F-15 COMPOSITE ENGINE ACCESS DOOR[+]

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SUMMARY

This paper presents a summary of the successfully concluded Phase I of the two-phase Design and Manufacture of Advanced Thermoplastic Structures (DMATS) program. It addresses the design, manufacture and validation testing of a thermoplastic F-15E forward engine access door and includes lessons learned during the concurrent product and process design development phases of the program.

INTRODUCTION

The F-15 forward engine access door is moderately sized (42 in. x 38 in.) with a contour curvature that varies from gentle to relatively severe. The door is a built-up, channel stiffened, titanium structure on the F-15C/D and a superplastically formed/ diffusion-bonded (SPF/DB), hat-stiffened titanium structure on the F-15E (Figure 1).

The F-15 door is located approximately eight feet aft of the main landing gear, directly underneath the engine compressor section. The component requires structural integrity and durability in a high temperature (300°F) and severe acoustic (156 dB max.) environment. Due to its location, the door is impacted with runway debris and is removed frequently by maintenance personnel during routine maintenance. Engine equipment located above the door includes the main oil tank and fuel filter; thus the door is exposed to aircraft fluids. The door is a secondary structure and is loaded primarily in shear.

[+] Work reported in this paper was performed in Phase I of an ongoing Northrop/WRDC contract F33615-87-C-5242, titled "Design and Manufacture of Advanced Thermoplastic Structures". Ms. D. Carlin and Ms. T. B. Tolle are the WRDC technical monitors.

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Major longerons located inboard and outboard of the door carry [redacted] of the fuselage bending loads. Air loads are [redacted] (3.75 psi). The door structure contains two non-structural service doors for oil and fuel filter service. When open, the door is attached to the surrounding structure by two metal gooseneck hinges.

MATERIAL SELECTION

Thermoplastic matrix composite (TP) material selection for the F-15E forward engine access door was dependent primarily on the maximum continuous service temperature the structure is exposed to during aircraft operations. Recorded flight temperatures for the critical speed and altitude show a maximum temperature of 280°F. Therefore, a material system with a 300°F service temperature was deemed adequate to meet temperature requirements.

Originally, Imperical Chemical Industries' (ICI) AS4/HTX was selected as the material system for the door. The AS4/HTX material's 350°F service temperature met the temperature requirements, had the necessary mechanical/physical properties, and was available. However, micro-cracking and processing problems that occurred during trial manufacturing runs led to the withdrawal of the HTX material system from the program.

ICI's AS4/ITX was subsequently selected to replace AS4/HTX. The AS4/ITX material's 300°F service temperature met the temperature requirements for the door, and it had mechanical properties comparable to AS4/HTX. The processing characteristics of ITX are significantly better than those of HTX, and no micro-cracking was identified in the parts.

TP DOOR DESIGN

The initially selected coconsolidation concept for the TP F-15E door was finally replaced by an amorphous-bonded structure containing autoclave-consolidated outer mold line (OML) and diaphragm-formed inner mold line (IML) skins (see Figure 2). To facilitate diaphragm forming of unidirectional TP, the hat stiffeners on the TP door are shallow and the bend radii of the hat stiffeners (at the corners of the bays) are generous. The two nonstructural service doors were redesigned to be compression molded using chopped AS4/HTX tape. Due to the difference in the stiffener cross-sectional geometry between the titanium and the TP access door, all attachment and reinforcement hardware were redesigned to fit the TP hat stiffeners on the door. This included changes to the aluminum hinges for the service doors and the titanium gooseneck hinges that attach the access door to the aircraft. The gooseneck hinges were also designed to permit adjustment during installation. Two brake-formed sheet metal parts attach the hinge to the hat stiffener (Figure 3). This allows for manufacturing tolerances in the hat-stiffener geometry.

The OML and IML skin layups result in a laminate design that is a series of five-ply symmetrical sublaminates. The individual components (OML and IML skins) are symmetrical to reduce fabrication-induced warpage. Also, the ply build-ups in the OML skin are symmetrical to reduce warpage, and ply drop-off spacings are no smaller than 0.1 inch to enhance performance and producibility. Titanium fasteners were used, and all non-titanium metallic hardware were isolated from the composite door through the use of non-metallic shims.

