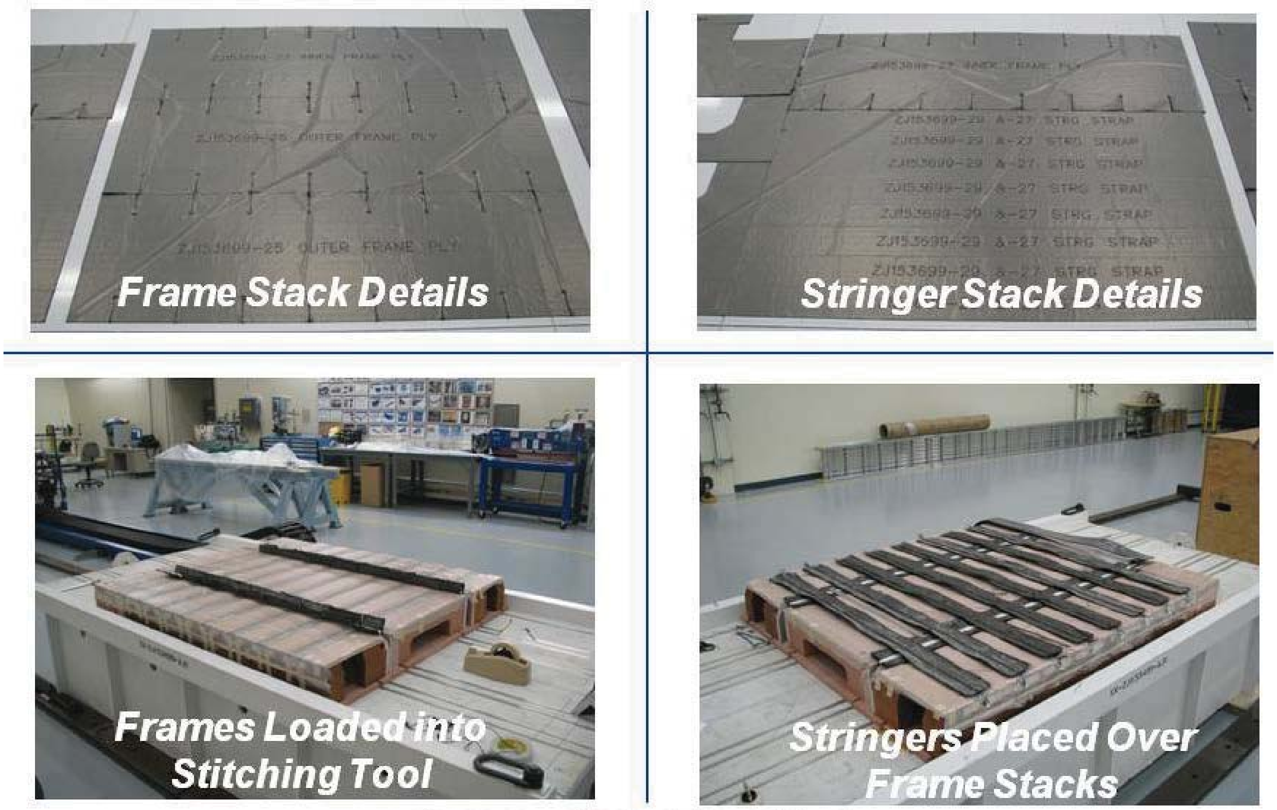


FIGURE 16. STRINGER AND FRAME DETAILS INSERTED INTO PREFORM

The preform was stitched using two types of stitching methods. The stringer details were individually stitched with two rows of stitching placed through the webs using a conventional two-sided needle-and-bobbin arrangement prior to being loaded into the preform assembly fixture. Once all the preform details were located in the fixture, they were stitched together using the numerically controlled-and-driven single-sided stitching process pictured in Figure 18.

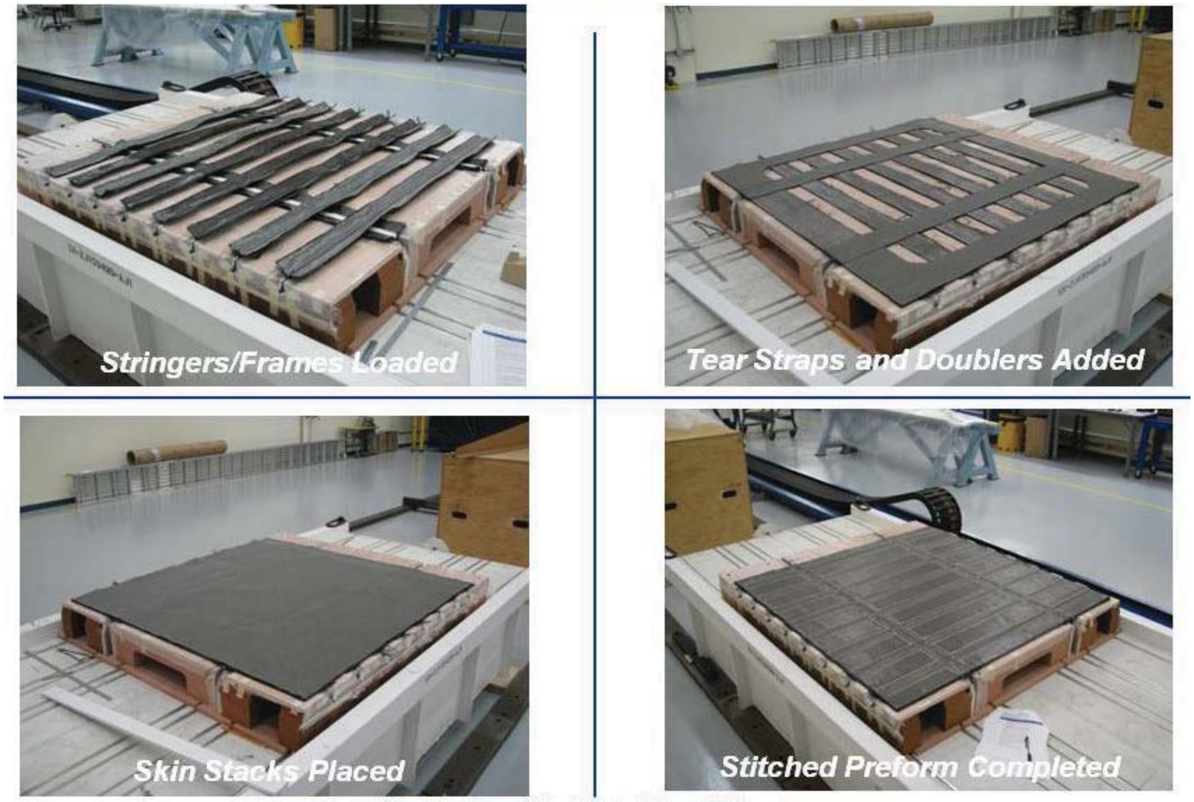


FIGURE 17. DOUBLER AND SKIN DETAILS ADDED PRIOR TO STITCHING

FIGURE 18. SINGLE-SIDED STITCHING TECHNIQUE (DIFFERENT PANEL SHOWN)

The six-axis robotic stitching system inserts two seams simultaneously, one vertically and the other at a 45-deg angle to produce a modified single-sided chain stitch of 1200d Vectran sewing thread. The combined preform and assembly tool is then flipped upside-down as a single unit and placed onto the cure tool surface, where the stitching tool foam block details are released and removed.

2.2 Resin Infusion and Cure

The edges of the stringer and frame members of the dry preform are indexed to tooling features on the cure tool that provide positive dimensional control. Silicon bagging aids are placed over the stringers, and a pleated nylon bag is then placed over the entire preform and sealed against the cure tool surface. The bagged preform was then placed in an oven, where under vacuum pressure, a liquid resin system was infused at 140-deg F into the dry fabric (Figure 19), and then cured using the Controlled Atmospheric Pressure Resin Infusion (CAPRI) out-of-autoclave forming process.

