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Design Studies of Laminar Flow Control (LFC) Wing Concepts Using Superplastic Forming and Diffusion Bonding (SPF/DB)

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DESIGN STUDIES OF LAMINAR FLOW CONTROL (LFC) WING CONCEPTS USING SUPERPLASTIC FORMING AND DIFFUSION BONDING (SPF/DB)

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FOREWORD

This is the Final Report for the "Design Studies of Laminar Flow Control (LFC) Wing Concepts Using Superplastic Forming/Diffusion Bonding (SPF/DB)" program which was performed by the Los Angeles Division of Rockwell International for NASA, Langley Research Center under Contract No. NAS1-15488. the NASA Technical Representative for the program was Mr. Albert C. Kyser. Rockwell International personnel directly participating on the program were:

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This report covers the work performed from August 1978 through September 1979.

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1.0 SUMMARY

An earlier Rockwell study of the application of superplastically formed and diffusion bonded (SPF/DB) titanium structure to laminar flow control (LFC) wing design (reference 1) demonstrated that the process can produce uniquely fabricated panels which can be assembled into a structurally efficient LFC wing.

This second study was based on the accomplishments of the first program, and design concepts have been developed for integrating the SPF/DB titanium panel designs into a complete LFC wing. This wing concept is approximately three percent lighter than a conventional aluminum wing without LFC provisions. A structural weight estimating program (SWEEP) was used to make preliminary structural sizing comparisons.

The LFC wing cover panels were designed to provide for the LFC airflow requirements using an efficient structural configuration. The LFC airflow requirements and the resulting parameters such as slot or perforation spacing, duct sizing and duct spacing were determined. Structural constraints such as panel sizes and loads to be used for structural sizing were also determined.

A structurally efficient wing cover stiffener arrangement was developed. These stiffeners are also used as spanwise LFC ducting. The resulting design therefore satisfied the LFC airflow requirements as well as the structural requirements. The SWEEP program was used to optimize an initial structural stiffener arrangement which was then modified to accommodate LFC airflow requirements. It was determined that the stiffener spacing should be made as wide as can be allowed by LFC requirements, in order to achieve higher structural efficiency.

A cost effective LFC concept using removable LFC strips was developed. Three integral LFC feature concepts and 10 separate LFC strip concepts were studied. Evaluated as the best concept is a separate slotted or perforated strip that is adhesively bonded into a wide groove in the mold line surface of the wing cover. Although the integral slotted concept was judged to have the lowest initial fabrication cost, the separate strip concept, considering repairability, was judged to have the lowest Life Cycle Cost (LCC). Since there would be approximately 3000 meters (10000 feet) of LFC slots required for a complete wing, considerable effort was devoted to developing concepts for an automated production process for the slotted LFC strips.

Methods were also studied for fabricating a complete semi-span wing cover. While a one-piece SPF/DB wing cover is beyond present technology, a complete wing cover can be fabricated by joining SPF/DB panels together by welding or mechanical fasteners. Welding was determined to be the most practical method for making chordwise joints. Welding is also preferred for a minimum weight spanwise joint; however, mechanical spanwise joints can be used where needed to satisfy fail safe requirements.

2.0 INTRODUCTION

Laminar flow control, with its potential for increasing aircraft efficiency is expected to be a vital system on the new generation of energy efficient transport aircraft. The need for saving energy is important both for conserving the world's limited supply of fossil fuels and for reducing the operating cost of aircraft.

The LFC system must be efficient in terms of aerodynamic performance improvements, system energy requirements and weight added. The ability of LFC to increase aerodynamic performance has been well documented, however, the efficiency is dependent on ability to provide LFC provisions on the moldline surface which meet the airflow requirements and will continue to do so, with a minimum of upkeep, over an extended useful life.

The LFC system energy requirement is dependent on the efficiency of the LFC ducting configuration. The weight added to the aircraft as a result of the LFC installation will depend on whether primary structure can be made in a configuration which will provide for much of the LFC ducting thus reducing the weight added for the LFC system.

Titanium structure, fabricated into the unique configurations which are possible using superplastic forming and concurrent diffusion bonding (SPF/DB), provides solutions to these problems. The corrosion and abrasion resistance of titanium make it an ideal material for the LFC surface features. Configurations possible using SPF/DB allow the primary structure to provide much of the LFC internal ducting requirements.

The program, documented in this report, is the second Rockwell LFC program and is based on the accomplishments of the first program (reference 1) and has developed alternate design approaches for suction panels, as well as techniques for integrating the panel designs into a complete LFC wing. The program included a definition of the problems, conceptual design studies and analysis of the concepts, design integration and evaluation of the results.

3.0 BACKGROUND

Laminar flow control, as a method of reducing aerodynamic drag, has been known since the early 1900's and both the theoretical methods and the design techniques have been available since the late 1940's.

The feasibility of the LFC concept was demonstrated in the 1960's by the X-21A airplane which was built at Northrop under the direction of Dr. W. Pfenninger. Flight testing of this airplane showed that significant decrease in aircraft drag was realized and demonstrated technical feasibility by achieving predictable and repeatable performance.

Currently, the energy shortage has resulted in a need for improving the efficiency of long range transport aircraft and has renewed interest in LFC. A number of new programs have documented the advantages and identified the problem areas of LFC systems.

The LFC moldline surface is a problem area for current designs using either aluminum or composite materials. Corrosion can have a disasterous effect on the suction slots in an aluminum surface. This is particularly severe where the slots are machined after panel fabrication, thus restricting the use of effective corrosion protective systems. Erosion is a severe problem with composite materials, employing Kevlar, fiberglass, or graphite in a resin matrix. The high velocity air with entrained dust, grit, and ice particles erodes away the soft matrix material leaving the fibers exposed to the air stream. The effect of corrosion and erosion is to disturb and restrict the airflow, in addition to trapping debris at a more rapid rate than clean slots, further restricting the airflow.

Current designs employing a parasitic LFC panel on the moldline over the structural wing, are structurally inefficient since the wing structure necessary to react the wing bending and torsion loads must be smaller to fit under the LFC panels.

Based on the X-21 wing design, Northrop has estimated (reference 2) that incorporation of LFC provisions will increase airframe cost by 13 percent. Since this increase is primarily wing cost, which is historically about 15 percent of the total airframe cost, the effect on wing cost would be an increase of approximately 70 percent. In a study by the Boeing Company (reference 3) the complexity of adding LFC provisions increases the cost of wing structure by 100 percent.

The previous Rockwell study, "Study of the Application of Superplastically Formed and Diffusion Bonded (SPF/DB) Titanium Structures to Laminar Flow Control (LFC) Wing Design", demonstrated that the process can produce effective LFC Wing panels which provide solutions to these problems. The titanium material will not experience the corrosion or erosion problems which afflict the aluminum or composite materials. The LFC skin panels designed and fabricated in this program demonstrated that structurally efficient panels can be made which incorporate provisions for LFC surface and duct features thus reducing both cost and weight of the LFC system.

The first Rockwell LFC program demonstrated the applicability of the SPF/DB process to the fabrication of LFC wing structure. However, the program studied only the point design wing section at the maximum bending moment. Recommendations were made that the problems involved in integrating the panel designs into a complete LFC wing should be addressed. This second Rockwell LFC program is structured to provide that information.

4.0 OUTLINE OF THE PROGRAM

The objective of this program is to develop one or more design approaches for applying the SPF/DB technology to the problems of design, fabrication, operation, and maintenance of wings for LFC transport aircraft.

This program was primarily analytical, and conceptual design studies, based on the first Rockwell LFC program, were used to develop a number of alternate design approaches for suction panels and techniques for integrating these panel designs into a complete LFC wing.

This was accomplished by conducting the program in five tasks:

Task 1 - Problem Definition
Task 2 - Conceptual Design Study
Task 3 - Analysis of the Concepts
Task 4 - Design Integration
Task 5 - Evaluation of Results

A description of the approach used in each of these tasks is given below.

TASK 1 - PROBLEM DEFINITION

The baseline data were obtained from the first Rockwell LFC program and used the "LFC 200R" wing and airflow requirements from the Lockheed System Study. See reference 2. Using these data, geometric parameters including slot spacing, chordwise duct spacing and duct sizing were determined.

Loads were developed from data on the "LFC 200R" wing and structural constraints were determined using fabrication limitations for the SPF/DB process.

TASK 2 - CONCEPTUAL DESIGN STUDY

Using the structural suction surface panel concepts developed in the previous Rockwell LFC program as a base, new concepts, with slots and plenums integral with the surface panel and concepts where the LFC surface features are separate from the structural panel, were developed.

Chordwise ducting concepts were developed both as an integral part of the surface panels and as separate nonintegral ducts.

TASK 3 - ANALYSIS OF THE CONCEPTS

The design concepts developed in Task 2 were analyzed to assure that they would meet the strength, stability and internal volume requirements established in Task 1. Cost and weight comparisons of the concepts were also made.

TASK 4 - DESIGN INTEGRATION

Problems of integrating the concepts, developed in Task 2, into a complete aircraft system were addressed. Developed were: methods for making splices, both chordwise and spanwise; fuel tight joints and internal duct installations. Manufacturing problems addressed included: slot alignment, tapered slot spacing, high production methods of producing LFC slots and high production tooling concepts for SPF/DB panels. Techniques for repairing fabrication anomalies and field damage were studied.

TASK 5 - EVALUATION OF RESULTS

The design integration methods, manufacturing methods and repair techniques studied during Task 4 were evaluated for producibility, aerodynamic efficiency, cost and weight. An assessment of the program, in terms of lessons learned and conclusions reached, was made and used to develop a list of recommendations for the next phase in the development of SPF/DB for LFC wing structure.

5.0 TASK 1 - PROBLEM DEFINITION

5.1 BASELINE INFORMATION

The aircraft configuration used as the baseline for this program is the "LFC 200R" (figure 1) which was studied by Lockheed (reference 4) and used in the first Rockwell LFC program (reference 1). NASA concurred in this baseline selection prior to program go-ahead. This aircraft is a 200 passenger transport, with a range of 10,200K (5500 n. miles), which is designed to fly Mach 0.8 at 11,600 meters (38,000 ft.). It is a low wing T-tail aircraft powered by four, aft fuselage mounted jet engines.

The LFC-200R has suction surface requirements for the upper and lower wing surfaces which extend from 4 percent to 74 percent chord. The LFC suction requirements are met by two bleed-burn suction pump units which are installed in the wing root fairings. The LFC airflow is ducted from each wing into these pump units. Crossover ducting is provided so that reduced but symmetrical LFC suction is possible even with failure of one pump unit.