The door was designed to fit to an existing metal substructure. Therefore, the edge distance (E) on the peripheral Milson fasteners was only two fastener diameters (D). To obtain an allowable bearing stress for an E/D of 2, bearing tests were performed. An allowable ultimate bearing stress of 40 ksi was determined from the test. In order to meet the bearing stress requirements, the door thickness around the edges was increased to 35 plies.

The door was designed to buckle below limit load and operate in the postbuckling range as an additional weight savings measure. The SS8 computer code was used to predict the initial buckling of individual door bays. Assuming that the hat stiffeners provide clamped supports, the center bay was found to be critical at an initial buckling load of 319 lbs/in shear flow. Therefore, at a maximum shear load of 850 lbs/in, the postbuckling ratio was 2.66.

The nonstructural service doors were designed using chopped AS4/HTX material (Figures 4 and 5). The basic shape of the service doors remained similar to the current aluminum service doors. However, because of the difference in material properties between aluminum and chopped AS4/HTX, the thickness of the door was resized to withstand air pressure and handling loads. Material properties for chopped AS4/HTX were determined from test results.

Amorphous bonding of AS4/ITX skins with polyetherimide (PEI) was shown to have strengths equivalent to coconsolidation. This is because PEI is a low melt temperature thermoplastic material with matrix properties compatible with thermoplastic materials including PEEK and ITX. A typical amorphous bond process has one 0.005 inch PEI ply consolidated to the joining surface of each detail during the consolidation of the details. When the two details are joined together, two additional 0.005-inch PEI plies are inserted between the details to effect joining/ subassembly. The resultant consolidated bondline is typically 0.010 inch thick.

Based on the results from two subcomponent tests, a design change was made to install fasteners around the hats in the amorphously bonded door full-scale assembly (Figure 6). This was required because of the inconsistency in the bondline quality, resulting in a premature failure during one of the subcomponent tests. However, a second subcomponent went to 150% of the design ultimate load, with no failure in the bond region. Therefore, the fasteners were installed as a safety precaution since a reliable database on amorphous bonding was not available. The fastener pattern design for the door (see Figure 6) uses 4D and 6D spacing, depending upon the proximity to highly stressed areas. The fasteners chosen were 3/16 inch tension head hi-loks with self-aligning washers and collars.

MANUFACTURING PROCESS DEVELOPMENT

Significant technical challenges were encountered in transitioning from the preliminary manufacturing processes at the initiation of the program to the processes that were eventually applied on the flightworthy TP F-15 engine access doors. The challenges were posed by material-, design-, tooling- and equipment-related issues, and are summarized in the "Lessons Learned" section of this paper. The manufacturing processes used for the "production" TP doors are described below:

Fabrication of AS4/ITX IML Skin

Diaphragm forming, using an SPF aluminum diaphragm, was chosen as the manufacturing process for the IML skin because of the proven ability of this process to fabricate high quality, complex, efficient composite parts (Figure 7). The skin was fabricated in a press on a female carbon/ceramic tool. Dual diaphragms were utilized to maintain location of the ply pack during forming.

Fabrication of AS4/ITX OML Skin

Autoclave consolidation was the selected manufacturing process for the OML skin (Figure 8). Diaphragm forming in a press with a contoured vacuum frame was recommended for a future production scenario and was used in the cost analysis for the fabrication of the OML skin. The fabrication process consisted of envelope bagging on the OML carbon/ceramic tool utilizing an aluminum caul sheet. Processing parameters were set as close as possible to those used in the diaphragm forming process. The caul sheet was roll- formed to the approximate contour of the OML tool.

Amorphous Bonding of AS4/ITX OML and IML Skins

The IML skin and the OML skin initially had one layer of PEI film coconsolidated on the bonding surface. These surfaces were cleaned prior to bonding using cheesecloth and isopropyl alcohol. The OML skin was then placed on the OML tool. Twelve layers of dried .005 inch PEI film were placed over the skin to ensure the filling of any gap due to IML/OML mismatch. The IML skin was then placed on top of the PEI film layers and envelope bagged to the OML tool. The periphery of the part was periodically taped with high temperature tape to allow air to escape and to control PEI squeeze-out. To aid in air/gas removal, fifteen 0.040-inch diameter holes were drilled at strategic locations through the IML skin into the bondline. Amorphous bonding was effected during a 45 minute hold at 20 psi and 575^{o}F. A 3-5^{o}F/minute cool down was used to minimize any resulting thermal stresses.