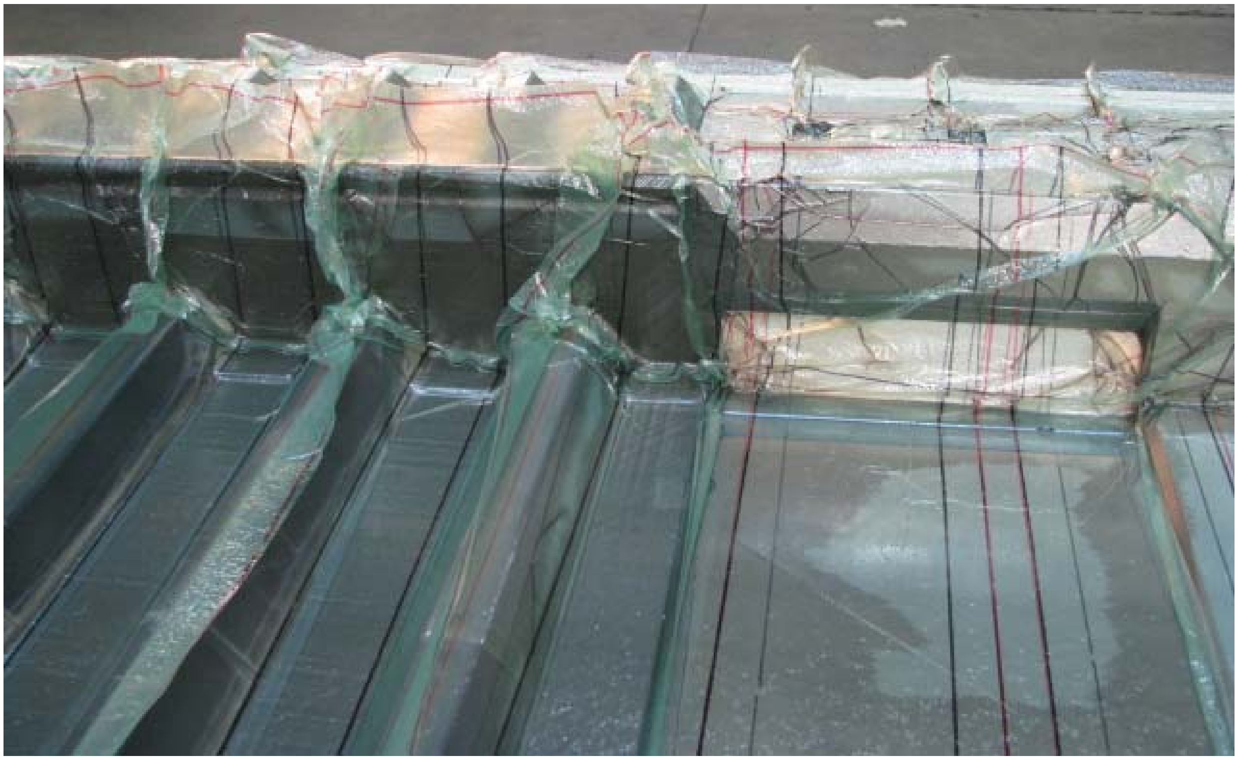


FIGURE 19. ACOUSTIC PANEL DURING RESIN INFUSION

The infused panel was initially cured at 250-deg F (Figure 20), before being removed from the oven and stripped of the bagging material and resin infusion lines. It was then placed back in the oven for the final 350-deg F free-standing post-cure operation. The final cured specimen is shown in Figure 21.

FIGURE 20. COMPLETED RESIN INFUSION OPERATION

FIGURE 21. CURED SPECIMEN BLANK PRIOR TO EDGE TRIM

The surface quality and overall appearance of the panel was good (Figure 22 and 23). Visual inspection of the part surfaces, along with a detailed inspection of the discarded flow media, indicated that resin flow and penetration went as expected and there was no suggestion of voids or resin starved areas. Therefore, an NDI inspection was not needed nor performed.

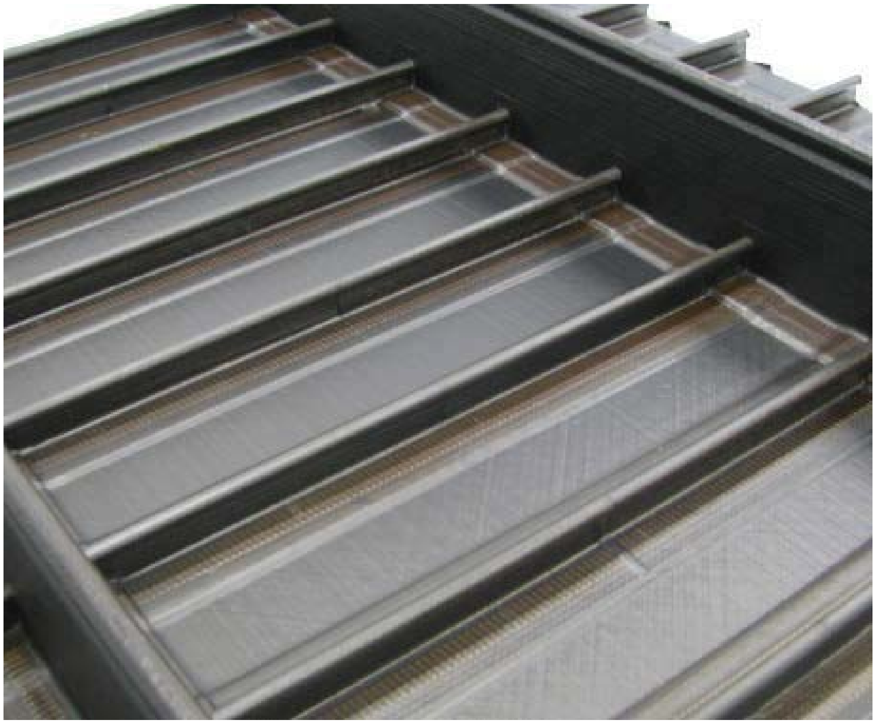


FIGURE 22. CLOSE-UP OF CURED IML SURFACE

FIGURE 23. CURED SPECIMEN OML SURFACE

2.3 Edge Trim Machining

The final edge trim and land grinding operations were performed by a local machining vendor. The stringers and frame elements were machined away at the ends to create a 1/8-inch gap relative to the test frame holding fixture. Once the edge trim was completed (Figure 24), the panel was boxed up and shipped to NASA-LaRC where the perimeter holes were match-drilled to the existing hole pattern in the test fixture opening.

FIGURE 24. SPECIMEN EDGE TRIM MACHINING AT VENDOR FACILITY

2.4 Panel Dimensional Check

Depending on the panel size, curvature, fiber orientation, and edge configuration, PRSEUS panels are known to display some degree of panel warping; particularly washout at the edges caused by the thermal residual stresses that build up during the cure cycle. For panels with free edges, i.e. those not restrained by a parallel stiffening element (stringer, frame, or integral cap feature), the out-of-plane displacements are more pronounced and can be up to a .10 inch. In the center regions of the panel where the skins are restrained by the highly rigid stringer and frame elements, skin displacements that cannot be seen with the naked eye can be measured. In these regions, the skin bows slightly toward the IML side of the panel (which will be pushed out during pressurization). These out-of-plane displacements were measured for the acoustic panel by NASA-LaRC and are shown plotted in Figure 25. Although the panel deflections are within typical airframe assembly tolerances, more work should be done to characterize these distortions since they can be compensated for in the cure tooling so that the final part positions are net-molded to the nominal engineering dimensions.

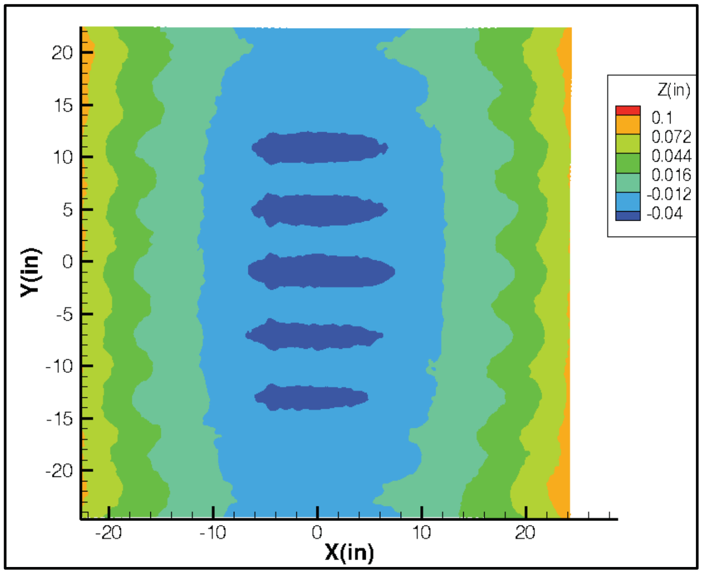


FIGURE 25. PANEL OML SURFACE DISPLACEMENT (INCHES) – FRAMES ARE VERTICAL

2.5 Panel Adaptor Frame and Shim Fabrication

An adaptor frame required to install the test panel in the SALT test facility has been manufactured and is shown in Figures 26-28. The adaptor frame is a stiff, 6-inch wide sandwich configuration consisting of a two inch thick medium density fiberboard (MDF) core bonded between two 0.25-inch thick aluminum face sheets. Inner and outer hole patterns were machined in the frame corresponding to the test panel perimeter and SALT window hole patterns respectively. The inner hole pattern was assigned a uniform distribution while the outer hole pattern was developed from a 2D projection of the actual SALT window hole pattern measured with a LTD-901-B Leica scanning system. 0.25-inch thick by 1.125-inch wide clamping bars are applied to secure the panel to adaptor frame with a nearly uniform pressure distribution. The clamping bars were overlapped at the corners to avoid significant discontinuities in the boundary condition. Material properties of the adaptor frame components used for modeling purposes are given in Table 10.