The size and shape of the baseline wing was defined using information supplied by Lockheed for the LFC-200R configuration. Table 1 presents the airfoil dimensions for five wing stations. Figure 2 shows the typical airfoil shape. Figure 3 shows the wing planform dimensions.

Table 2 lists the wing static loads supplied by Lockheed for the LFC-200R configuration. These are the only loads made available to Rockwell for this configuration. Rockwell has developed wing torsion loads which were used for structural analysis in Task 3.

5.2 AIRFLOW REQUIREMENTS AND GEOMETRIC PARAMETERS

The LFC system, including both the suction surface and the internal ducting must be designed to remove the low-energy boundary-layer air from the airfoil surface so that the boundary layer is prevented from building up, on the wing surface, sufficiently to cause the transition from laminar to turbulent flow. The inflow of the boundary air through the suction surface and the flow through the ducting must be regulated so it is sufficient for LFC but not excessive. Additional airflow, beyond that needed for LFC would increase the size and cost of system and the system fuel costs.

5.2.1 SLOT REQUIREMENTS

The slot spacing necessary to satisfy the airflow requirements has been determined by using analytical techniques based on the following criteria.

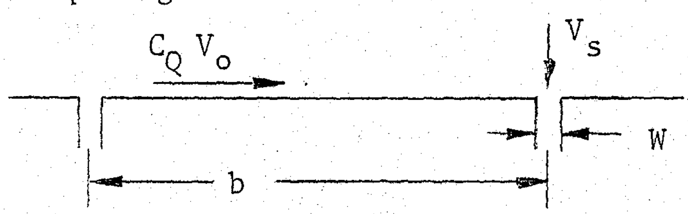
Three primary considerations determine the criteria for slot spacing on the LFC wing.

1) The slot width Reynolds number, according to research conducted for the X-21 aircraft, should be no more than 100.

2) The design (cruise) altitude is nominally 11,600 meters (38,000 feet), but it would be desirable to maintain laminar flow at lower altitudes, e.g., during climbout or let down.

3) The suction distribution for the LFC-200R wing has been determined by Lockheed (reference 4) and uses a suction rate reduced by a factor of .636 on the basis of relaxed stability criteria that allow boundary layer disturbances to amplify, but not reach the level of transition. The latter, reduced suction level has not been justified by experiment and may be unconservative, because the theory is based on an oversimplified model of distributed suction.

The design equation for slot spacing relates the slot spacing b and the slot width Reynolds number R_w and the surface suction coefficient C_Q is outlined below. Equating flow rates on the surface and through the slots,



$$C_Q \; V_o \; b = V_s \; W$$

where C_Q = Surface suction coefficient

V_o = Free stream velocity

b = Slot spacing

V_s = Slot velocity

W = slot width

and $R_w = \frac{\rho}{\mu} \; V_s \; W = C_Q R' b$

where R_w = Slot width Reynolds Number

ρ = Density

μ = Kinematic viscosity

and $R' = \frac{\rho}{\mu} V_o$, the unit Reynolds number. Then slot spacing

$b = R_w / C_Q R'$

An example of the application of the equation to the upper surface of the wing in the region between wing spars, and the criteria of items 1, 2, and 3 above is shown below.

(1) Approach Risk	(2) Flight Altitude ~ ft.	(3) R' @ M = .80	(4) $\bar{c}_Q$	(5) R_W	Eq. (2) (6) Slot spacing b ~ inches $\left[\frac{12 \; (5)}{(3)\;(4)}\right]$
Unconservative	38,000	$1.686(10^6)$	$1.21(10^{-4})$	100	5.88
Conservative	32,000	$2.132(10^6)$	$1.90(10^{-4})$	80	2.37

The maximum slot spacing selected is approximately 4.5 inches, intermediate between the "unconservative" and "conservative" values calculated in Column 6 above. According to NASA guidelines we could take the "unconservative" value, but experience leads one to a lower value which was used in this study (see figures 4 and 5).

There are 13 slots between the wing spars in the upper surface outboard of wing station 22.73m (895 inches). This meets the .114 meter (4.5 inches) slot spacing in the outboard panel, but inboard the number of slots must be increased to 25 between the spars to meet the spacing requirements. This requires that new slots must be started near wing station 22.73m (895 inches). Inboard of wing station 9.04m (356 inches) the increased chord dimension requires the introduction of additional new slots to meet spacing requirements.

This slotting concept where slots are started in mid-span was used and was satisfactory on the X-21 LFC wing and has been used in this program for the development of the slot diagrams for both the upper and lower surfaces, as shown on figures 4 and 5.

5.2.2 DUCT REQUIREMENTS

The LFC suction collector ducts and the pumping system were defined as shown in figure 6. The air is collected from the slots into the panel integral stiffener ducts and routed spanwise through them to a chordwise collector duct. Separate chordwise ducts are provided for the upper and lower wing surface. The upper chordwise duct routes the air from the upper surface to a main low pressure trunk duct forward of the front spar. The lower chordwise duct routes air from the lower surface to a main higher pressure trunk duct aft of the rear spar. These two trunk ducts then route the air inboard to the suction system compressors and then overboard through the exhaust nozzle.

The internal duct system was sized to provide a low level of pressure loss while matching the suction flow requirements for the LFC surface. In order to accomplish this, experience with LFC systems has indicated that the ducts should be sized so that the velocity of the ducted air will be no more than 15 percent of the free stream velocity.

The duct area and flow through the duct is related to the LFC surface area which must be handled by the duct, the average suction coefficient and the free stream velocity.

$$\text{Flow Rate} = SC_Q V_o = A_D V_D$$

where:

S = Wing panel surface area (contributing to flow at the point under consideration)

C_Q = Suction coefficient

V_o = Free Stream velocity

A_D = Duct area

V_D = Duct velocity

then using $V_D = .15\, V_o$;

$$A_D = \frac{SC_Q}{.15}$$ has been used to size the ducts.

The spanwise stringer ducts due to structural requirements are large enough so that air collected through the suction surface can be routed the length of a skin panel to a chordwise collector duct. This is true for both upper and lower surface panels.

The outboard chordwise duct which collects air from the outer panel upper surface will be 0.009 square metres (14.0 in^2) area. This will also be the area required for the outboard end of the front trunk duct. The chordwise duct sizes increase inboard as the suction area of the wing becomes larger. The inboard chordwise duct will be 0.030 square metres (46.0 in^2) area for the upper surface. The area required for the inboard end of the front trunk duct is 0.071 square metres (110.0 in^2) which will handle all the air removed by the entire upper wing LFC suction panels.

The lower surface suction air flow requirements are less so that the collector ducts can be smaller. The outboard end of the rear trunk duct is 0.006 square metres (10.0 $in.^2$), increasing to 0.050 square metres (78.0 $in.^2$) at the inboard end to handle all the air removed by the entire lower wing surface suction panels. Sizes of the other collector ducts are presented in figure 6.

5.3 CONSTRAINTS ON MAXIMUM PANEL SIZE

Constraints on the size of the wing cover panels have been established, see figure 7. Width of titanium sheet available requires that one spanwise splice be made from the wing "break" outboard to the tip. Inboard, from the wingbreak to the wing root, three spanwise splices are required.

The length of the wing panels fabricated using SPF/DB have been established as 6 to 7 meters (20 to 25 feet) maximum. It is felt that the cost of a program to develop methods and tooling to make a SPF/DB full semi-span wing panel would be excessive. Application of the "stop-off" required for controlling the bond areas during the SPF/DB process could be a major problem in a very large part. The large number of loose pieces to be located in the die for bonding during the fabrication cycle in a large part would also be a problem. Differential thermal expansion between the titanium part and the "22-4-9 steel" tool, which amounts to 45.7 mm (1.8 in.) for a 7 meter (25 feet) panel, presents another problem area. Handling problems with very large parts, particularly while hot from the SPF/DB fabrication process, must be considered. Failure during the fabrication cycle of a part that large would result in very high repair or scrap cost.

5.4 STRUCTURAL LOADS AND SIZING

The vertical shear and bending data supplied by Lockheed for the LFC-200R configuration, as shown in table 2, were the basis for all preliminary sizing performed in this study. That data did not include any wing torque data. The external loads group of The North American Aircraft Division of Rockwell International used their own historical data in conjunction with Lockheed shear and moment data, along with the configuration definition and weight information presented in the Lockheed report, NASA CR-133949 (reference 4) to estimate the torsion loads. The two conditions considered were 2G flaps down and 2.5G flaps up. Since the Lockheed study used 2.5G's, the data for the 2.5G flaps up condition was used and is shown in figure 8.

This data was used for the subsequent SWEEP runs described in section 7.1.1.

SWEEP is an aircraft structural weight estimating computer program. The basis for the structural sizing and weight analysis in SWEEP is an approximation of the procedures and methods used in structural analysis and design processes used in early preliminary design.

SWEEP performs preliminary sizing of composite and metal lifting surfaces and fuselage structure using a beam theory approach. Major structural elements are sized to strength, stiffness, local crippling, column stability, and general stability criteria, as well as to fit within physical geometric constraints based on manufacturing process limitations, handling, volume or other considerations. The structure is optimized with respect to weight.

The SWEEP program was used to investigate two wing structural arrangements. One arrangement was a multi-rib supported skin panel that utilized integral hat section stiffeners (see figures 9 and 10). The other was a multi-spar supported, truss core sandwich skin panel (see figures 11 and 12).

In addition to the definition of the structural arrangement, data required for the SWEEP program includes wing geometry, loads and material properties. The planform geometry and spar locations shown in figure 3 were used. In the case of the multi-rib arrangement, the SWEEP program was set up to investigate stringer spacings of 76.2 mm (3.0 in) to 203.2 mm (8.0 in) at 12.7 mm (0.5 in) increments. The load data shown in table 2 and the material properties for 6Al-4V titanium were also used.

The SWEEP program investigated a series of cover panels for both the multi-rib and multi-spar structural arrangements. For the multi-rib design it searched to find the skin gage, the stiffener size and spacing, as well as the rib sizing and spacing that resulted in the lightest weight structure, that will meet the strength requirements. In the case of multi-spar design it searched to establish facesheet and core gages for the truss core, sandwich, skin panel as well as the sizing and spacing of the intermediate spars that make up the lightest weight, most efficient wing structure.