TESTING AND TP DESIGN VALIDATION

An extensive test program was conducted to validate the TP F-15 door design. Results of the test program were used to evaluate the flightworthiness of the door. A building block approach was used, as evidenced by the testing of elements, subcomponents, and finally the full-scale door.

One full-scale production door (without hardware, access doors, or finishes) was subjected to structural verification testing consisting of static, spectrum fatigue, and residual strength tests. All tests were performed under room temperature ambient (RTA) conditions. The door, to be structurally qualified for flight test, had to meet the following test criteria:

(1) No delaminations or disbonds occur that result in permanent set of the composite material at or below 100% design limit load (DLL). No yielding or fracture of the the composite material at or below 100% DLL. Disbonds between the hat and the skin would be allowed if the disbond were arrested by the fasteners placed around the hats.

(2) The door must survive two (2) lifetimes of spectrum fatigue loading (1 lifetime = 8000 spectrum flight hours).

(3) After completing two lifetimes of spectrum fatigue testing, the door must reach 150% DLL with no catastrophic failure.

The full-scale door was subjected to shear loading using a picture frame arrangement. The shear loads applied were based on loads taken from the F-15E aft fuselage finite element model. This shear load is slightly lower than the original 850 lb./in. shear that the door was designed to.

Before the door was tested, a baseline ultrasonic A-scan and C-scan were performed. The door was A-scanned after being subjected to the limit load and during the fatigue tests to determine if any nonvisible damage had occurred. A C-scan was taken of the door after the ultimate test was performed to determine the extent of the damage.

The full-scale AS4/ITX F-15 door test was successful. Test results validated the TP door design and established its capability to withstand 100% DUL after two lifetimes of F-15 fatigue loading.

LESSONS LEARNED

The Phase I effort described in this paper culminated in the successful delivery of flightworthy TP F-15 forward engine access doors to the U.S. Air Force. However, the path to success was punctuated by challenges, some of which could not be overcome, in technology areas that included materials and processes, manufacturing technology, tooling technology, processing equipment and structural design. A summary of the lessons learned is presented below:

Materials

(1) Materials-related challenges faced on the DMATS program included high melt viscosity, narrow processing window and limited reprocessibility. The last issue (limited reprocessibility) was primarily introduced by long process cycles, due to a lack of rapid heating/cooling capability in the processing equipment. Consequently, the preferred assembly process for the OML/IML skins was changed from coconsolidation to amorphous bonding.

(2) Selected Phase I TP materials (AS4/HTX and AS4/ITX) were only available in the unidirectional tape (UDT) product forms. This posed a forming challenge for the complex-contoured, stiffened IML skin. The use of a Kapton/Upilex polyimide film in Northrop's diaphragm forming press setup increased diaphragm rupture occurrences at forming pressures in excess of 100 psi. But, the IML skin did not completely form at 100 psi, exhibiting small regions of "bridged" plies. This necessitated the use of the SPF aluminum diaphragm in MCAIR's diaphragm press setup, and the application of a 200 psi forming pressure. If drapeable AS4/HTX and AS4/ITX product forms had been available, forming of the IML skin and the concurrent OML/IML coconsolidation could have been demonstrated on the program.

Manufacturing Processes

(1) Diaphragm forming of small flightworthy F-5 and T-38 details had been established by Northrop as a producible and cost-effective process prior to the DMATS Phase I effort. However, the scaleup of this process to the F-15 door IML skin was a major challenge. The replacement of the polyimide diaphragm by the SPF aluminum diaphragm, and the use of a 200 psi forming pressure, overcame the IML skin forming challenge and resulted in a producible process.

(2) Autoclave consolidation of the gently contoured F-15 door OML skin, using an envelope bagging technique, required the use of a caul sheet to eliminate wrinkles.

(3) The use of a washaway mandrel to coconsolidate the OML and IML skins was successfully demonstrated on the program, though its application was considered risky due to the complexity in the final OML/IML cross-sectional cavity shape

compared to the simple hat cross section in the preliminary design.