FIGURE 26. ADAPTOR FRAME DETAIL

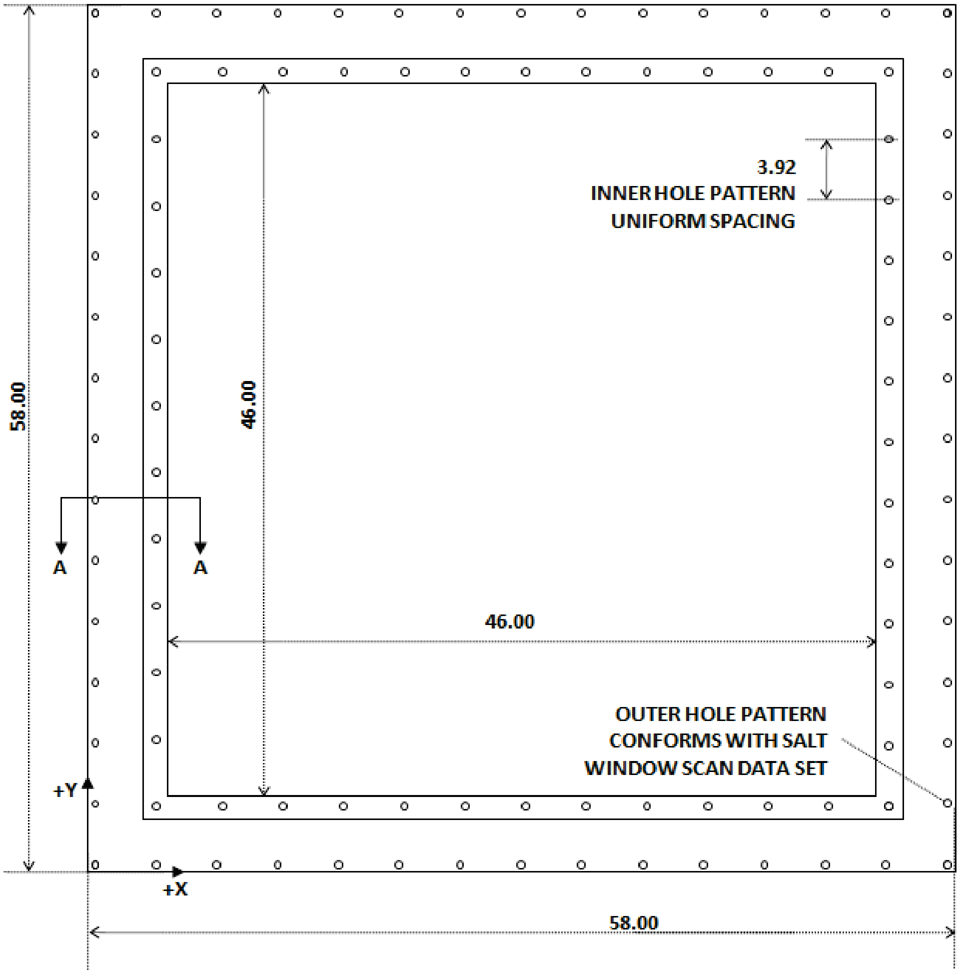


FIGURE 27. ADAPTOR FRAME GEOMETRY

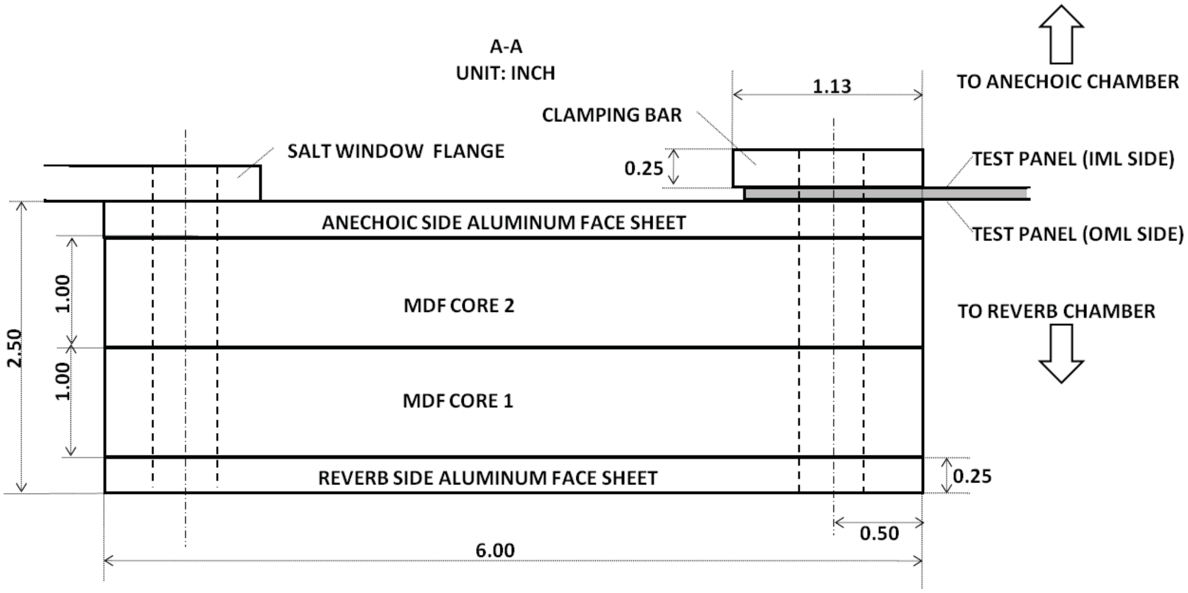


FIGURE 28. ADAPTOR FRAME CROSS SECTION GEOMETRY

TABLE 10. FRAME COMPONENT MATERIAL PROPERTIES

	Tensile Modulus (Msi)	Poisson's Ratio	Density (lb/ft^3)
Aluminum	10.59	0.33	173.55
MDF	0.13	0.25	45.20

The panel warp described in the previous section was accommodated with the layered aluminum shim shown in Figures 29 and 30. The shim consists of two parts conforming to the IML and OML sides of the panel perimeter respectively and is comprised of approximately 23 layers of 3M™ 438 Heavy Duty Aluminum Foil Tape in total. The tape was applied in layers to the adaptor frame and clamping bar underside according to the panel OML scan data set to provide a contoured shim fitted to the perimeter. The shim was then compressed between clamping bars and adaptor frame with 15 ft-lbs torque applied to each fastener and left to relax over time. Prior to this, a 10-layer deep test shim was applied to one leg of the adaptor frame and compressed in a similar manner to assess relaxation and measure the final layer thickness. The layer thickness was found to approach the nominal aluminum backing thickness after relaxing.

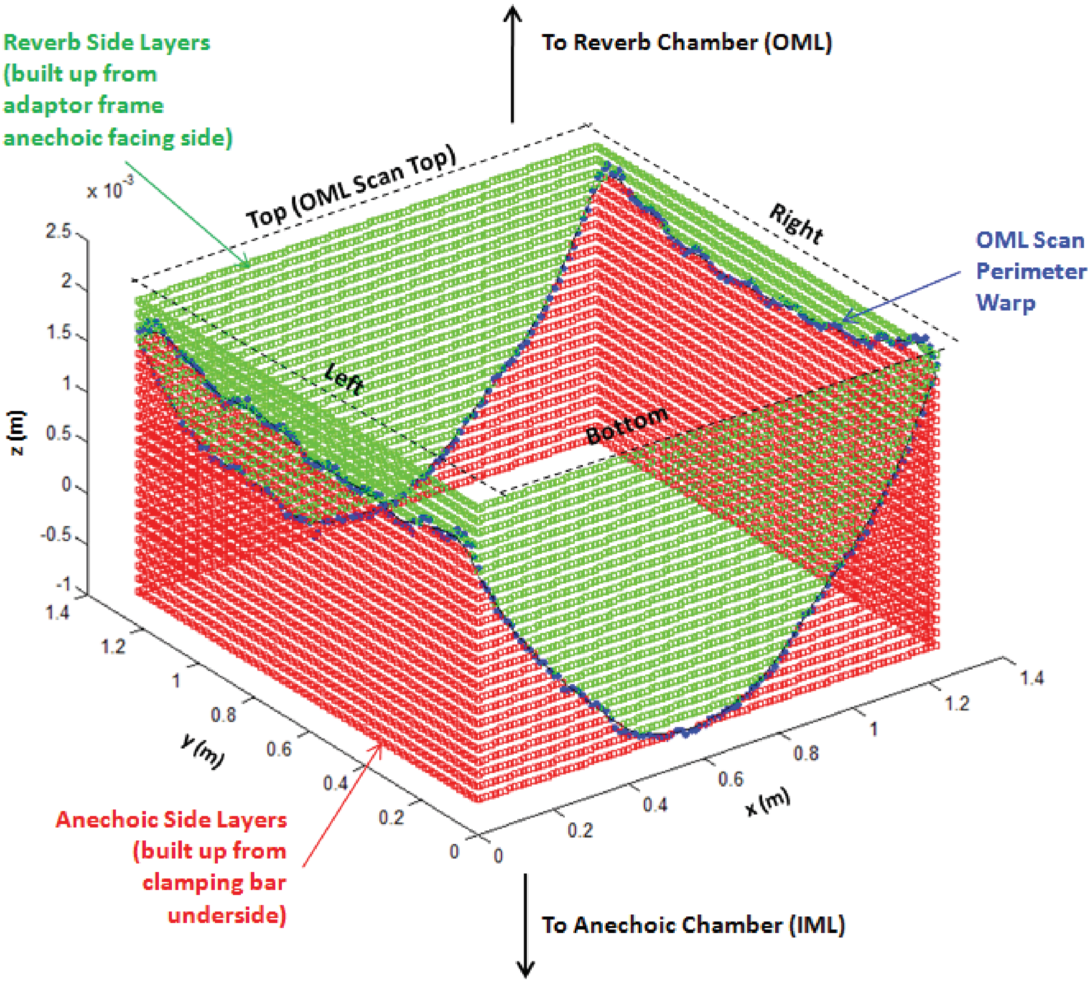


FIGURE 29. LAYER SHIM MAP

FIGURE 30. SHIM FABRICATION

3.0 TEST SPECIFICATION PREPARATION

The purpose of the planned testing is to establish baseline vibroacoustic characteristics of the HWB PRSEUS minimum gauge pressure panel geometry under point force and diffuse field acoustic excitations. Acoustic TL measurements of the panel will be taken and compared with historical TL measurements from conventional fuselage configurations. Experimental results will also be used to update and verify Finite Element Analysis (FEA) and Statistical Energy Analysis (SEA) models of the test article so that the noise reduction capability of the HWB PRSEUS concept under representative flight acoustic loads can be further studied with reduced uncertainty. The testing is divided into freely hung structural vibration and in-situ vibroacoustic tests as described in the following sections.