The weight summaries of the SWEEP data for the multi-spar and multi-rib structural arrangements were compared. The difference in total weight was approximately 2.5 percent, with the multi-rib design being the lighter of the two. Figure 13 shows the weight per unit length distribution, along the wing semi-span for the two structural arrangements.

The SWEEP sizing data was used subsequently as a guide in the conceptual design study, in which a more detailed comparison using flutter data was conducted.

6.0 TASK 2 - CONCEPTUAL DESIGN STUDY

The baseline design data on the LFC-200R wing together with the airflow requirements, the geometric parameters and the structural constraints presented in Task 1 have been used to develop a wing surface panel concept which will meet these conflicting requirements. This panel is based on the work done in the first Rockwell LFC program and uses the hat section skin stiffener concept selected for the feasibility panel which was built during that contract, as shown in figures 14, 15, and 16.

A number of other LFC wing panel structural concepts were investigated in the first Rockwell LFC program. Studied were: truss core and sinewave truss core sandwich panels, dimple core sandwich panels; semi-sandwich panel concepts using semi-circular stiffeners, hat section stiffeners and other stiffener variations, all using the SPF/DB fabrication method. Comparisons of these concepts considered weight, production cost, air-load rib attachment, panel splicing, tailorable geometry, LFC airflow, inspectability and maintainability. Based on this comparison, the hat section stiffened semi-sandwich was selected for the feasibility panel and was used as the baseline for this program.

6.1 LFC WING STIFFENER REQUIREMENTS

The development of a wing cover that integrates LFC features with the primary structure required adjustments between differing design requirements. The SWEEP program considers many design features and variables, however, it considers only strength related requirements in its search to establish a minimum weight structure. The LFC requirements such as slot or perforation spacing and collector duct sizing are based on aerodynamic improvement. The SPF/DB process is dependent on producibility requirements. All facets were considered for the conceptual design task.

The SWEEP study considered only parallel, square cross section stiffeners, with all elements pin connected (see figure 10). A stringer spacing of 165.10 mm (6.50 in) was established as most efficient, from a weight consideration. The LFC requirements have established a maximum, streamwise slot spacing of 114.3 mm (4.5 in) for the upper wing surface and 152.4 mm (6.0 in) for the lower wing surface, (see figures 4 and 5). The average true slot spacing, because of wing sweepback, became 106.3 mm (4.2 in) for the upper surface and 141.7 mm (5.6 in) for the lower surface. Since there is a stringer associated with each slot, the resulting stringer spacing is appreciably less than the idealized SWEEP spacing. The tapered wing planform and the requirement for continuous slots required the usage of stringers tapered in both cross section and spacing.

An extensive study was made to develop a stringer arrangement for a wing cover that is compatible with SPF/DB fabrication techniques and also satisfies structural requirements regarding strength and LFC. Figure 17 shows a stringer/slot arrangement for the upper surface. In order to avoid excessive spacing between slots, across the spar caps, one slot and its associated stringer is located adjacent to and parallel to the spar caps. The remaining slots and stringers are uniformly spaced over the LFC area.

Panel 4, the most outboard panel between WS 895 and WS 1123, uses 13 stringers and 14 LFC slots. There is one slot per stringer except the stringer adjacent to the rear spar has two slots to avoid excessive distance between slots across the rear spar cap.

Panel 3, between WS 613 and WS 895, also uses 13 stringers, but provides 26 LFC slots by cutting two slots per stringer. The stiffener size is reduced and the spacing is increased from WS 895 inboard to WS 613. At the inboard end of this panel the LFC slots will be arranged in groups of two slots with a larger space between the groups. This provides acceptable slot spacing while allowing the stiffener spacing to increase so that additional stiffeners and LFC slots can be added to the next panel inboard while maintaining the continuity of the slots from Panel 3.

Panel 2, between WS 356 and WS 613, has 25 stringers with 38 slots in the arrangement shown, or with 26 slots in the alternate arrangement. Either concept provides for adequate slot spacing. The disadvantage of the primary arrangement is the cost of cutting 38 slots. The alternate arrangement has smaller stringers without slots between the larger slotted stringers.

Panel 1, the inboard panel with 25 stringers, would continue either of the stringer configurations from Panel 2. The LFC slot requirements would be met by having two slots in each stringer for a total of 50 slots.

Figure 18 shows a stringer/slot arrangement for the lower surface, which is similar except that fewer stringers and slots are required.

The superplastic forming of the hat section stringers resulted in tapered walls. The amount of thinning is a function of the ratio of height to width of the stringer and the slope of the side walls. In order to preclude excessive thinning, the width of a stringer was never allowed to be less than the height and the slope of the side wall was established at 17° from vertical.

Although the SWEEP program establishes dimensions for stringers and skin panels, that data was used only as a guide. The difference in the stringer spacing and shape required revision in material distribution in order to meet the local and general stability requirements.

T-bar ($\bar{t}$) is an average thickness dimension that is used as an index for weight comparison. It is derived for the wing cover panels by dividing the width of the panel into the summation of the areas of the skin and stringers.

The SWEEP values for $\bar{t}$ were maintained while developing cross sections of the skin and stringer arrangements for both the upper and lower wing surfaces at wing stations 95, 356, 613, 895, and 1123. Generally the reduced stringer spacing allowed a reduction in skin gage as compared to the SWEEP dimensions. After allocating material for the skin panels, to satisfy local stability requirements, the remainder of the material, corresponding to the local $\bar{t}$ was distributed in the hat section stringer and its cap so as to achieve the greatest moment of inertia. Also considered was the material required to form the plenums and stiffeners in accordance with the SPF/DB fabrication techniques. Examples of the skin-stringer arrangements are shown in figures 19 and 20.

6.2 LFC DESIGN CONCEPTS

The design concepts are divided into four groups; the integral slot concept, the integral perforated panel concept, the separate (removable) slotted LFC strip concept and the separate perforated LFC strip concept. Design concepts for each group are discussed in the following sections.

6.2.1 INTEGRAL SLOT CONCEPT

The feasibility panel from the first Rockwell LFC program (figure 15) is an example of this concept. This concept uses the SPF/DB process to form the LFC plenum and the dimensions of the hat section can easily be varied to match the load requirements. The provisions for slots can also be varied by having one slot per hat section in one area and then, where required doubling the number of slots per hat as shown in figure 21.

The concept shown in figure 22 is a modification of a truss core sandwich. This concept uses four sheets, two facesheets and two core sheets. The main feature of this concept is that the upper core sheet is formed into a built-in plenum. The four sheets are diffusion bonded together according to a pattern so that when the sandwich is expanded during superplastic forming, the lower core sheet pulls the upper core sheet down to form the plenum. The size of the plenum is determined by adjusting the ratio of thickness and length of unbonded core material which is stretched to form the truss core.

The sandwich upper facesheet is the aerodynamic surface and is .635 mm (.025 in) thick where the LFC slots are cut over the plenums. The upper core (plenum) sheet is thicker to control the plenum size and to provide additional material for the outer sandwich facesheet to carry bending loads as well as to stabilize the thin outer ply. The lower truss core sheet is the major shear carrying element. The sandwich lower facesheet is thick to provide material to carry the panel axial loads from wing bending as well as to provide sufficient panel moment of inertia for panel column stability between wing ribs. Although this concept is relatively complicated, it does offer the advantage of providing plenums formed in the SPF/DB cycle without the use of removable inserts.

6.2.2 INTEGRAL PERFORATED PANEL CONCEPT

As an alternate to slots, strips of perforation can be used so that air can be drawn through the wing skin for LFC (figure 23). Each strip consists of a pattern of four rows of plenums, with 15 surface holes in each plenum and one metering hole per plenum. Each perforated strip is equivalent to one slot.

The strips are made up with three prefabricated sheets. The outer or moldline sheet is perforated with a pattern of .203 mm (.008 in) diameter holes. The holes are arranged in regularly spaced groups of 15 holes each. The holes, which are produced by an electron beam process are cone shaped, with an eight degree slope. The sheet is placed in the panel with the small diameter hole side on the moldline side so small particles carried by the air stream will not become trapped in the cone shaped hole. This perforated sheet is backed up by an intermediate sheet which has elongated holes chem-milled in it to provide a pattern of plenum chambers. Each plenum accumulates air that enters through one group of 15 holes in the moldline sheet. The third sheet, which forms the inner side of the plenums is also perforated, by the electron beam process. The .406 mm (.016 in) diameter holes are spaced so that each one serves as a metering hole, through which the air exits from one plenum. These three sheets are fabricated and inspected so that flawed sheets can be repaired or rejected prior to joining with other parts.

The size of the prefabricated sheets is limited by existing production methods. Therefore, the prefabricated parts are welded together to make the sheets used to make up the mold line skin of the SPF/DB wing panel. The precise alignment necessary for the LFC features of this concept will require maintaining extremely close tolerances during fabrication of the detail parts, preparation of the weldments and positioning in the SPF/DB processing. The sheets must be tack-welded together to maintain alignment during the SPF/DB process in which the perforated sheets are bonded to two additional sheets which form the plenum and stiffeners.

The concept shown in figure 23 illustrates how the perforated strip could be bonded into an SPF/DB LFC panel using a configuration similar to that used for the slotted concept. The perforated strip can be located at both sides of the hat section, if necessary, to meet spacing requirements.

A variation, using three pairs of plenums per pattern, is shown in figure 24. In this concept, the perforated strip is located on the centerline of the hat section and would be used where spacing requirements can be satisfied using one perforation pattern per stiffener. The use of perforated sheet in the SPF/DB process has recently been demonstrated during the previous LFC study by Rockwell, in which perforations were incorporated in the plenums.

6.2.3 SEPARATE SLOTTED LFC STRIP

The main advantage of a separate LFC strip is that it can be removed and repaired or replaced if it is damaged. The concept shown in figure 25 uses a hat stiffened panel similar to the integral slot concept except that the plenum is larger and the outer moldline skin has been cut out, over the plenum, to provide space for the separate LFC strip.

The LFC strip is fabricated to provide a slotted moldline sheet, a second sheet which has chem-milled holes which become plenum chambers when sandwiched between the first sheet and the third or inner sheet which has the metering holes. The three sheets will be diffusion bonded together to form the LFC strip. This strip will be slipped into panel plenums and held in position by the retainer springs which will be slid into place in short sections after the LFC strip is in position.