(4) The implementation of the amorphous bonding process was challenged by three factors: (a) the unknown interlaminar (bondline) properties for the ITX/PEI combination; (b) the lack of dimensional control of the IML and OML bonding surfaces, due to the design of the forming tools for the preliminary coconsolidation process; and (c) the use of a low amorphous bonding pressure (20 psi) to eliminate the need for washaway IML cavity mandrels. Significant process development efforts were expended to accommodate these factors, and to establish the reprocessability of the amorphous bonding operation to eliminate any PEI/moisture-induced porosity in the bondline.

(5) Compression molding of the oil and fuel filter service doors, using AS4/HTX offal, was successfully demonstrated on the program.

Tooling

(1) The complex pan-stiffened F-15 door IML skin design and the high processing temperature (700-800°F) requirement for TPs, established the need for a match in the coefficient of thermal expansion (CTE) between the tool and the part. Though only partially successful in the reported effort, a matched CTE tooling concept that lends itself to rapid forming is essential for successful application of TPs to composite structures.

(2) Polyimide diaphragms (Kapton and Upilex) were barely adequate for processing AS4/ITX under 720-750°F, 100 psi conditions. SPF aluminum alloy diaphragms performed very well and withstood a 200 psi forming pressure at 720-750°F.

(3) For the F-15 door details, the forming tools were designed to control the OML side of the OML skin and the IML side of the IML skin, based on the original coconsolidated assembly concept. This created a mismatch between the bonding surfaces when the coconsolidation process was replaced by amorphous bonding, requiring a variable thickness of PEI along the bondline and raising the issue of bond strength variation with PEI thickness. Had the OML and IML tools controlled the bonding surfaces, this issue may not have arisen.

Equipment

(1) The diaphragm forming process is unique to TP applications, and has only been demonstrated in a press setup for small parts. Transitioning this process to the F-15 door application required considerable equipment development efforts at Northrop and MCAIR. In extending the process to larger primary structural parts, the capability to adapt existing high temperature (>800°F) autoclaves to this process is essential.

(2) The feasibility of economically rapid forming TP parts has been established in many programs. However, the development of large rapid thermoforming equipment has been slow.

Design

(1) A concurrent design development effort was successfully demonstrated on the program and contributed to the selection of the preliminary coconsolidated F-15 door concept, and its change to the final amorphous bonding process. However, the use of developmental materials, manufacturing processes and tooling concepts, and the ambitious Phase I schedule constraints, forced the concurrent design development effort to falter at times and accept too many changes without the necessary supporting data.

(2) In transitioning from the preliminary design (uniform thickness OML and IML skins) to the final design (multiple drop-offs, local doublers, etc.), producibility was partially sacrificed in favor of structural performance, and a large weight reduction (39%) over the baseline SPF/DB titanium door was aimed for. This played a major role in introducing drop-offs and local build-ups, and in changing the assembly process from coconsolidation to amorphous bonding. The program demonstrated that considerable cost and weight savings are realizable with TP designs, but these have to be achieved without compromising producibility.

CONCLUSIONS

Phase 1 of the DMATS program was concluded very successfully with the structural qualification/design validation of the TP F-15E engine access door via full-scale static and fatigue tests and the delivery of flightworthy TP doors.

For the selected F-15E engine access door application, the TP design developed and validated on this program was projected to yield significant weight (39%) and cost (25%) savings over the SPF/DB titanium production doors. The viability of using TP materials in secondary structures, and their potential for primary structural applications, was established beyond doubt. Lessons learned from this Phase I effort are being incorporated into ongoing Phase II tasks to identify cost-effective primary structural applications for thermoplastic matrix composites.