3.1 Freely Hung Structural Vibration Testing

The HWB PRSEUS minimum gauge pressure panel is expected to exhibit multiple wave types including flexural and in-plane plate waves in the bay and frame regions as well as torsional, flexural, and in-plane waves in the pultruded rod stiffeners. The wave type of most interest is the flexural plate waves as they are the largest contributors to normal velocity in the bays and frames, which are expected to be the most significant radiators. By measuring the normal velocity of the OML under point force excitation, the behavior most important for interior noise consideration can be studied and used to verify numerical models of the structure. The test procedures described below are designed to do this over three decades of frequencies – approximately from 10 Hz to 10 kHz.

Low Frequency Range: The low frequency range is qualitatively defined as the frequency range within which the modal overlap is low and separate modes are easily discernable from one another. Modes of the panel in the low frequency range are considered global in nature, that is, the characteristic flexural wavelength in the panel is large and spans multiple bays. In this frequency range, it is suitable to model the structure with deterministic FEA.

The panel will undergo a modal survey and the results will be used to evaluate the FE model's ability to adequately represent the low frequency dynamics. It will be situated in a freely hung boundary condition and excited with normal point force excitation at specified locations while the OML normal velocity is recorded with a scanning laser vibrometer. The freely hung configuration is desired to avoid additional complexities due to boundary effects. Bungees are to be used to approach a freely hung boundary condition and should be situated along the perimeter of the panel near the frames to avoid bungee interaction with the lowest frequency modes (ignoring rigid body modes). With the vibrometer scan data set, a modal correlation can be made using the Modal Assurance Criterion to evaluate mode shape accuracies and, subsequently, natural frequencies. Modal curve fitting methods can also be used to evaluate the panel's modal damping.

To evaluate the vibroacoustic capabilities of the FEA and SEA models, the test panel will be installed in the SALT facility window (Figure 31) separating reverberant and anechoic chambers for TL and sound radiation testing. The in-situ configuration requires an adaptor frame, which has been designed as discussed previously to provide a nearly clamped boundary condition at the panel perimeter. The adaptor frame will, however, introduce a boundary condition at the panel perimeter that is influenced by a combination of the adaptor frame's modal content and the stiffness of the panel-to-adaptor frame coupling.

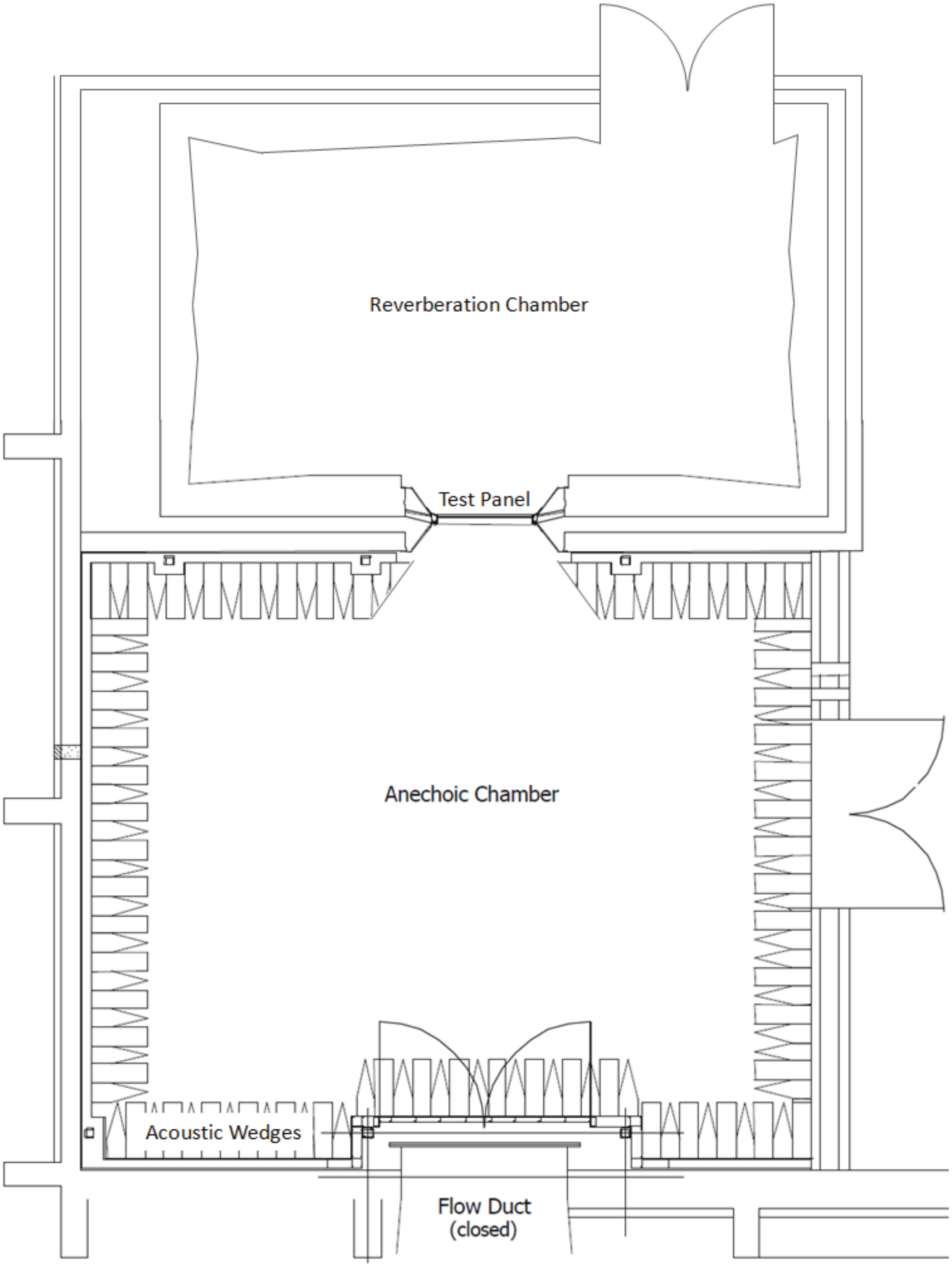


FIGURE 31. SALT FACITILY LAYOUT

An extension to the panel FE model including the adaptor frame has been developed. The veracity of the extended model, shown in Figure 32, is to be evaluated by first evaluating the model of the adaptor frame in isolation. A modal survey of the adaptor frame in a freely hung configuration will provide the low frequency modal content for model correlation. Once this is completed, an evaluation of the panel-to-adaptor frame coupling can also be made by repeating the modal survey with the panel coupled to the frame in a freely hung configuration.

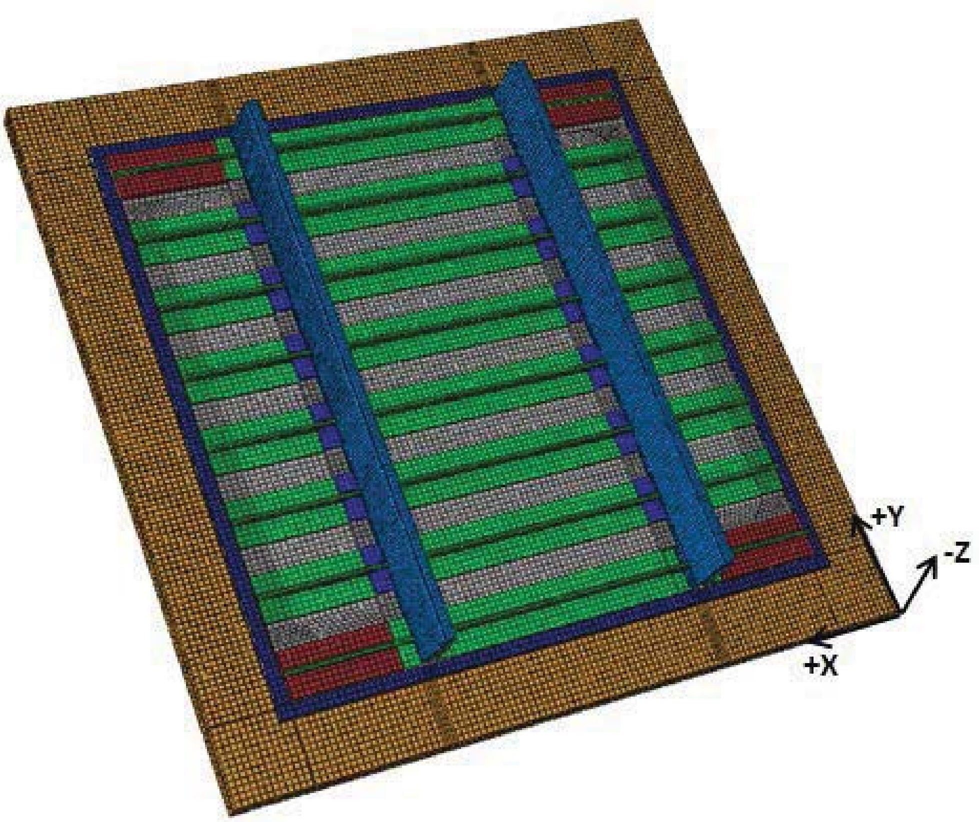


FIGURE 32. PRSEUS TEST PANEL FEM WITH ADAPTOR FRAME (235,914 DOFS)