Another concept, shown in figure 26, is similar to the above described concept except that the LFC strip is removable without sliding. The LFC strip is held in place by two wavy wire spring retainers, which hold it against a land machined in the wing panel skin. The strip and the wing skin recess are machined so that the springs and the LFC strip can be positioned over the skin recess and snapped into place on the exterior of an assembled wing. Removal can be accomplished by inserting a tool under the end of the strip.

The concept shown in figure 27, provides two slots by blind fastening a removable strip into a wide slot in the skin. The gaps between the edges of the skin and the edges of the strip will be controlled to provide the correct slot width.

Another concept which will also provide two slots is shown in figure 28. In this concept blind fasteners are not required since the back side is accessible. However, fasteners are in a fuel area and must be sealed.

All of the above concepts would require extremely close tolerances on the LFC strips and on the skin recess to meet smoothness requirements for the moldline surface and, in the case of the double slot concepts, to meet slot width requirements.

A concept which would alleviate the tolerance problem is shown in figure 29. Tooling will hold the LFC strip on the moldline and epoxy will be forced into the edge retainer spaces and cast in place so that, when cured, the epoxy will hold the strip in place.

The concept shown in figure 30 uses an LFC strip, which consists of three thicknesses of .81 mm (.032 inch) sheet diffusion bonded together. The outer sheet is slotted, the second sheet has the plenum holes and the third or inner sheet has the metering holes. An alternate LFC strip concept uses only two sheets with the second sheet formed to provide the plenum space and drilled to provide the metering holes. This LFC strip is bonded into a wide slot in the structural skin using a resilient organic adhesive.

6.2.4 SEPARATE PERFORATED LFC STRIP

In these concepts, the perforated LFC strips are removable, similar to the slotted strips in the preceding section.

The concept shown in figure 31 uses a diffusion bonded LFC strip in which the outer sheet is perforated, the center sheet has the plenum and the inner sheet has the metering holes. The structural panel has a wide cavity formed under the moldline skin of the hat section during SPF/DB fabrication. A wide slot is cut into the skin and the LFC strip is slid into place and held by retaining springs.

Another replaceable LFC strip concept is shown in figure 32. The LFC strip has two grooves milled on the underside which form the plenum chambers. The area above the plenum grooves is perforated with .203 mm (.008 in) holes made using the electron beam drilling process. The SPF/DB structural wing panel has metering holes through the skin surface connecting the plenums with the hat section stringer ducts.

The structural skin panel has wide grooves machined in it to match the LFC strip and in addition, an auxiliary groove is machined along one edge of the main groove to receive a locking wire. This locking wire is larger in diameter than the width of the groove, and is pressed into place thus wedging (locking) the LFC insert in the main groove. The installation will be completed with the installation of occasional blind fasteners through the LFC strip and the structural wing panel. The area above the wire would be filled with aerodynamic putty to smooth the moldline surface. The tolerances on this concept would have to be very close to assure that the wire would fit tight enough to provide a locking effect.

A concept in which the LFC strip is adhesively bonded to the structural wing panel is shown in figure 33. This strip is made by diffusion bonding a three sheet unit having perforations in the outer sheet, plenum chambers in the center sheet and metering holes in the inner sheet. It is fitted into a wide groove in the structural wing panel which is also recessed for the LFC outer sheet and an adhesive thickness.

An improved concept for a replaceable, perforated strip is shown in figure 34. This strip made of two prefabricated detail sheets which are weld bonded together. The outer or moldline sheet is perforated similar to the corresponding parts shown in figures 31 and 33. However, in order to reduce the number of parts and the total thickness of the strip assembly, the chem-milled plenums and the metering holes have been combined into a single sheet. The strip is installed in a machined groove that allows a nominal .71 mm (.028 inch) gap to accommodate the adhesive thickness and fabrication tolerances. The adhesive system utilizes a strip of open cell polyurethane foam impregnated with a controlled amount of resinous adhesive. The free height is 1.52 mm (.06 inch) which is greater than the gap allowed. At the time the strip assembly is installed, tooling is used to hold it in alignment with the moldline surface. This slightly compresses the adhesive impregnated foam strip.

After the adhesive cures, the foam becomes rigid and the strip is held in position on the mold line. The gaps between the edges of the strip and the machined groove are filled with aerodynamic filler. The installation procedure, using the foam adhesive strip, can also be used to install a replaceable slotted strip assembly.

The cross section of the strip assembly is made small as practical, to minimize the axial load it will pick up. This in turn holds the stress in the adhesive strip to a low level. The adhesive used will adequately hold the strip assembly in place, but will also allow the strip to be removed without damage to the supporting structure.

6.3 DUCT CONCEPTS

The LFC suction system is shown in figure 6 and consists of spanwise stringer ducts which collect the LFC air and route it to a number of chordwise collector ducts. The spanwise stringers have crosswise integral partitions which will divide the stringer duct into LFC airflow sections and deflect the airflow into the chordwise ducts. The chordwise ducts conduct the air to the main trunk ducts which route the air inboard to the suction pumping unit and then overboard.

The chordwise collector ducts may be fabricated as an integral part of the LFC structural panels or as a separate duct which is attached to the structural panel during wing assembly.

6.3.1 INTEGRAL CHORDWISE DUCT

The concept shown in figure 35 is a chordwise duct in which a preformed duct section is diffusion bonded to the structural panel during the SPF/DB fabrication cycle. The top of the duct is left off so that, the preformed duct section can be placed in the SPF/DB tool and later, the holes can be cut in the duct-stringer interface to provide the air flow path from the stringer duct to the chordwise duct. Since the duct section is diffusion bonded to the hat section stiffeners, it provides the reinforcing doubler necessary around the air flow holes through the hat section.

To match the airflow requirements, the duct will increase in size as it picks up LFC air from each stringer. The upper surface duct will increase in size as it extends forward to the upper surface trunk duct and the lower surface duct will increase in size as it extends aft to the lower surface trunk duct. The top of the duct will be mechanically fastened and sealed to the integral duct section prior to wing assembly.

Another concept, using wing structure as part of the chordwise duct is shown in figure 36. The duct is integrated with a chordwise splice in the wing outer cover and uses both the panel splice plate and the wing rib as walls of the duct with a quarter cylindrical duct section mechanically fastened and sealed during wing assembly.

Air would be routed through holes in the ends of the hat section stringer ducts and down through holes in the splice plate and into the chordwise duct. Duct losses would be high, in the air transfer area between stringer duct and chordwise duct, with this concept.

6.3.2 SEPARATE CHORDWISE DUCTS

Chordwise ducts described in this section are separate and nonintegral with wing structure. However, they are supported by the wing ribs and attached to the structural stringer/ducts to transfer the LFC air from the spanwise ducts to the chordwise duct.

Figure 37 shows a duct manifold concept which is fabricated from two sheets of titanium using the SPF/DB process. After forming, the end flanges are welded to the integral feeder ducts. The air from the stringer ducts is routed thru a hole in the bottom stringer cap. The duct flange, when fastened to the cap, serves as a doubler for the hole in the stringer. The tolerances on the parts would have to be excessively tight to effect the required fit for this concept.

Another duct concept, shown in figure 38, also uses the SPF/DB fabrication processes. However, this concept ports the LFC air through the sidewall of the stringer duct and into a separate transition duct which is mechanically fastened to both the chordwise duct and the stringer ducts. This concept will have improved airflow over the figure 37 concept, and will also be less stringent in its tolerance requirements for assembly. It is also more structurally efficient in that the air transfer hole is in the sidewall of the stringer rather than through the cap area.

A better chordwise duct concept is shown in figure 39. The duct manifold is fabricated by the SPF/DB process by forming two sheets into the manifold configuration. The ends of the feeder ducts are titanium tubing which has been superplastically formed into a corrugated bellows configuration and diffusion bonded to the end plate. This will give greater flexibility for duct installation so that normal fabrication tolerances can be specified. The corrugated duct sections and the duct manifold will be joined by tungsten inert gas (TIG) welding. The basic duct material thickness after forming is 2.5 mm (0.1 in). It will remain at that thickness where it is picked up by supporting brackets. Between support points it will be chem-milled to approximately .50 mm (.02 in). Experience with ducting routed through fuel tanks on other aircraft reveals that the most severe design criteria result from fuel sloshing. The resulting assembly is therefore somewhat heavier than necessary to serve as an air duct.

6.3.3 TRUNK DUCT

The trunk ducts, (figure 6) which accumulate and route the air from the various chordwise ducts to the suction pumping unit, are located in the leading and trailing edge sections of the wing. The pressure difference across the duct walls is comparateively low for these ducts. Experience with similar ducting on other aircraft shows that the most severe design criteria result from handling and installation trauma. The basic duct sections incorporate circular stiffening beads at approximately 51 mm (2.0 in) on centers. They are formed out of two sheets of titanium using the SPF/DB process. The thickness of 1.0 mm (.04 in) after forming is required to accommodate welding and joining with brackets and adjacent ducting. The remainder of duct sections, including the stiffening beads are chem-milled to 0.5 mm (.02 in).

7.0 TASK 3 - ANALYSES OF THE CONCEPTS

7.1 STRUCTURAL ANALYSIS

7.1.1 STRENGTH, LOCAL CRIPPLING, GENERAL STABILITY

The skin and stringer configuration established by the SWEEP computer program were sized to meet the strength criteria, (see section 5.4). The SWEEP arrangement did not accommodate the LFC requirements regarding slot and/or perforated surface spacing. Wing cover panel sections that were developed to accommodate the LFC requirements and also to conform to SPF/DB fabrication practices required a material distribution that was substantially different than the SWEEP configuration. See figures 10, 19, and 20.

In the areas of reduced stringer spacing the skin gages were reduced in accordance with the reduced local crippling requirements. Wing cover cross section area not required for the skin panels was distributed into the stringers.

An analysis of sections at three wing stations, reveals that margins of safety were positive for local crippling of all structural elements.

General stability was checked, using the wing rib spacing established by the SWEEP program. The sections in which the stringer spacing was such that the height and width of the stringers were similar to the SWEEP dimensions, had a positive margin of safety when checked for general stability. These sections also had the same weight index (i.e., $\bar{t}$) as was established by SWEEP. The sections in which the stringer height was substantially less than the SWEEP dimension had negative margins of safety. It was necessary to add additional material to the stringer cap to increase the moment of inertia. In order to achieve a positive margin of safety, it was necessary to increase $\bar{t}$, in the vicinity of wing station 613, by 23 percent over the $\bar{t}$ in the SWEEP data. An alternate solution would be to develop an LFC/structural arrangement that allows usage of a wider and more constant stringer spacing. The wider-spacing in turn would allow for a stringer sizing that is more structurally efficient.