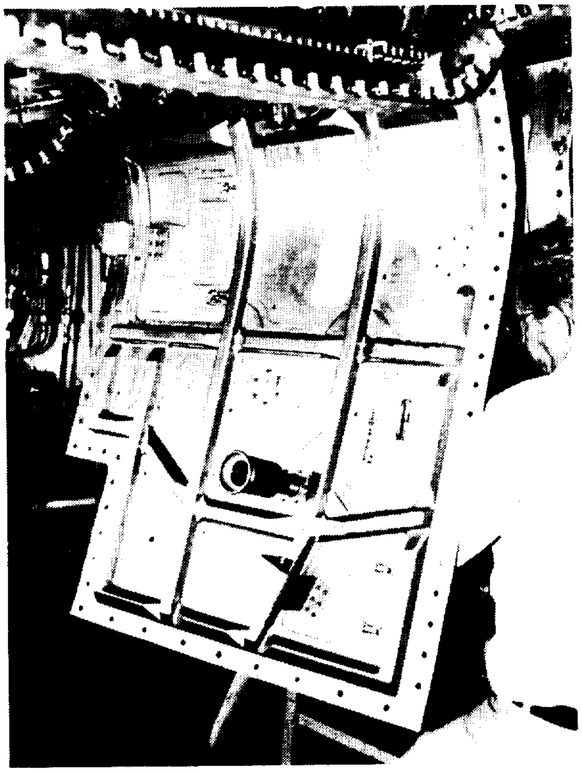

Figure 1 F-15E SPF/DB Titanium Door

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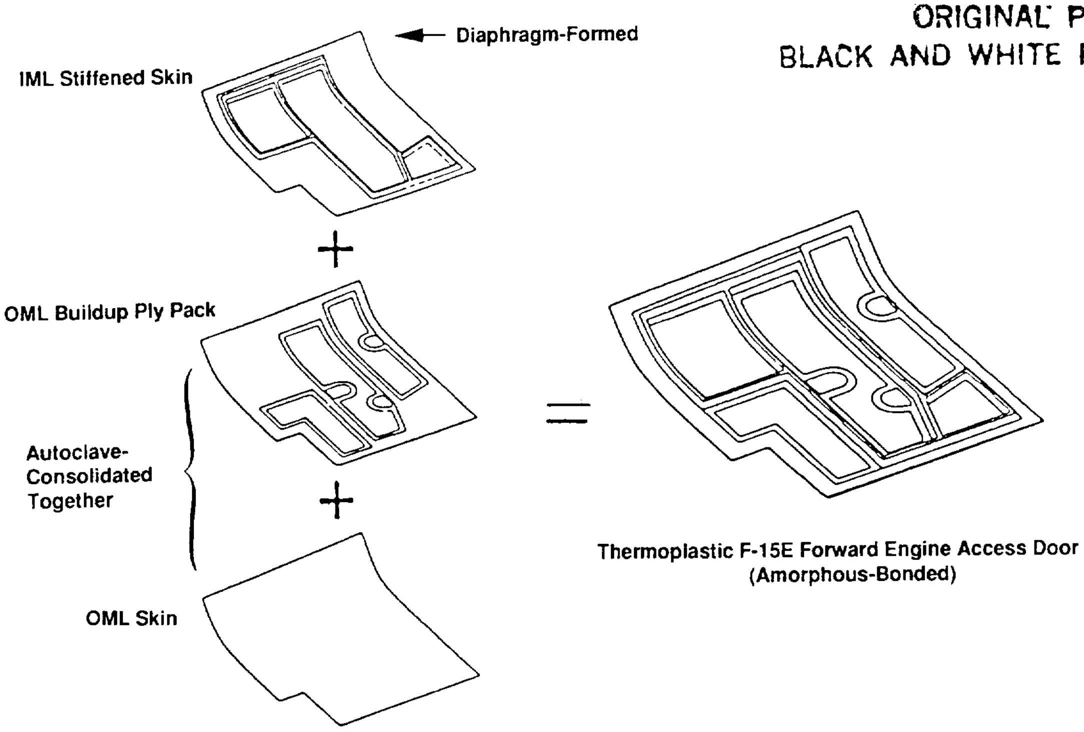