Mid Frequency Range: The mid frequency range exhibits both global and local mode behavior. In this frequency range, the modal overlap becomes too great to study the dynamic behavior deterministically, but the global mode dynamics require a deterministic modeling approach (as opposed to a statistical modeling approach such as SEA) to be effectively represented. The approach taken here is to use a deterministic FE model to capture the dynamics of the structure up to 3 kHz, which is expected to overlap the early frequencies of the high frequency range. FE model results up to 3 kHz are then to be post processed in terms of frequency band averaged subsystem energy content and power input. Here, a subsystem is defined as a group of modes with similar characteristics, such as the flexural modes in a bay.

The FE model in the mid frequency range is to be correlated with experimental results. For this, the panel is to be situated in a freely hung condition and excited with normal point force excitation while the normal velocity is recorded from the OML side with a scanning laser vibrometer. Multiple point force excitations are required in this case to assess the spatial variation of input mobility and power input. Data from the vibrometer scan can then be used to determine subsystem energy content relative to power input. Correlation of the test results with the FE model in the mid frequencies would then be evaluated in a band and space averaged sense as opposed to correlating mode by mode. Structural damping is expected to play a significant role in the amount of energy seen in the subsystems relative to the power input. Given this, the damping loss factor of the panel should be estimated from experiment and applied to the numerical model a priory in order to make a meaningful mid frequency correlation. Estimation of the damping can be made using, among others, the Impulse Response Decay Method, which is used to estimate the damping in a band averaged sense.

High Frequency Range: The high frequency range exhibits local mode, small wavelength behavior with high modal overlap. SEA becomes more applicable in the high frequency range and is often useful even in the mid frequencies.

An SEA model of the PRSEUS panel has been developed and is shown in Figure 33. Energy methods will be used to correlate SEA model results with experimental data. The experimental data used here will be taken from the same vibrometer scan data sets used when correlating the FE model in the mid frequency ranges as discussed previously. Experimental damping estimations will be required to arrive at meaningful estimates of subsystem energy.

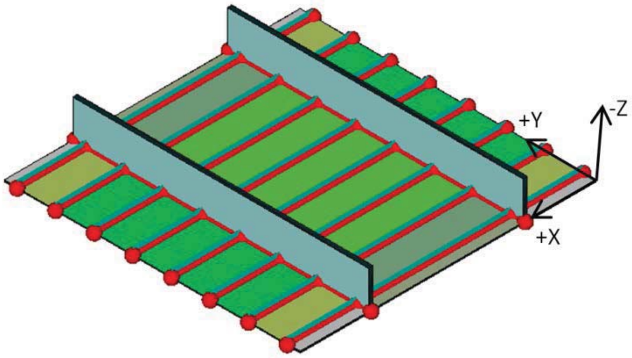


FIGURE 33. STATISTICAL ENERGY ANALYSIS (SEA) MODEL OF PRSEUS TEST PANEL

3.2 In-situ Vibroacoustic Testing

The interaction of the HWB PRSEUS panel with the coupled acoustic field is of additional interest for interior noise assessments and concept evaluations. The characteristic structural wavelength relative to that of the exterior pressure field and interior acoustic volume determines the exterior acoustic loading acceptance and interior acoustic radiation efficiency, respectively. Wavelengths in the structure are frequency dependant and are influenced by the substructure geometry and laminate configurations among others. The diffuse field excitation TL and point force excitation sound power radiation are useful metrics when verifying the numerical models' capability to represent coupled structural acoustic interactions. TL can also be shown in comparison with other conventional fuselage types while taking into account mass differences.

The diffuse field excitation TL of the HWB PRSEUS test panel is to be measured using the reverb and anechoic chambers at NASA Langley's SALT facility. During the TL test, a traversing array of acoustic intensity probes will be used to measure the panel's radiated sound power due to OML side diffuse field excitation. The reverberation chamber speaker system is capable of exciting room modes from 100 Hz to 12.5 kHz center frequency 1/3 octave bands. Reverberation chamber sound levels are measured during the intensity probe scan with an array of randomly distributed microphones. The intensity TL measurement method is described further in ASTM E2249.

Sound radiation due to point force excitation is to also be measured in-situ. Point force loading tends to excite a more replete set of modes relative to diffuse field excitation, which tends to only excite the odd modes. This loading is more characteristic of turbulent boundary layer excitation. By using the intensity probe array during shaker excitation, the radiated sound power of the panel relative to point excited power input can be measured.

3.3 Testing Responsibilities and Contact Information

Specimen Configuration:
Drawing Number: ZJ153699-1 Acoustic Panel Assembly, initially released November 2010.

NASA Test Responsibilities:

1. Prepare SALT test facility and install specimen.
2. Develop loading profiles and testing sequence.
3. Develop instrumentation package, install and calibrate gages.
4. Conduct testing and record data.
5. Prepare and distribute test report.

Boeing Test Responsibilities:

1. Deliver test specimen and support panel rigging questions.
2. Provide panel design and material property data as requested.
3. Witness testing.

Cognizant NASA/Boeing Personnel:

1. Richard Silcox, NASA Acoustics, (757) 864-3590, r.j.silcox@nasa.gov
2. Albert Allen, NASA Acoustics, (757) 864-8462, albert.r.allen@nasa.gov
3. Adam Przekop, NASA Acoustics, (757) 864-2278, adam.przekop@nasa.gov
4. Alex Velicki, Boeing Structures, (562) 797-2753, alexander.velicki@boeing.com
5. Gopal Mathur, Boeing Acoustics, (714) 714 896-1475, gopal.p.mathur@boeing.com

4.0 ADVANCED CONCEPT DEVELOPMENT

As with the development of most new composite structure technologies, the PRSEUS development activities have been focused primarily on reducing airframe weight under structural loading conditions. Only recently, has consideration been given to optimizing the overall fly-away weight, which would also include system-related weight increases for such items as lightning strike or as in this case, acoustic treatments. By modifying the base materials and design parameter selections, the potential for improving the acoustic response of the cabin structure can be more thoroughly explored. Such a multidisciplinary approach at this early stage in the development cycle should lead to the lightest weight solution, as well as, identify cost-effective improvements that can easily be added during the preform assembly operations completed at the material supplier - rather than later in the airframe assembly cycle when fabrication costs are proportionally higher. Such simple modifications as depicted in Figure 34 would be of particular interest to include in future design trades and testing activities.

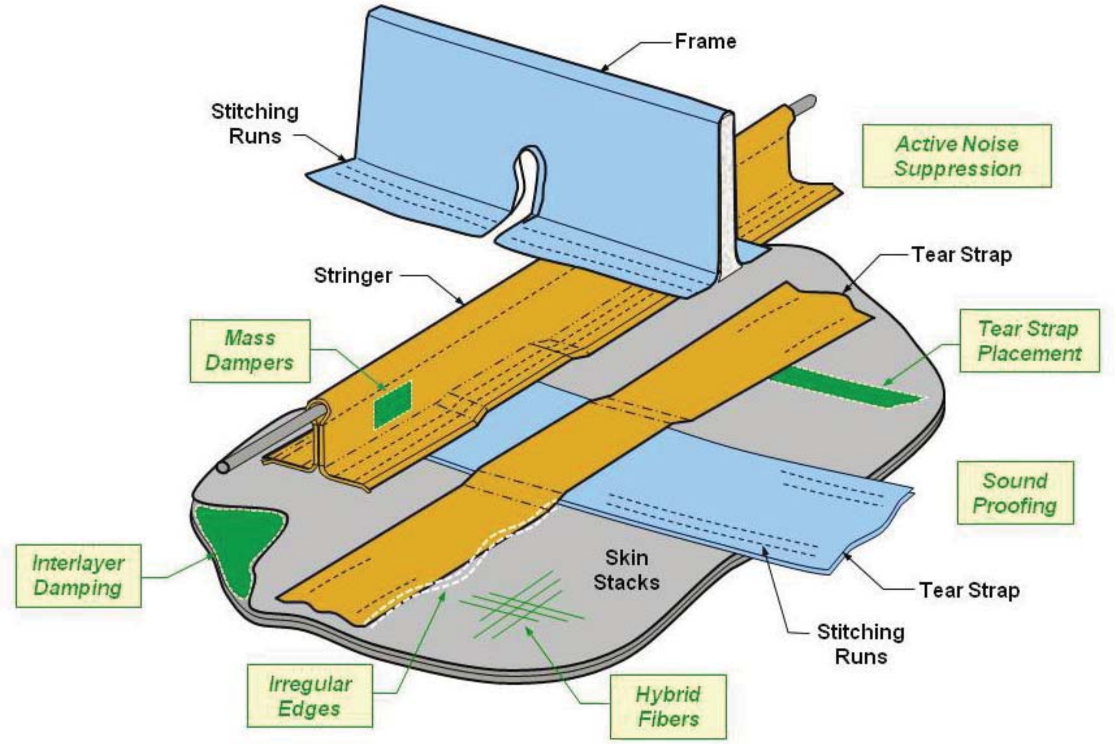


FIGURE 34. CANDIDATE INTEGRAL ACOUSTIC IMPROVEMENTS UNDER CONSIDERATION

4.1 Possible Areas of Study

Once the baseline acoustic characteristics of the PRSEUS panel are established, possible areas of study could also include the following:

Interlayer Damping – A highly damped layer embedded in the laminate can potentially reduce vibration and sound radiation efficiently by increasing the inherent damping of the structure prior to the addition of parasitic damping treatments. In a constrained layer damping configuration, the effectiveness of the core damping material is maximized when embedded in the region of highest shear strain near the neutral axis. The neutral axis is expected to be located near the middle of the laminate cross section for flat or low curvature laminates found in the HWB concept. Reductions in interlaminar shear strength are of concern with this approach and may be compensated for with additional stitching or tailored stitch patterns that could encompass entire damping layers or discrete features.

Hybrid Fibers - Increasing the stiffness of the skin laminate is expected to reduce the coincidence frequency above which the bending vibration radiates noise most efficiently. Conversely, a higher stiffness will tend to have a lower acceptance of exterior acoustic excitation such as the TBL. Using numerical models to vary the laminate material properties may provide an opportunity to effect an acoustically beneficial change in the early design stages by modifying the laminate configurations.

Irregular Edges- Frame and stringer flanges may be tailored (possibly in conjunction with tear strap placements) to promote poorly radiating even modes and impede efficiently radiating odd modes within the early bay local mode frequency range. Such highly contoured edge features at stack drop-offs can easily be accommodated within the PRSEUS fabrication approach because the interior surfaces are not hard tooled, thus requiring less precision in material fit-up and tool design tolerances.

Tear Strap Placement - Creating periodic structures within the bays may be used to promote band gap effects within target bandwidths. In terms of the wave description, band gap wave propagation is prohibited and enforced motion tends to decay evanescently. In modal terms, modal structures are not allowed to form at frequencies within the band gap, thus effecting a reduction in response. Periodicity may be applied to the bays through additional tear straps running transverse to the pultruded rod stringers. The addition of periodic tear straps solely as a noise treatment is not much different than additional parasitic noise treatments late in the design stage. However, other multidisciplinary benefits may offset the additional mass. For example, the load path created at the tear strap may allow for removal of nearby laminas as mass compensation. Tear straps may also be designed to allow systems attachments directly to the bays. Systems running along the fuselage would then be able to provide extra mass and damping to the bays with little overall added mass. Mid-bay tear straps have also been shown by preliminary analyses to reduce bay pillowing due to cabin pressurization. Bay crack arresting capabilities may also be improved with additional tear straps.

Mass Dampers - Distributed vibration absorbers are masses integrated into an insulation foam matrix and are used to provide distributed mass-spring tuned damping.

Sound Proofing - Conventional noise treatments consist of stand-off layer damping tiles affixed to bays with bagged fibrous material placed in channels between frames. Possible areas of investigation for conventional noise treatments are:

- Surveying existing damping tile materials, designs
- Surveying existing fibrous material or foam acoustic treatments
- Optimizing area coverage of damping tiles for PRSEUS
- Optimizing acoustic fiber or foam arrangements for PRSEUS

Newly available materials and configurations for damping tiles and acoustic foams may provide increased performance per weight over their predecessors. For example, newer polyimide foam insulations may have the physical property characteristics to meet aerospace requirements, including aircraft sidewall insulation. These new polyimide foams are produced at low densities ranging from .2 to 1.0 lb/cu-ft and can be utilized as thermal and/or acoustical insulation. It is important to note that polyimide materials are inherently fire retardant due to their chemical composition. This new foam technology has the advantage over previous polyimide foams of being manufactured and cured using microwave energy at a lower cost and faster production rate. (Ref 5)

Active Noise Suppression - Active noise systems tend to be cost, complexity, and weight prohibitive and have not been well suited for broadband noise control historically. However, for tonal noise sources produced by, for example, open rotor engines, active noise control may become a viable option. Others have effectively applied active noise control near propeller noise sources, e.g. Bombardier's Q400 series aircraft. Such an approach could also be applicable for the PRSEUS near open rotor engines currently being assessed as a means of propulsion for the HWB.

Analytical Methods and Testing Improvements – Analytical improvements in the areas of TBL uncertainty from existing experimental data sets and Random Ensemble approaches applied to diffuse field and TBL excitation could also be pursued and then validated with panel testing.

4.2 Proposed Future Work

Further development activities aimed at improving the acoustic response of PRSEUS structures will be undertaken once the initial test results are evaluated relative to known structures. As the basic sound transmission characteristics of a PRSEUS structure become better understood, different panel design parameters will be analytically assessed, compared back to the test database and then ultimately considered for further experimentation – characterized first analytically and then validated by further testing.

5.0 SUMMARY

The primary objective of this task order contract was to design, fabricate, and then deliver a test panel to NASA-LaRC for acoustic testing in the SALT test facility. The test results will be used to quantitatively measure the fundamental sound transmission characteristics of a PRSEUS structure, while also serving as a basis of comparison to calibrate future advanced analysis methods development activities. The intent of this testing is to begin addressing the concern that a lighter, stiffer, cocured PRSEUS panel construction could be more efficient in transmitting sound than a conventional built-up aluminum structure - which has more mass and a multi-part attachment scheme that helps provide dampening effects. If such a premise is true, then a portion of the weight savings achieved by improving the structural efficiency could be lost when the system-level weight allocation for sound proofing material must be increased. The test data derived from this activity will ultimately be used to minimize these adverse effects by modifying PRSEUS materials and design parameters to reduce the overall sound transmission levels through the integral panel construction.

References

[1] NASA Phase I Final Report, “Damage Arresting Composites for Shaped Vehicles”, Velicki, A., NASA/CR-2009-215932, Contract NNL07AA48C Project No. 4200208122, September 2008.

[2] NASA Phase II Final Report, “Damage Arresting Composites for Shaped Vehicles”, Velicki, A., NASA/CR-2011-216880, Contract NNL07AA48C Project No. 4200208122, October 2010.

[3] Mirsamadi, Syd, Advanced Subsonic Technology (AST) Composite Wing Material Stiffness and Allowable Strength Properties for Stitched Composite Laminates, 98K0318, Rev. C, September 1998.

[4] Hawley, Art, BWB Material Stiffness and Allowable Strength Properties, March 2005.

[5] J. Stuart Bolton, Validation of a polyimide foam model for use in transmission loss applications, Journal Acoustic Soc. Am. Volume 127, Issue 3, pp. 1872-1872, March 2010.

APPENDIX – SPECIMEN DESIGN DRAWINGS (5 PAGES)