7.1.2 WING TORQUE LOADS

In addition to the effects of spanwise bending and vertical shear loading, the wing structure analysis included the effect of torsion and flutter requirements. The SWEEP program does not make allowances for wing torque shears; however, it does have capability to evaluate flutter requirements.

The wing loads data described in section 5.4 were used for the following analysis.

Inasmuch as the SWEEP computer program does not make allowances for wing torque loads, an independent analysis was made. The earlier stress analysis of the wing cover considered only vertical shear and bending loads. The sections analyzed were sized to near zero margins of safety in most cases. When torque shear stresses were added, the combined stresses made it necessary to increase $\bar{t}$ at wing station 356 by approximately six percent to attain a positive margin of safety. This was considered to be representative of the other wing sections.

The flutter stiffness was evaluated by a rerun of the SWEEP computer program. In addition to the wing torque loads, a speed profile was required for the SWEEP airloads module. Inasmuch as the data provided for the LFC-200R configuration did not include this data, the speed profile for a transport aircraft of approximately the same size and same speed range as the LFC-200R was substituted.

It was learned from the SWEEP run that approximately 7.6 percent of the wing weight for the multi-rib arrangement and 8.6 percent of the multi-spar arrangement weight was required to satisfy the flutter requirements. The SWEEP program flutter module tends to be conservative, and a more refined analysis could probably reduce the structural weight required for the flutter requirements. The additional material required to meet the flutter requirements is more than adequate for the torque shear requirement.

7.1.3 CHORDWISE COMPRESSION

Wing cover, chordwise compression stress resulting from horizontal bending about a vertical axis is of such low magnitude that it is not usually considered in preliminary structural design. For this study, however, it was analyzed to determine the effect it would have on the slot opening, used with an integrally formed plenum chamber, see figure 40 . Inasmuch as the loading data provided for the LFC-200R configuration did not include horizontal bending wing bending loads, a check was made to determine the compression load (Pc) required to close the slot .025 mm (.001 in). The section developed for wing station 613 was selected for analysis. It was determined that approximately 95,400 N/m (595 lb/in) load will change the slot width .025 mm (.001in). This allowable loading is greater than the expected actual loading, and this item is not considered to present a problem for this configuration. Later concepts for replaceable LFC strip assemblies that are installed in grooves machined in the wing cover surface (see figure 34) are an improvement, in that the strips are self-stabilized regarding slot width, and the local eccentricities in the skin panel are reduced.

7.2 AIRFLOW ANALYSIS

The ducting system and sizing described in section 5.2.2 and shown in figure 6 was based on functional requirements of the LFC system; duct construction and interface with structural elements had not yet been considered.

The air drawn off of the surface of the wing is first collected into the integral, hat section wing cover stiffeners that serve as collector ducts. The cross section areas of the stringers shown in figures 17 and 18 were checked. It was determined that the stringers were large enough to serve as collector ducts, for the ducting system shown in figure 6. Generally the area available exceeds the area required by a minimum of 10 percent. The most restricted ducts are on the upper wing cover at wing station 613, where the stringer/duct sizes are smaller because of the narrow spacing. Elsewhere, where spacing allows, larger sized stringers or where additional stiffeners are available to serve as ducts, the excess cross section area available varies from 45 to 250 percent.

The transfer of air from the stringer collector ducts to the chordwise ducts requires evaluation of various design features. The size and location of the required orifice in the stringer wall is of fundamental importance as it relates to LFC system efficiency, stringer strength, and accessibility for assembly operations.

Because of the relatively small size of the stringer ducts at wing station 613, it was apparent that design of the transfer ducting at this location would be most challenging. If the chordwise duct spacing shown in figure 6 is maintained, the orifice area required is approximately 90 percent of the stringer cross section area, therefore, it was apparent that a single opening would have a severe impact on the strength of the stringer. A more reasonable approach was to transfer the air in smaller volume increments, which can be accomplished by using a greater number of smaller sized chordwise ducts.

The impact of the penetration of the chordwise ducts through the front and rear spar webs is of concern. The ducts sized per figure 6 require cutouts in the front spar shear webs which vary from 37 to 47 percent of the spar height. The cutouts in the rear spar vary from 19 to 30 percent of the spar heignt. It was again determined that usage of a smaller sized chordwise ducts would be desirable. The diameter of the cutout required for a duct of one third the cross section area would be approximately 42 percent of the requirement for the larger duct. The height of the cutout through the front spar will become 16 to 20 percent of the spar height. The cutouts in the rear spar become 8 to 16 percent of the spar height.

This evaluation indicates that a chordwise duct arrangement using a greater number of smaller sized chordwise ducts has advantages. Such a duct arrangement is shown in figure 41. The chordwise ducts were located so that each one collects the air from its proportionate area of the wing surface.

7.3 COST ANALYSIS

In the first Rockwell LFC program to study application of SPF/DB panels, 18 wing cover concepts were evaluated. They included various arrangements of integrally stiffened panels as well as sandwich panels, using slotted or perforated LFC features. The most feasible arrangement resulting from that study was a hat section stiffened panel with slots through the mold line surface of integrally formed plenums. That design was used as a baseline design for this study. See figure 14.

The concepts developed in this study, as described in section 6.2, employ different methods of incorporating the LFC features, which in turn influence the fabrication of the basic panels. One exception is the modified truss core sandwich shown in figure 22.

The concepts described in section 6.2 have been evaluated parametrically and an order of preference was established. The resulting fabrication cost ranking is shown in table 5.

The integral slot concept, shown in figure 19, was determined to be the simplest design to manufacture for the least cost. A value of 100 was assigned to that design. All other designs were ranked as a percentage variation to the basic concept.

7.4 WEIGHT ANALYSIS

The structural weight estimating program, SWEEP, described in section 5.4, was used to estimate structural sizing, discussed in section 7.1.1 as well as to estimate weights of the basic configurations considered for this study.

The first SWEEP runs used the baseline information, described in section 5.1, to estimate structural sizing and weight distribution for two titanium configurations. First was a multi-rib, integral, hat section stiffened skin arrangement. Second was a multi-spar supported, sandwich panel cover assembly. In the process of estimating a total wing weight for each concept, a weight of the component parts was determined. Included were the wing torque box, the leading and trailing edge fixed structure, as well as the trailing edge hinged surfaces. The torque box weight was further broken down to sub-components, as the upper and lower covers, the front and rear spars, and the ribs.

In addition to the weight summary, a spanwise weight distribution, shown in figure 13, was determined. Comparison of SWEEP idealized light weight designs for both multi-rib and multi-spar indicated that the multi-rib design was approximately 2.7 percent lighter than the multi-spar design. This multi-rib SWEEP run was used to develop the wing cover arrangements shown in figures 17 and 18. The SWEEP weight data was used as a target weight.

After wing torsion loads were developed by the Rockwell loads group, another SWEEP run was made to determine the effect of flutter stiffness requirements. The results of the two sets of SWEEP runs are not directly comparable. The first run considered only structural and weight optimization, where as the second run used the stringer spacing developed and shown in figures 17 and 18. The stringers were spaced to accommodate the LFC slot requirements. There were no additional restrictions for the multi-spar arrangement, and SWEEP was allowed to search for an idealized light weight deisgn, which resulted in an approximate 3.5 percent lighter weight than the LFC constrained multi-rib arrangement. The total wing weight for the multi-rib arrangement is 16556 kg (36501 lb).

A third series of SWEEP runs was made to determine the weight difference between the titanium multi-rib, integral, hat section stiffened LFC wing design with more conventional aluminum and titanium structure employing "I" and "L" section stringers. Table 3 shows a comparison of the total wing weight results from the second and third SWEEP runs. It is of interest to note that, while the two idealized titanium concepts are about 3.5 percent lighter than the titanium, multi-rib, hat section stiffened design which was constrained somewhat by LFC requirements, the idealized aluminum concepts were approximately 3 percent heavier.

8.0 TASK 4 - DESIGN INTEGRATION

Fabrication of a complete wing cover using SPF/DB techniques requires the merger of the design features which meet many requirements. The panels must be cost effectively produced and must meet the aerodynamic, strength and weight criteria. Surface smoothness as well as slot continuity and/or porous surface regularity are especially critical for laminarized surfaces. Efficient joining of panels and other structural elements is required in order to satisfy the strength requirements while maintaining an acceptable structural weight. A continuous, root to tip, wing cover is advantageous from the weight standpoint.

An early consideration was to form a complete semi-span wing cover in one SPF/DB cycle. Continuous sheets of titanium are required for the SPF/DB process as well as for structural continuity of the panel. The available sheet sizes of titanium would require joining of several pieces, as shown in figure 7, to produce the continuous sheets needed for a complete semi-span wing cover. Joining methods that were considered include fusion welding and/or overlap scarf joints that would be diffusion bonded prior to superplastic forming. Although fusion welding is a reliable method of joining the separate sheets the material in the weld heat affected zone may no longer be superplastic. It is possible that the spanwise weld joints could be located between stringers in areas that would not be superplastically formed, see figure 42. The chordwise weld joints always fall into an area requiring superplastic forming. An in-depth investigation and development program is required before use of any welded material can be considered for a SPF/DB panel.

Because of the differences in thermal expansion between the titanium part and the stainless steel tooling, the SPF/DB part must be removed before it cools and locks into the die. A complete wing cover panel would be approximately 30.5 meters (100 ft.) long. It will weigh in excess of 1700 kg (3750 lb.). The temperature when removed from the tool would be approximately 900°C (1650°F). Handling a part of this size and at the elevated temperature will require rigorous safety precautions and the risk to the part will be high. Although it may be theoretically possible to fabricate such a panel, it is beyond the capability of the present SPF/DB technology and is not considered practical at this time.

Tooling to fabricate a complete wing cover as a single part would require a major development program. The die blocks needed are larger than presently available tool steel billets.

The conclusion reached is that it is not economically feasible to consider fabrication of a complete SPF/DB wing cover as a single part. A more feasible approach is to fabricate smaller SPF/DB panels and join them to make a continuous wing cover. The panels would have a maximum length of approximately 7.5 meters (24.6 feet) and would be the approximate size and shape as in figure 7.