Figure 2 TP F-15 Engine Access Door Design

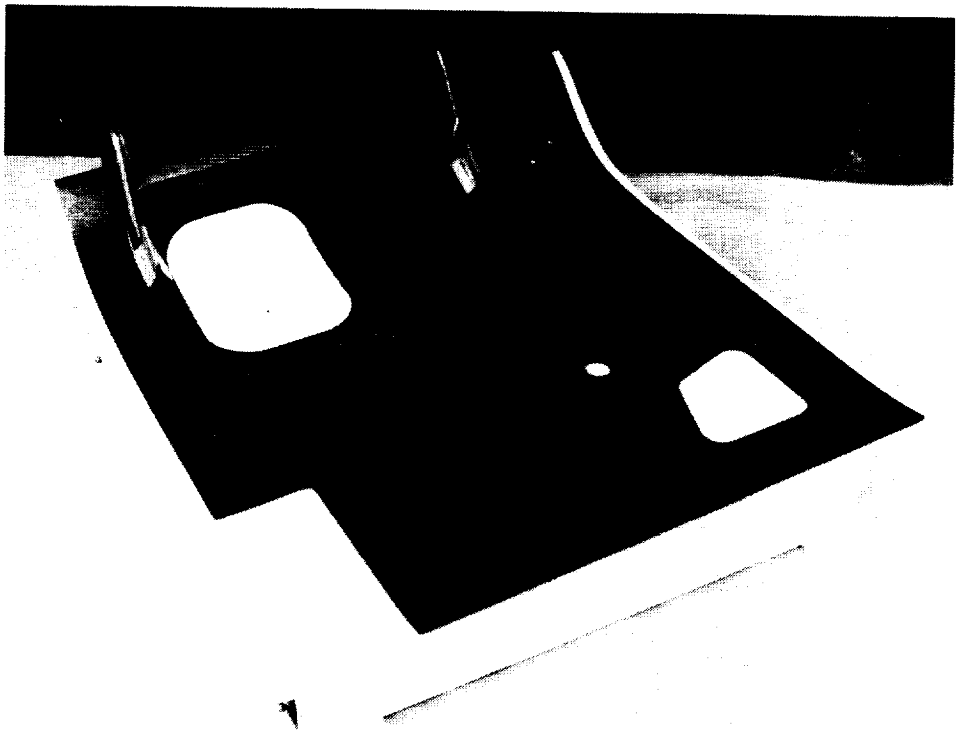

Figure 3 Redesigned Gooseneck Hinges

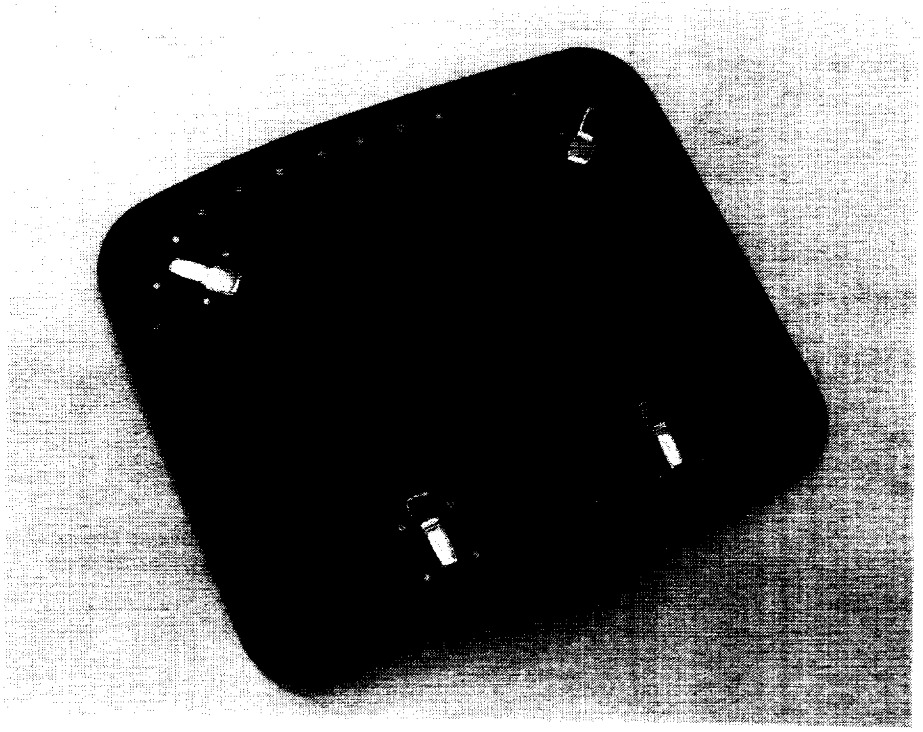