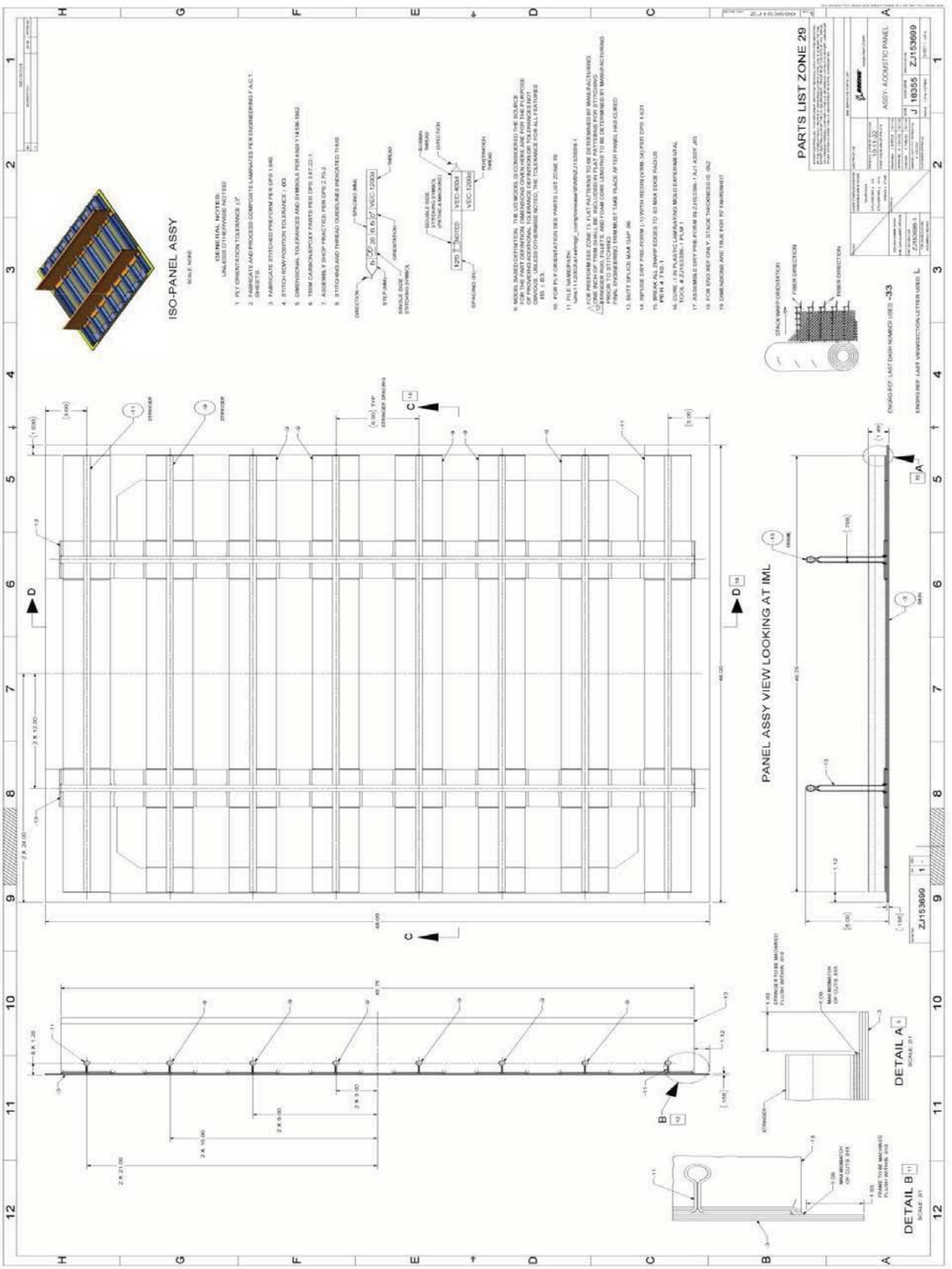


FIGURE 35. SPECIMEN DRAWING SHEET 1 OF 5

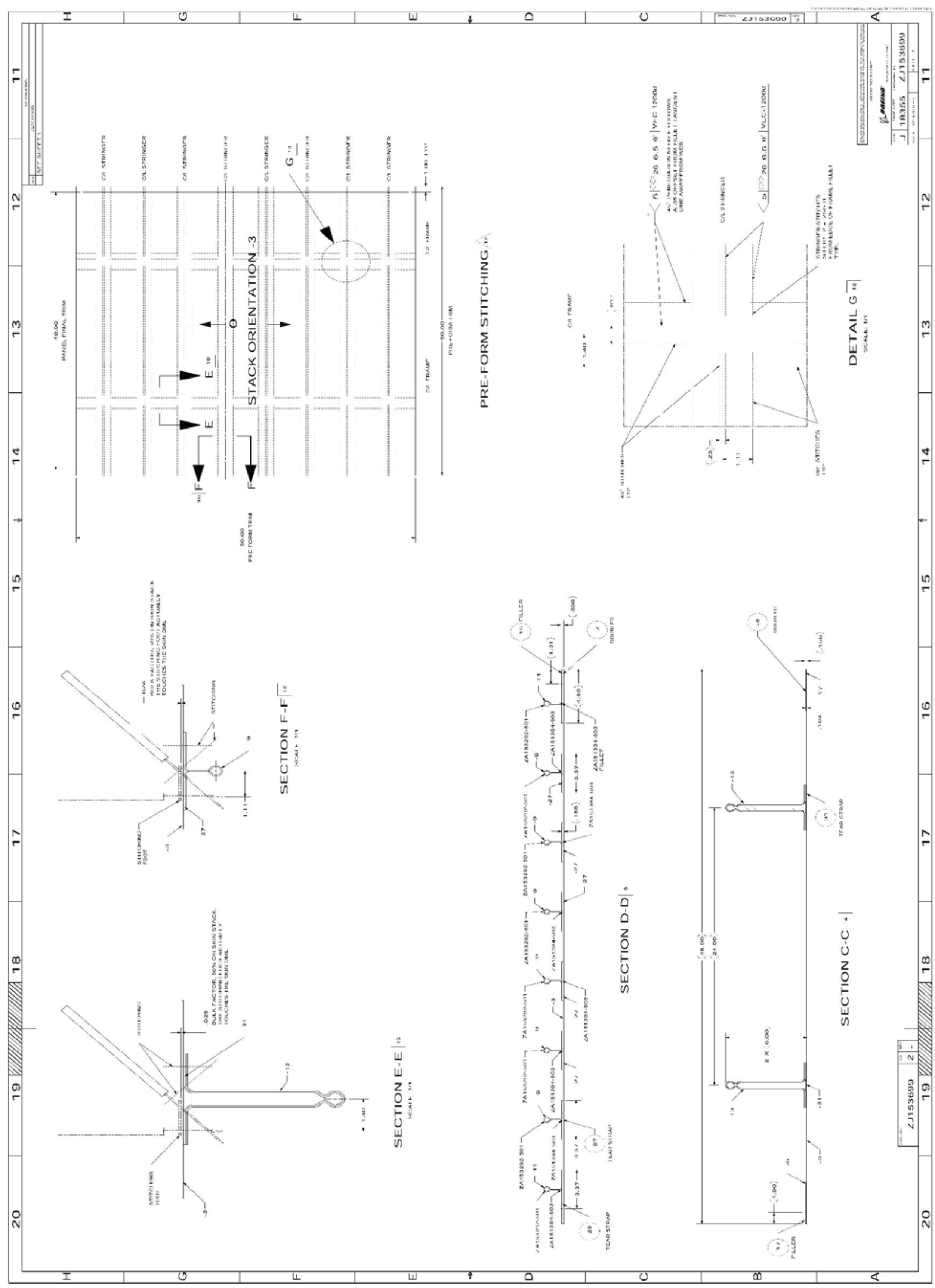


FIGURE 36. SPECIMEN DRAWING SHEET 2 OF 5

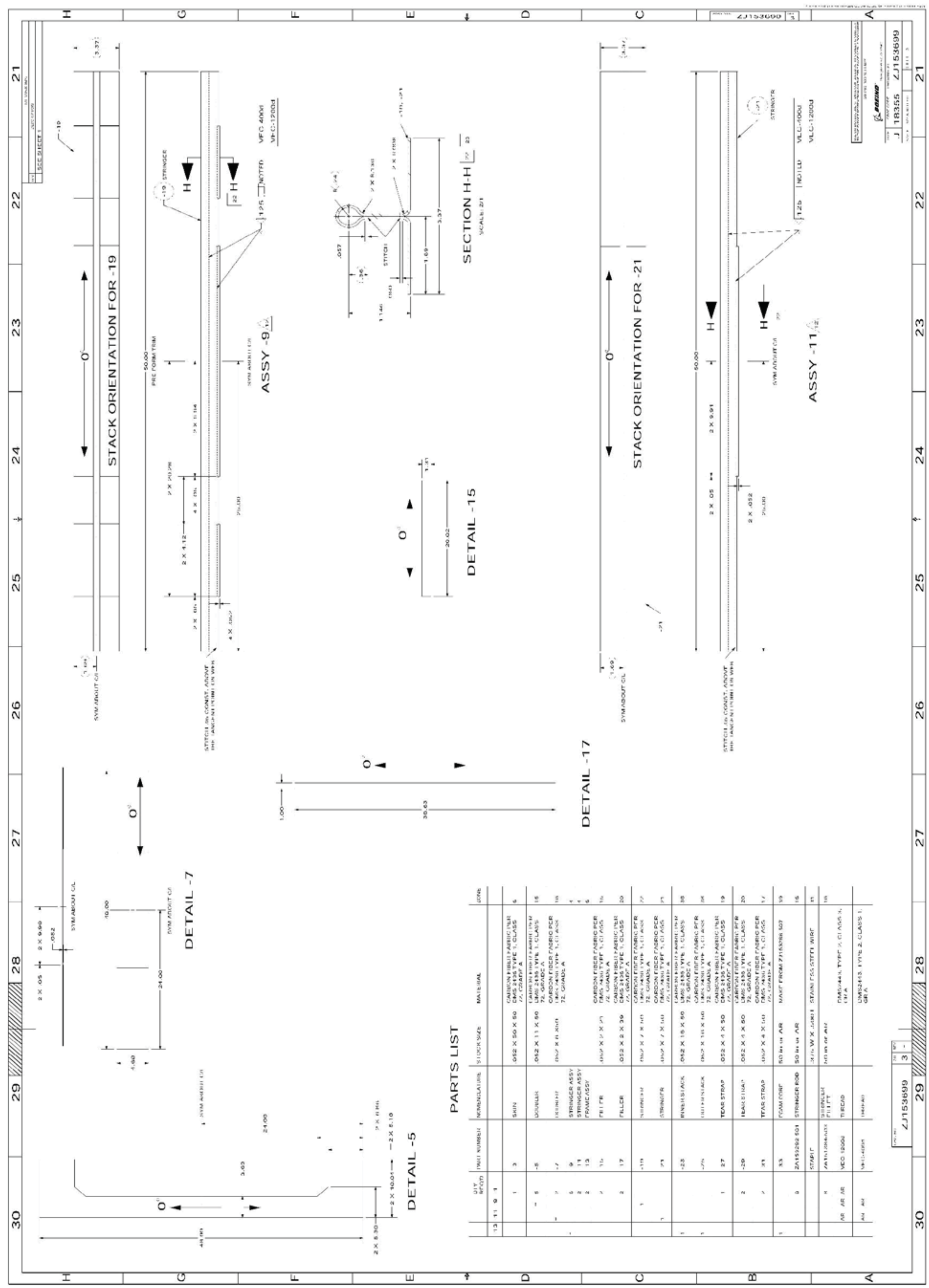


FIGURE 37. SPECIMEN DRAWING SHEET 3 OF 5

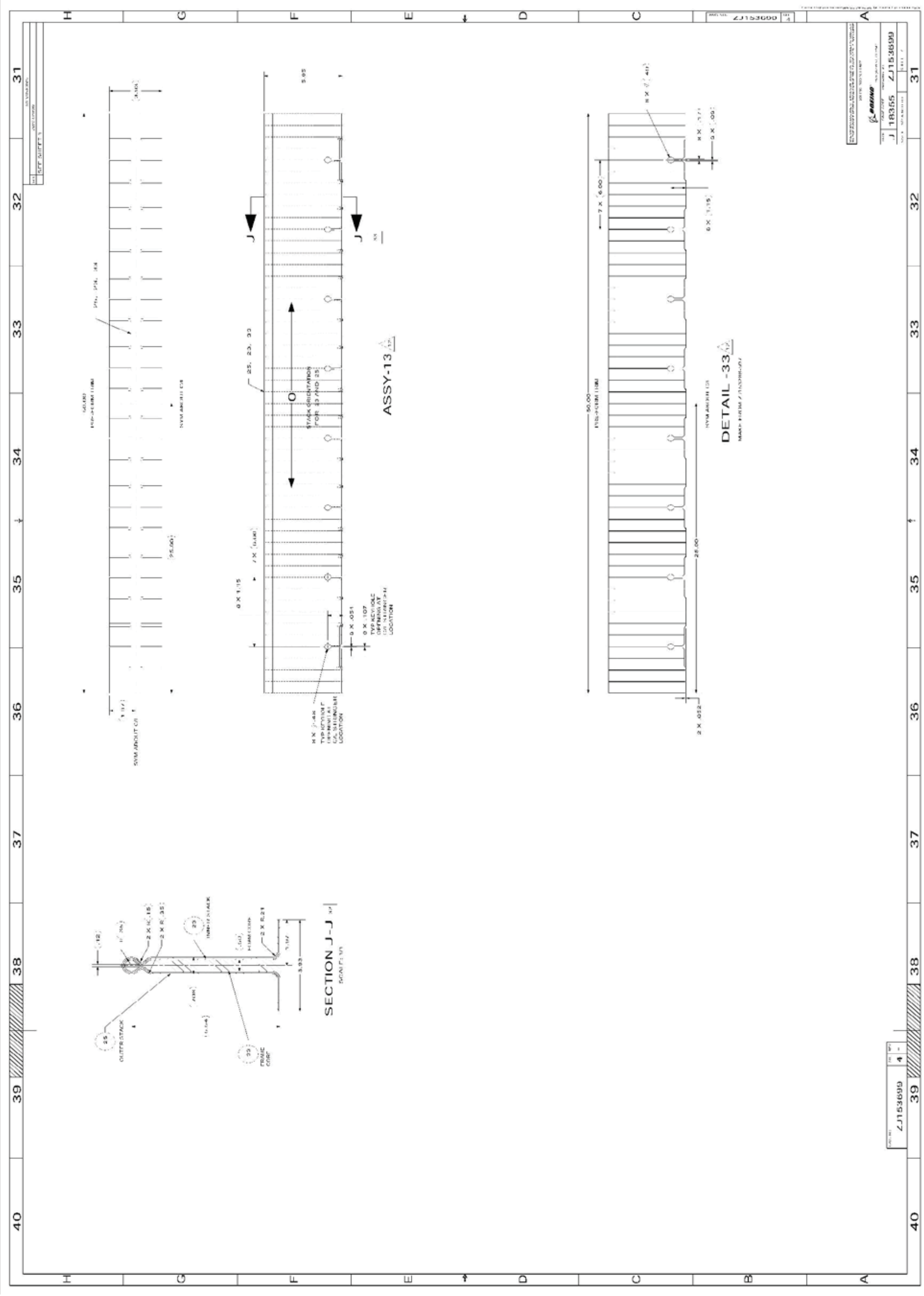


FIGURE 38. SPECIMEN DRAWING SHEET 4 OF 5

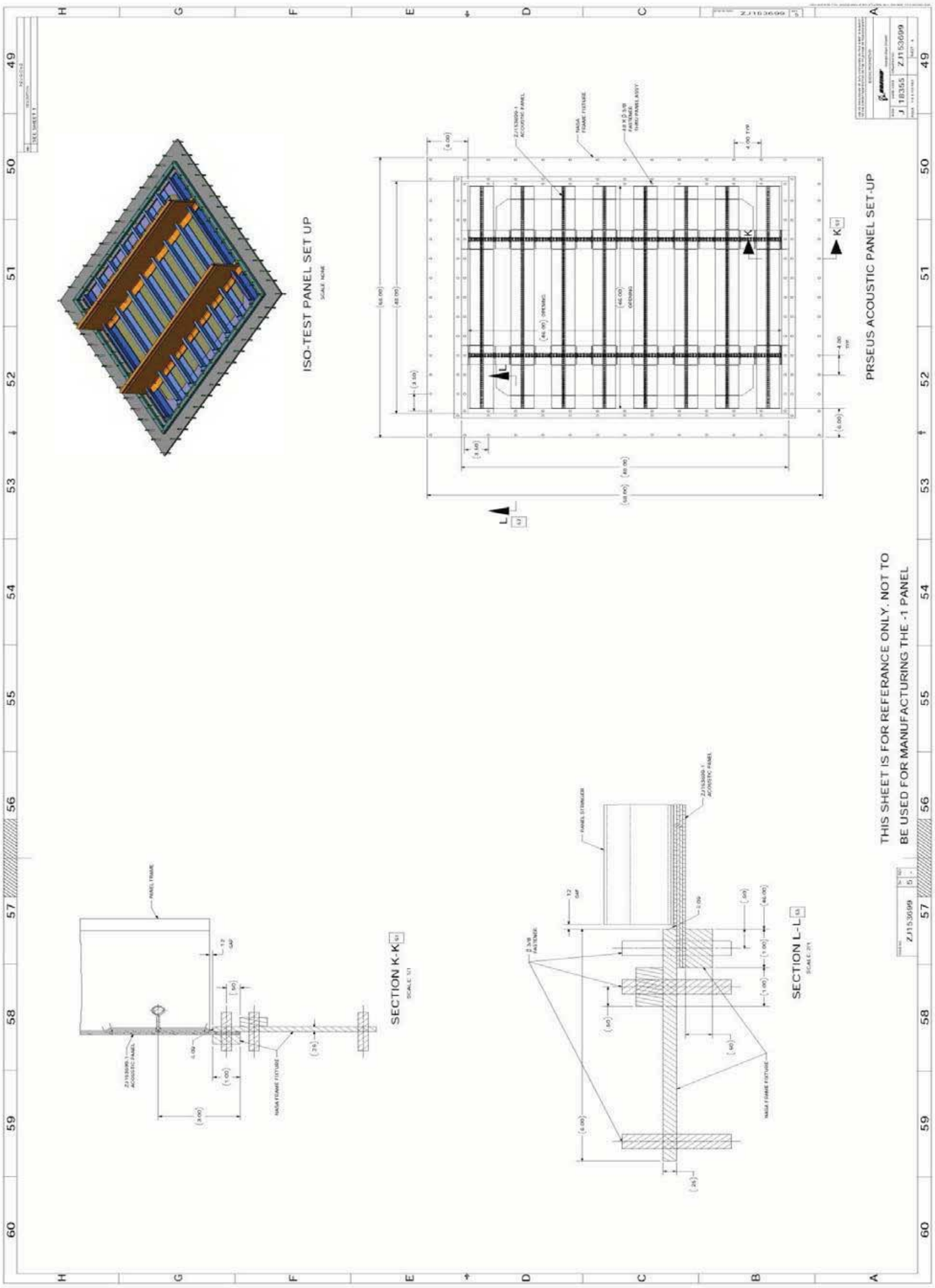


FIGURE 39. SPECIMEN DRAWING SHEET 5 OF 5

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14. ABSTRACT

This report describes the development of a novel structural concept, Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS), that addresses the demanding fuselage loading requirements for the Hybrid Wing or Blended Wing Body (BWB) airplane configuration with regards to acoustic response. A PRSEUS panel was designed and fabricated and provided to NASA-LaRC for acoustic response testing in the Structural Acoustics Loads and Transmission (SALT) facility). Preliminary assessments of the sound transmission characteristics of a PRSEUS panel subjected to a representative Hybrid Wing Body (HWB) operating environment were completed for the NASA Environmentally Responsible Aviation (ERA) Program.

15. SUBJECT TERMS

Acoustics; Blended wing body; Composites; Integrated structures; Pultruded rod; Resin infusion; Stiffened panel; Stitched composites

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