8.1 SPANWISE SPLICE CONCEPTS

Spanwise splices, as indicated in figure 7, run between wing root and wing tip to join panels into a wing cover that is continuous from front to rear spar. Spanwise joint concepts have included mechanical fasteners and welding. One type of splice would employ two rows of fasteners that join adjacent edges of two panels to a common splice plate, see figure 43. Fuel sealing of the two rows of fasteners and fillet sealing the edges of the splice plate is required. This type of joint requires more space than is available between stiffeners in much of the upper wing cover. However, because of the wider stiffener spacing, this type of splice can be accommodated in the lower wing cover, where it is more important for fail safety. A wider stringer spacing, as discussed in section 7.1.1, would allow space for usage of a splice plate in the upper wing cover.

A more usable panel splice would use one row of fasteners through the overlapping edge of adjacent panels, see figure 44. It would require additional material in the panel edges to allow for preparation of the overlapping joint features. This type of splice would also be located between stiffeners. Space is available for this type of splice, although it is marginal in the vicinity of wing station 613 where the hat section stiffeners are most closely spaced. This type of splice also requires fuel sealing of the joint and one row of fasteners. A sealing groove is provided in this concept.

The most promising spanwise panel splice would employ fusion welding, shown in figure 45. Welded joints are fuel tight and they are lighter than mechanically fastened joints. Two types of weld have been considered, tungsten inert gas (TIG) weld and plasma arc weld. From a review of earlier studies regarding welding of titanium wing skins it appears that the material thickness in the vicinity of the joints is such that use of plasma arc welding is most advantageous. An advantage of the plasma arc weld over the TIG weld is that it is accomplished in a single pass and the resulting heat affected zone is much smaller.

There are two items of concern regarding large, welded titanium wing covers that require development and more in depth investigation. First, in order to develop the fatigue resistant properties the welds must be stress relieved. Stress relief is most readily accomplished by heating the weldment in an oven. The size of the wing covers, approximately 30.5 meters (100 ft.) by 4.6 meters (15 ft.) would require construction of a large oven. A more advantageous approach is to achieve stress relief with localized heat treatment; however, such a process remains to be developed.

Secondly, a monolithic wing cover, such as a weldment, does not provide protection against fatigue failures, which is offered by mechanically joined spanwise planks. A welded wing cover must be designed to a stress level that will assure a safe life. The fatigue life of such a wing must be demonstrated by testing in the laboratory, before the design can be certified. An in-depth design study is required to determine the weight and cost trades between a welded safe life design wing cover and a mechanically joined fail safe wing cover.

8.2 CHORDWISE SPLICE CONCEPTS

Chordwise splices run from front to rear spars to join panels into a wing cover that is continuous from wing root to wing tip. Chordwise panel splices involve complications that can be avoided in the spanwise panel splices. The spanwise splices can be located between stiffeners and the laminar flow control features, so that only the mold lines skin needs to be joined. The chordwise splices must cross over these LFC features in such a way as to maintain both structural and LFC continuity.

Both mechanical and welded chordwise joint concepts were considered. Mechanical joints required many loose parts, in addition to the fasteners, see figure 36. Joint eccentricities required reinforcing that resulted in a weight increase. The space occupied by the moldline splice features resulted in discontinuities in the LFC features. Fuel sealing of the various loose parts as well as the fasteners was required. For these reasons, mechanical chordwise joints were discarded.

Welded chordwise panel joints appear to be much more efficient. Figure 46 shows a concept for a wing upper cover splice. In this concept a SPF/DB baffle inside the stringer duct forms a barrier between the air duct and the fuel. Doublers for both skin and stringers are DB inside the stringer. This allows both moldline skin and the structural stringer to be continuous into the splice. The moldline skin portion of the panels are joined by plasma arc welding. This type of welding was selected because it is made in a single pass. The resulting heat affected zone is narrower than for other types of fusion welding and shrinkage is minimized. The space required for preparation and accomplishing the weld is narrower and has a minimal impact on the LFC features.

The hat section stringers are joined with TIG fusion welding, after the moldline weld is completed. The TIG welds will be done by hand for prototype and automated for production.

Figure 47 shows a concept for a wing lower cover splice. Inasmuch as the major load in the lower wing cover is tension, less column stability is necessary to achieve panel stability. The rib spacing is modified in the vicinity of the panel splice so that the hat section stiffeners can be transitioned in such a way that they maintain the required stability. They still function as a collector air duct and at the same time the panel material is concentrated into a single thickness at the panel splice. This allows the splice to be made with an automated single plasma arc butt weld.

8.3 FUEL CONTAINMENT

The volume of the wing structural box that is not used for LFC ducting is used as a fuel tank. For that reason fuel containment is a continuing concern.

A fundamental feature of the integrally stiffened SPF/DB wing cover panel is that the hat section stiffeners are formed from a continuous sheet of material that is diffusion bonded to the mold line skin. This feature provides an effective barrier between the fuel and the stringer air collector ducts, as well as the exterior of the wing.

Diffusion bonding is used to advantage to reduce or avoid fuel tank sealing in other areas, such as wing rib attachment. Attaching clips for wing ribs are diffusion bonded to wing cover panels, see figure 46. As a result, fastener penetrations through the fuel barrier are avoided. The fasteners attaching the wing ribs will pick up an outstanding flange and will be entirely within the fuel cavity. No sealing of these fasteners is required. An exception exists where a bulkhead type wing rib is a fuel barrier. In such cases standard fuel sealing processes using an organic sealant, will be employed.

One of the reasons for selecting fusion welding for joining panels is that the welded joint provides an effective fuel barrier. The panel splices that employ mechanical fasteners are fuel sealed with an organic sealant, see figure 43. The panel splices are located so fastener penetrations are through the mold line surface only, and not into the LFC suction system.

Other areas that will employ standard fuel sealing procedures will include installation of the chordwise air ducts. Although fabrication of the ducts will employ diffusion bonding and welding, the interfaces with the stringer collector ducts and the front and rear spar penetrations will use mechanical fasteners through a mounting flange. The part edges and fasteners will be sealed with an organic sealant, see figure 38.

8.4 DUCT INSTALLATIONS

8.4.1 INTEGRAL CHORDWISE DUCT INSTALLATION

The integral chordwise duct described in section 6.3.1, is installed in stages. The first stage involves placing the preformed duct half in the wing cover SPF/DB tool. When the wing cover panel is diffusion bonded and formed the duct portion is integrally bonded to the inner surface of the panel. After the air transfer holes are cut in the stiffener collector duct walls, and during build up of the wing cover assembly, the upper or close out portion of the duct is installed. This involves mechanically attaching the duct closeout and proper sealing, inasmuch as the duct also provides a barrier for fuel containment. The interface connection at the front and rear spars is completed during the wing box structural buildup. The fuel slosh loads acting on the integral chordwise duct are transferred from the duct directly into the wing cover panel through the diffusion bonded interface.

8.4.2 SEPARATE CHORDWISE DUCT INSTALLATION

The chordwise duct described in section 6.3.2 is installed as a unit after the panels are joined into a complete wing cover. Mechanical fasteners are used to attach it to the collector stiffener ducts, during the wing cover assembly build up. As with the integral chordwise duct the attachment to the front and rear spars is done at the time the wing structural box is assembled. A significant difference between the integral and separate chordwise ducts is that the latter required additional support in order to withstand the fuel slosh loads. This is achieved by clamping the duct to brackets that are installed on an adjacent wing rib.

8.5 MANUFACTURING OPERATIONS

Scale up of the manufacturing processes to fabricate a complete wing cover, using SPF/DB techniques requires several innovations in material handling and fabrication procedures. Items of concern include maintaining the required moldline surface contours and smoothness during fabrication of the detail parts and the build up of the complete cover assembly. Another concern is producing the slots in the wing surface, that extend without discontinuities from wing root to tip.

8.5.1 LFC STRIP FABRICATION

The feasibility panel produced in the first Rockwell LFC program, incorporated the slots and plenums as integral features of the basic panel (see figure 16). The panel represented only a small portion of a complete wing cover. The .20 mm (.008 inch) wide slots were produced by electrical discharge machining (EDM) using a copper sheet anode. Slots produced by this method are limited to approximately 760 mm (30 inch) long segments. Alignments of ends of slots can vary by .25 mm (.01 inch). That amount of mismatch is not allowable, therefore, the ends of the slots must be joined by a handworked slot (see figure 48).

It was evident that an arrangement that would allow fabrication of continuous slotted or perforated surfaces was required. Such an arrangement would also provide for replacement of the LFC feature. An arrangement using a replaceable slotted strip or a replaceable perforated strip is shown in figure 49. Each of the concepts is made of detail parts that are fabricated from titanium strips which are joined to make the 30.5 mm (100 ft.) long assemblies. Diffusion bonding, adhesive bonding, brazing and resistance welding were considered as methods for joining the prefabricated parts.

It was determined that the weld bond joining process (a combination of spot-welding with adhesive bonding) was the most efficient way to produce the strip assemblies in a continuous operation. Figure 50 shows a concept for producing a continuous, slotted strip assembly. The titanium strip material is supplied from reels. One strip is punched and rolled to form the plenum chamber with the metering holes. The two upper strips are aligned and resistance welded in a continuous operation. After the adhesive cures the assemblies are cut to length and are ready for installation.

Figure 51 shows a concept for producing a strip assembly with a perforated surface. The LFC holes in the mold line strip are drilled using an electron beam process as the strip is continuously moved from a supply reel, through the vacuum chamber of the EB perforating machine, and onto a take up reel. The plenum chambers are spray chem-milled on titanium sheet, approximately 600 mm (24 in.) by 900 mm (36 in.). After the chem-mill masking is accomplished by a photographic process, the sheet is suspended in a booth where it is subjected to the etchant which is continuously sprayed through high pressure nozzles. This process produces more accurately controlled small details than the conventional immersion chem-mill process. The sheet is then sheared to size, i.e., into 25 mm (1.0 in.) wide strips. The metering holes are electron beam "drilled" in each plenum chamber. The perforated strip is straightened and sheared to length. Adhesive is applied, the parts are aligned and the strips are joined by weld bonding.

8.5.2 WING COVER FABRICATION

As described in section 8.0 the wing covers are fabricated in SPF/DB panels which are subsequently joined to form a complete wing cover. Individual panels will approach 7.5 m (24.6 ft.) in length and 1.2 m (4 ft.) in width and will weigh as much as 365 kg (805 lb.). The panels must be removed from the die while hot, to preclude locking into the tool. In order to facilitate handling and to minimize risk of damage, the panels are handled in the vertical position. Figure 52 shows a tooling and handling concept. The vertically suspended SPF/DB "pack" is first positioned in a radiant preheater. Next it is moved into the press where the diffusion bonding and superplastic forming is accomplished. After the part is removed from the press it is moved into a holding chamber, where it is allowed to cool. The holding chamber, which is not shown, is used to protect the hot panel from stray air currents, to assure cooling at a uniform rate. After cooling the panels are chem-milled, trimmed to size, and the edges are prepared for joining.