Figure 4 OML Side of the Compression Molded AS4/HTX Oil Service Door

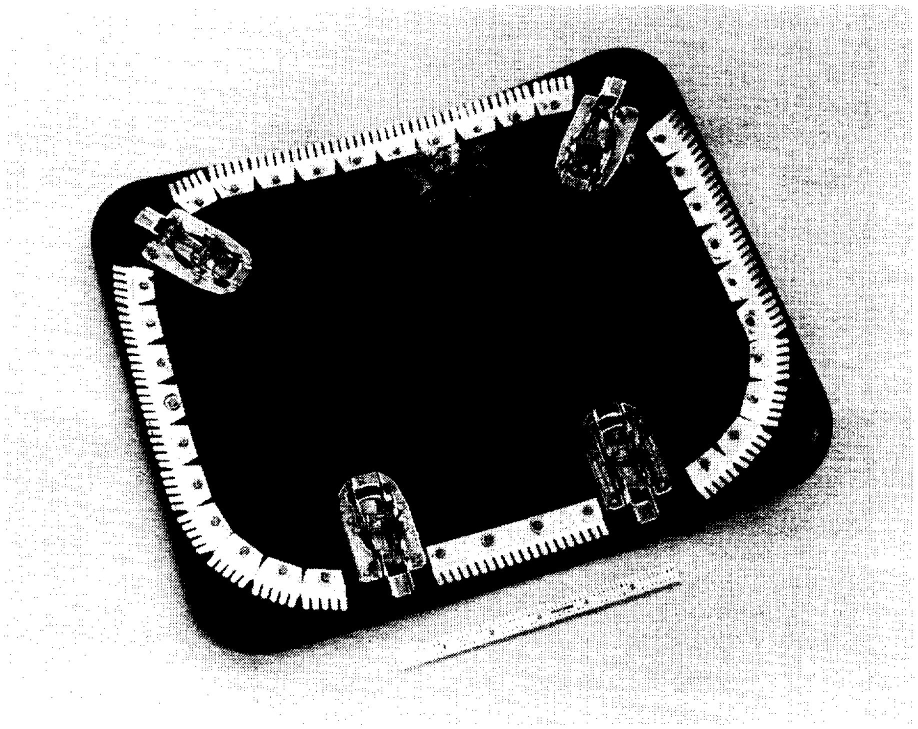

Figure 5 Electromagnetic Interface (EMI) Fingers on the IML Side of Oil Service Door

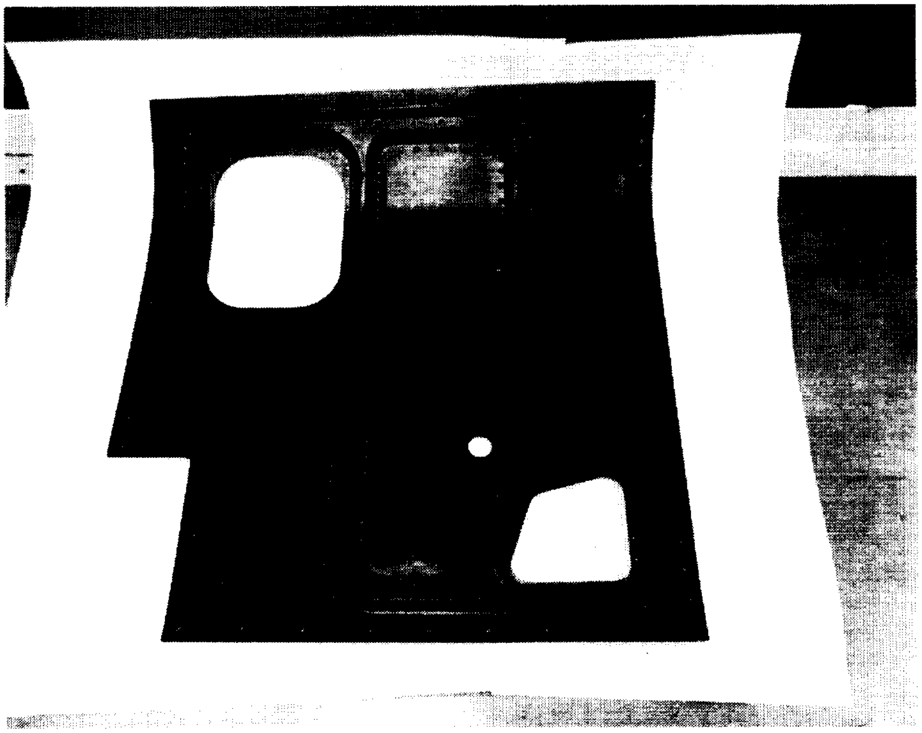

Figure 6 Fastener Pattern for Amorphous Bonded F-15 Door

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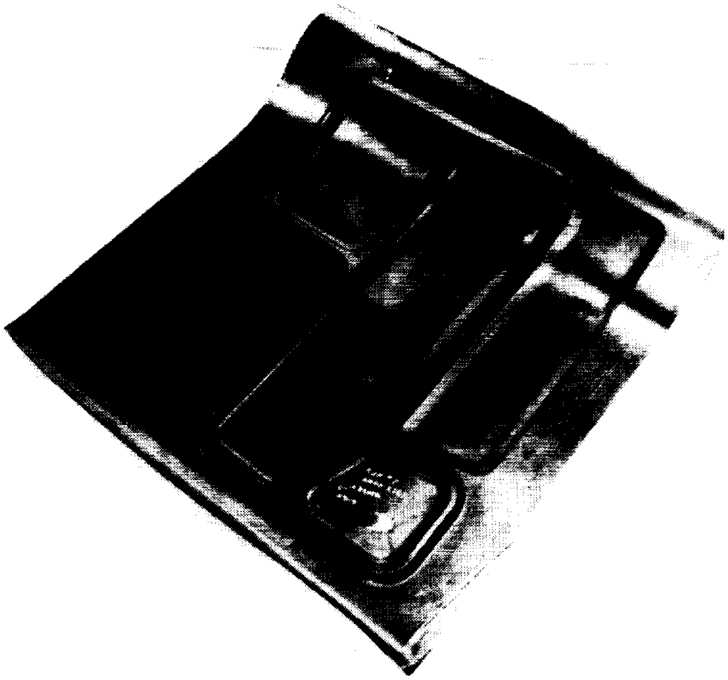

Figure 7 Diaphragm Formed F-15 Door IML Skin

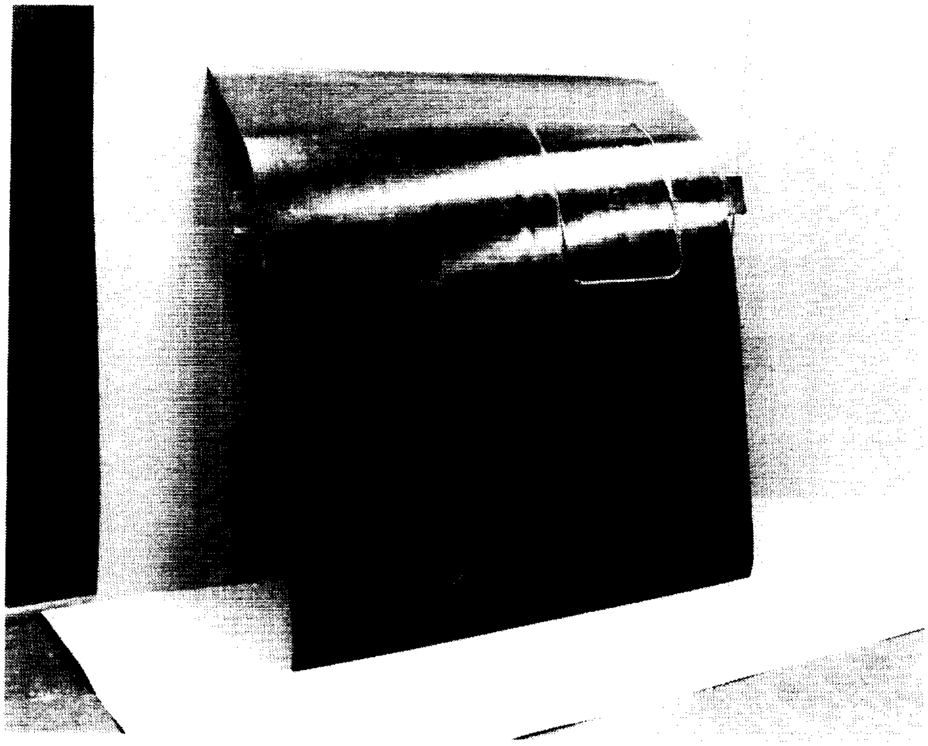

Figure 8 Autoclave Consolidated F-15 Door OML Skin