Moldline features of the panels are joined by plasma arc welding as shown in figure 53. Other welded features will utilize TIG welding, as described in section 8.2. After welding is completed, the weldment is transferred to a retort for stress relieve heat treatment. If the spanwise splice is mechanically joined, it is accomplished after stress relieve heat treatment is complete.

After the panels are joined into the complete wing cover, the assembly is abrasively milled to final contour, if necessary, see figure 54. This operation is to ensure compliance with the laminar flow control smoothness requirements. Subsequent finish cut machining of spanwise grooves and drilling of air transfer holes prepares the cover assembly for installation of the slotted and/or perforated strips.

The slotted or perforated strips are adhesively bonded into place as shown in figure 34.

8.6 REPAIR TECHNIQUES

Repair of titanium SPF/DB structures as applied to a LFC wing cover falls into two main categories. First is repair of the primary load carrying structures and second repair of the nonload carrying, LFC features of the wing. Need for repairs may be due to fabrication anomalies or physical damage due to improper handling or usage. The repairs must restore the structural integrity, and at the same time must not interfere with the functional requirements, such as fuel containment or aerodynamic smoothness.

In the case of small cracks a repair concept is to close the cracks with the use of TIG welding. Weld repairs made on a moldline surface must be machined to comply with contour and smoothness requirements. Titanium must always be shielded with an inert gas in the vicinity of any welding, to prevent corrosion of the heated zone. Gas shielding of detail parts, which are repaired by welding, will present little problem. Parts which have been joined into a major assembly will require development of fixtures and processes to ensure adequate shielding and protection.

Dents in a moldline surface of a wing panel that is otherwise sound, must be filled to maintain the moldline contour. This can be accomplished with organic fillers. Another repair technique is to use a metallic plasma spray to build up the dented surface. This type of repair has been successfully used with steel honeycomb structure; however, the techniques and materials for use on titanium need to be developed.

Major structural damage will require fabrication of repair sections which are installed with mechanical fasteners, or by welding, after the damaged portion is removed.

Repair of nonload carrying LFC features can be grouped in two categories. For those parts, for which air and/or fuel containment is a function, such as ducts, welding appears to be the most feasible repair method. In some cases a sealed, mechanically attached repair part may be used to advantage. Moldline features, such as the slotted or perforated LFC strips, that are damaged will be removed and replaced. Criteria for selection of the adhesive system, used to secure the strips, as shown in figure 34 is that it must adequately bond and hold the strip in place and must allow for removal of the strip without damage to the supporting structure. After the groove in the wing cover surface is cleaned, the replacement strip is installed using the production procedures described in section 6.2.4.

9.0 EVALUATION OF RESULTS

An evaluation of the key factors which influence the life cycle costs of the wing panel concepts has been conducted. Included in this evaluation are:

- Producibility Risk
- Initial Fabrication Cost
- Internal Aerodynamic Efficiency
- Damage Repair Cost
- Weight Effects

Compiling the assessment of these factors for each of the wing cover concepts results in the ranking shown in Table 4 in which the adhesive-bonded, separate strip design is rated best. Detail discussions of each of the evaluation factors considered in the ranking follow.

9.1 PRODUCIBILITY RISK

The single, integral slot concept shown in figure 21A was developed in the first Rockwell LFC study and was used as a baseline design for this study. The most practical method of cutting the slots, which is by electrical discharge machining (EDM), is limited to .75 m (29.5 in.) long segments. The ends of the slot segments can be aligned to approximately .25 mm (.010 in.) which is greater than the slot width of .20 mm (.008 in.). It has been estimated that the allowable mismatch must not exceed one half of the slot width, therefore, a customized transition using manually adjusted EDM must be made to join the slot ends (see figure 48). Over 3800 slot segments are necessary to produce the 2910 m (9550 ft.) of slots in one complete wing.

The wing panel concepts incorporating integral perforated strips, as shown in figures 23 and 24, are more difficult to fabricate due to small dimensions and close tolerances associated with the LFC details. The concept shown in figure 23 uses plenums in the SPF/DB panel that are not required in the concept shown in figure 24. The second concept is, therefore, more readily producible.

With the exception of the modified truss core concept shown in figure 22, all of the other concepts dealt with improving repair and/or replacement of the slotted or perforated strips and achieving the surface smoothness required.

The configurations shown in figures 25 and 31 use a replaceable LFC strip that is slid into the end of the panel prior to joining with adjacent panels. The strips are held in place by sheet metal springs that are subsequently slid into place. Any irregularity in forming the cavities in the SPF/DB panels will impede insertion of the strips and springs. Very close machining tolerances must be maintained to ensure mold line smoothness requirements are met.

The wire spring retainer concept shown in figure 26 is a variation of the slide-in concept shown in figure 25. Producibility of the SPF/DB panels and close tolerance requirements are similar for both concepts. These concepts and the arrangement shown in figure 32 are not readily producible due to the extreme tolerances required.

The concepts shown in figures 27 and 28 use mechanical fasteners to retain replaceable strips. The concept shown in figure 27 requires forming of a fairly deep plenum to provide clearance for the blind rivets. Close machining tolerance is required to ensure the correct slot width as well as mold line smoothness. The concept shown in figure 28 locates the replaceable strip so that conventional upset rivets may be used. Although the rivets are most accessible, they penetrate a fuel barrier and they must be sealed. The cavity in which the strip is installed requires displacement of a comparatively heavy wall during fabrication of the SPF/DB panel, which may lead to uneven forming.

The concept shown in figure 29 is another variation of the slide-in concept shown in figure 25. The strip can be installed, removed and replaced from the exterior of a completed wing. The cast-in-place epoxy retainer takes up the accumulated fabrication tolerances. It also fills the edge gaps. Tooling is required to hold the strips in moldline position until the epoxy cures.

The concepts shown in figures 30 and 33 use a faying surface adhesive bond to retain the replaceable strips. The strips are installed from the exterior of a completed wing. As with other replaceable strip concepts, the moldline surface smoothness requirements are met through close control of fabrication tolerance accumulation and control of the thickness of the glue line.

The concept shown in figures 34 and 49 is considered the best concept and is a refinement of the one shown in figure 33. The replaceable strip, which can be either slotted or perforated, is installed in a wide groove in the surface of the panel. The diffusion bonding configuration shown in this concept is adaptable to a more continuous process using weld bonding, as shown in figures 50 and 51 and described in Section 8.5. The number of parts is reduced so two laminates are used for either the slotted or the perforated strips.

The adhesive impregnated foam strip used to secure the LFC strip also accommodates the fabrication tolerance accumulation so that moldline smoothness is maintained.

The modified truss core concept shown in figure 22 has not been demonstrated and producibility is considered questionable.

9.2 COST EVALUATION

The cost ranking of the various concepts, as presented in table 5, shows the hat section integrally stiffened panel with integral slotted moldline surface to be the least expensive concept considering initial acquisition cost only. The concept using integrally diffusion bonded, perforated strips is slightly more costly because of the detail work required to produce the perforations and the associated plenums. A concern with any of the concepts with integral slots or perforations is that there is no provision for repair of a damaged area, which could result in a higher cost.

The concepts shown in figures 34 and 49, utilizing separate LFC strips which are secured with adhesive-impregnated open-cell foam strips, are cost ranked below the integral slotted concepts. However, these concepts have features that offer more producible solutions for replacement of LFC strips and achieving the required surface smoothness. The adhesive strip concept makes allowance for fabrication tolerance accumulation and makes the separate LFC strip more readily replaceable. The concepts using separate LFC strips which are mechanically attached, with either fasteners or springs, were generally higher cost. The higher cost is mostly due to the close manufacturing tolerances needed to maintain the required surface smoothness. Most of the loose strip concepts have very little allowance for tolerance accumulation. The weld-bonded strip configuration is more adaptable to continuous production than the diffusion bonded arrangements used with other concepts.

9.3 INTERNAL AERODYNAMIC EFFICIENCY

The ducting arrangements developed in this study are essentially alike except for the chordwise ducting that transfers the air from the stringer collector ducts to the spanwise trunk ducts. The initial collector duct arrangement, shown in figure 6, used only four chordwise ducts for the upper or lower wing surface on each side of the airplane. The structural problems associated with this arrangement, as discussed in Section 7.2, indicated that a greater number of smaller sized chordwise ducts (see figure 41) to handle the same volume of airflow would be desirable. In the case of the four chordwise duct arrangement, the volume of airflow to be transferred from each stringer to the chordwise duct would require a manifold transfer duct rather than a simpler, single large airway. The space available to install such a manifold would require some radical changes in airflow direction which would result in significant duct losses. Therefore, the arrangement using a greater number of chordwise ducts has airflow advantages as well as structural advantages. The usage of a greater number of chordwise ducts will result in a more efficient duct system, reduction in the size of penetration cutouts through the spar webs, will allow design of more efficient transfer ducts between the stringers and chordwise ducts, and also will result in injection of smaller increments of bleed air into the trunk ducts. The general airflow requirements for the trunk ducts, however, would be unchanged. The sizing of the ducting concepts shown in figures 35 through 39 have been based on the 11 chordwise duct arrangement shown in figure 41.

The integral chordwise duct, shown in figure 35, should have low loss air transfer from the stringers; however, the chordwise duct has numerous area changes due to traversing the stringers, which would cause airflow losses. These losses can be minimized by maintaining a larger cross section to keep the air velocity low enough so that the space between stringers will act as a plenum. Such a duct will occupy a greater portion of the fuel tank volume than some other arrangements.

The arrangement shown in figure 36 would have better airflow through the duct, however, it will have greater losses where the air is transferred from the stringers due to the two orifices and direction changes at each stringer.

The transition shown in figure 37 for the chordwise duct-stringer bottom interface has essentially two right angle turns with the second one dumping the airflow into the chordwise duct. This would be a high loss transition. The separate transfer duct, shown in figure 38, is a better configuration for merging the flow path from the stringer to the chordwise duct.

The separate chordwise duct with the flex transfer duct shown in figure 39, combines the best features of the earlier concepts. It combines improved producibility and installation features, as well as minimizes ducting airflow losses.

9.4 WEIGHT EVALUATION

Three groups of structural weight estimating program (SWEEP) runs were made, as described in Sections 5.4 and 7.4.

The first SWEEP runs used the Lockheed supplied loads and wing geometry to investigate multirib and multispar configurations. The results indicated that the multirib design was approximately 2.7 percent lighter than the multispar design.

The data used for the second SWEEP runs was modified as follows. Stringer spacing for the multirib configuration was constrained to be compatible with LFC slot spacing requirements. The results of the second SWEEP runs indicated that the multispar arrangement was slightly lighter. The difference was approximately 3.5 percent. SWEEP does not analyze the effect of the chordwise duct penetrations of the spars in the multispar configuration. Also, it was allowed to search for an idealized multispar design while it was constrained in the multirib design. For these reasons it is believed that the weight of a complete multirib LFC wing will actually be less than a multispar wing. The total wing weight for the SWEEP multirib arrangement is 16556 K_g (36,500 lbs.).

A third series of SWEEP runs was made to compare the weight of an LFC wing design with more conventional aluminum and titanium construction. The results are shown in table 3. It is of interest to note that the two idealized titanium concepts are about 3 percent lighter than the titanium multirib hat section stiffened design that was constrained somewhat by LFC requirements. Both aluminum concepts were approximately 3 percent heavier.

9.5 REPAIRABILITY

The simplest design to repair is the spring wire retainer concept shown in figure 26. For this design, the LFC strip can be removed by inserting a tool into the LFC slot and lifting the strip to expose the spring so it can be removed, freeing the strip. For repair of the panel, a new strip can be easily inserted.

The adhesive-bonded LFC strip designs shown in figures 29, 30, 33, 34 and 49 are also relatively simple to repair. Damaged strips can be removed by inserting a tool in the LFC slot and pulling the strip free of the bond. After cleaning the slot in the panel surface, a new strip can be bonded in place as described in 9.1.

The fastener-retained strip concepts, figures 27 and 28, also allow replacement of the strip if damaged, by drilling out the rivets. However, after a strip is removed from the concept shown in figure 27, remnants of the drilled-out rivets will remain trapped in the plenum. The concept shown in figure 28 locates the replaceable strip so that conventional upset rivets may be used. Although the rivets are accessible, they penetrate a fuel barrier and they must be sealed. This will require access to the interior of the wing or the use of blind, self-sealing fasteners for replacement.

For the integral slot concepts (figures 23 and 24) and the slide-in strip designs (figures 25 and 31) no simple repair procedure has been developed. Damaged LFC slots or strips would be repaired by patching with weld or braze alloy and remachining the slots.

10.0 CONCLUSIONS

This study of the application of SPF/DB titanium construction to LFC wing structure has led to the following conclusions.

- SPF/DB titanium construction is feasible for LFC structure, and can be used to advantage for chordwise and trunk ducts as well as for the wing cover panels.

- The weight of an SPF/DB titanium LFC wing structure compares favorably with conventional wing structure. The basic structure of an SPF/DB titanium LFC wing is 3 percent lighter than an aluminum wing. The LFC titanium wing was found to be only 3 percent heavier than a non LFC titanium wing using conventional construction.

- A complete semi-span LFC wing cover panel can be fabricated by joining SPF/DB panels by welding or mechanical fasteners, but a one piece SPF/DB wing cover panel is considered beyond the state-of-the-art.

- Welded chordwise joints are preferred to mechanically joined panels. Welded joints occupy less space, they are lighter and they are less likely to offer disturbance to air sucked off the wing surface.

- Spanwise joints may be welded or mechanically joined. Welded joints are lighter, however, a mechanically joined fail safe design may be required.

- Separate slotted or perforated LFC strips, adhesively bonded to the wing cover panels provide the best configuration for LFC surfaces considering initial cost, weight, risk and repair. (see figure 49 and table 4). The panels, using separate LFC strips made using automated fabrication methods, should be more cost effective than the other concepts considered mainly due to producibility and ease of damage repair.

11.0 RECOMMENDATIONS FOR FUTURE WORK

The thrust of this study has been to develop conceptual solutions to specific proglems related to the application of titanium SPF/DB construction to LFC wing structure. Much additional work is required to develop fabrication procedures and to demonstrate the feasibility of the concepts so that confidence is established and future design effort on LFC transport aircraft can include SPF/DB structure. This work should include investigations into methods of producing acceptable moldline smoothness, separate LFC strips (see figure 49), surface repairability, large LFC panel fabrication and LFC wing fabrication.

11.1 SMOOTHNESS

Moldline smoothness is a basic requirement for an effective LFC wing. Low cost smoothing operations, such as abrasive machining, not only of panel surfaces, but also panel joints need to be demonstrated. Effectiveness of the smoothing operation should be extended to demonstration hardware that includes panel joints.

11.2 SEPARATE LFC STRIPS

The concepts for separate LFC strips developed in this program should be demonstrated by fabrication and installation of the strips in a section of a wing cover panel.

Fabrication of both a slotted strip and a perforated strip needs to be demonstrated. The slotted strip should be fabricated by locating and fastening two separate strips to make the slot. The perforated strip should be drilled using the electron beam (EB) process. The method of joining the component parts of both types of strip should include resistance welding or weld bonding.

Installation of the LFC strips in a groove in the wing cover panel, as shown in figure 34, should be demonstrated. The selection of the foam and the adhesive system should be made and installation procedures developed and tested.

11.3 SURFACE REPAIRABILITY

Improperly formed or damaged LFC features, such as slots and perforations, in a production panel will require repair. Separately fabricated LFC strips that are adhesively secured in a wide groove in the surface of a wing panel provide for such a repair.

Surface repairability specimens should be fabricated to verify the concept.

11.4 WING COVER PANEL SPLICES

Limitations on maximum size SPF/DB panels that can be fabricated with available materials and technology, require joining of panels to construct a complete wing cover. Plasma arc welding in conjunction with tungsten inert gas welding offers a practical method of making both chordwise and spanwise joints. The processes for making the welds and the subsequent stress relief heat treatment need to be adapted to the unique form of the SPF/DB panels used in LFC wing structure.

Fabrication of typical panel splices and joints using SPF/DB panels should be accomplished to confirm the producibility of the concept.

11.5 LARGE LFC PANEL FABRICATION

The next step in hardware fabrication is to scale up to large SPF/DB feasibility structures. Wing panels approximately 1.0 x 3.0 meters (40 x 120 inches) would be the next logical size to demonstrate. The feasibility structure should include demonstration of panel joining, surface smoothness, installation of the separate LFC strips, and provision for attaching the wing ribs.

11.6 LFC WING FABRICATION

A complete LFC wing, fabricated using SPF/DB titanium and incorporating the concepts developed in this program, needs to be designed, fabricated and tested to validate the concepts.

12.0 REFERENCES

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4. Sturgeon, R. F., Bennett, J. A., Etchberger, F. R., Ferrill, R. S., and Meade, L. E.: Study of the Application of Advanced Technologies to Laminar-Flow Control Systems for Subsonic Transports. NASA CR-133949, May 1976.

Table 1

LFC AIRFOIL DIMENSIONS

Wing Station % Semi-Span	Front Spar Height in mm (in)		Maximum Height in mm (in)		Rear Spar Height in mm (in)	
95	167.64	(6.6)	219.96	(8.66)	165.10	(6.5)
75	240.03	(9.45)	314.96	(12.4)	234.95	(9.25)
55	312.17	(12.29)	408.18	(16.07)	304.80	(12.0)
36	380.24	(14.97)	497.08	(19.57)	372.11	(14.65)
14	629.92	(24.8)	822.81	(32.39	640.08	(25.2)

Table 2

LFC WING LOADS

Wing Station % Semi-Span	BP		Moment Limit		Nx-Ult.*		V-Limit	
	m	(in.)	MN-m	(in-lb x 10^{-6})	kN/M	lbs/in)	kN	lbs x 10^{-3}
95	27.05	1065	.019	(.17)	-142	(-809)	31.14	(7.0)
75	21.36	(841)	.54	(4.8)	-1,927	(-11,000)	155.68	(35.0)
55	15.67	(617)	1.92	(17)	-4,205	(-24,000)	311.36	(70.0)
37	10.52	(414)	4.41	(39)	-6,325	(-36,100)	533.76	(120.0)
14	3.99	(157)	8.70	(77)	-4,240	(-24,200)	889.6	(200.0)

* Negative "Nx" denotes Compression Load in upper wing surface

Table 3

COMPARISON OF SWEEP TOTAL WING WEIGHT

Structural Concept	Total Wing Weight kg	(lb)	Difference [3] Percent
[1] Titanium, Multi-Rib Hat Section Stringers	16556	(36501)	-
[2] Titanium, Multi-Spar Sandwich Skin Panels	15974	(35217)	-3.5
[2] Titanium, Multi-Rib Integral "I" Stringers	16042	(35367)	-3.1
[2] Aluminum, Multi-Rib Integral "I" Stringers	17058	(37607)	3.0
[2] Aluminum, Multi-Rib Integral "L" Stringers	17040	(37568)	2.9

[1] SWEEP search restricted by LFC stringer spacing.
[2] SWEEP searched for idealized, minimum weight structure.
[3] Compared to titanium, multi-rib, hat section stringer.

Table 4

PANEL CONCEPT RATING

SUCTION STRIP CONCEPT	WEIGHT	FABRICATION RISK	FABRICATION COST	DAMAGE REPAIR COST	INTERNAL AERO-DYNAMIC EFFICIENCY	RANKING
ADHESIVE BONDED	GOOD	FAIR	GOOD	GOOD	GOOD	1
FASTENER RETAINED	GOOD	FAIR	FAIR	FAIR	GOOD	2
SPRING RETAINED	POOR	FAIR	FAIR	GOOD	GOOD	3
INTEGRAL	GOOD	POOR	GOOD	POOR	GOOD	4

Table 5

INITIAL FABRICATION COST COMPARISON RANKING

Figure	Description	Cost Rank
21A	Single slot, integral plenums (baseline)	100
21B	Two slots, integral plenums	110
49	Replaceable slotted strip, foam/adhesive retainer	120
34	Replaceable perforated strip, foam/adhesive retainer	130
23	Integral perforations, diffusion bonded	140
27	Separate slot strip, blind fasteners	160
26	Separate slotted strip, wire spring retainer	170
28	Separate slot strip, convention rivets	200
33	Separate perforated strip, faying surface adhesive bond	250
31	Separate perforated strip, sheet spring retainer	280
22	Sandwich, modified truss core, integral plenums	300

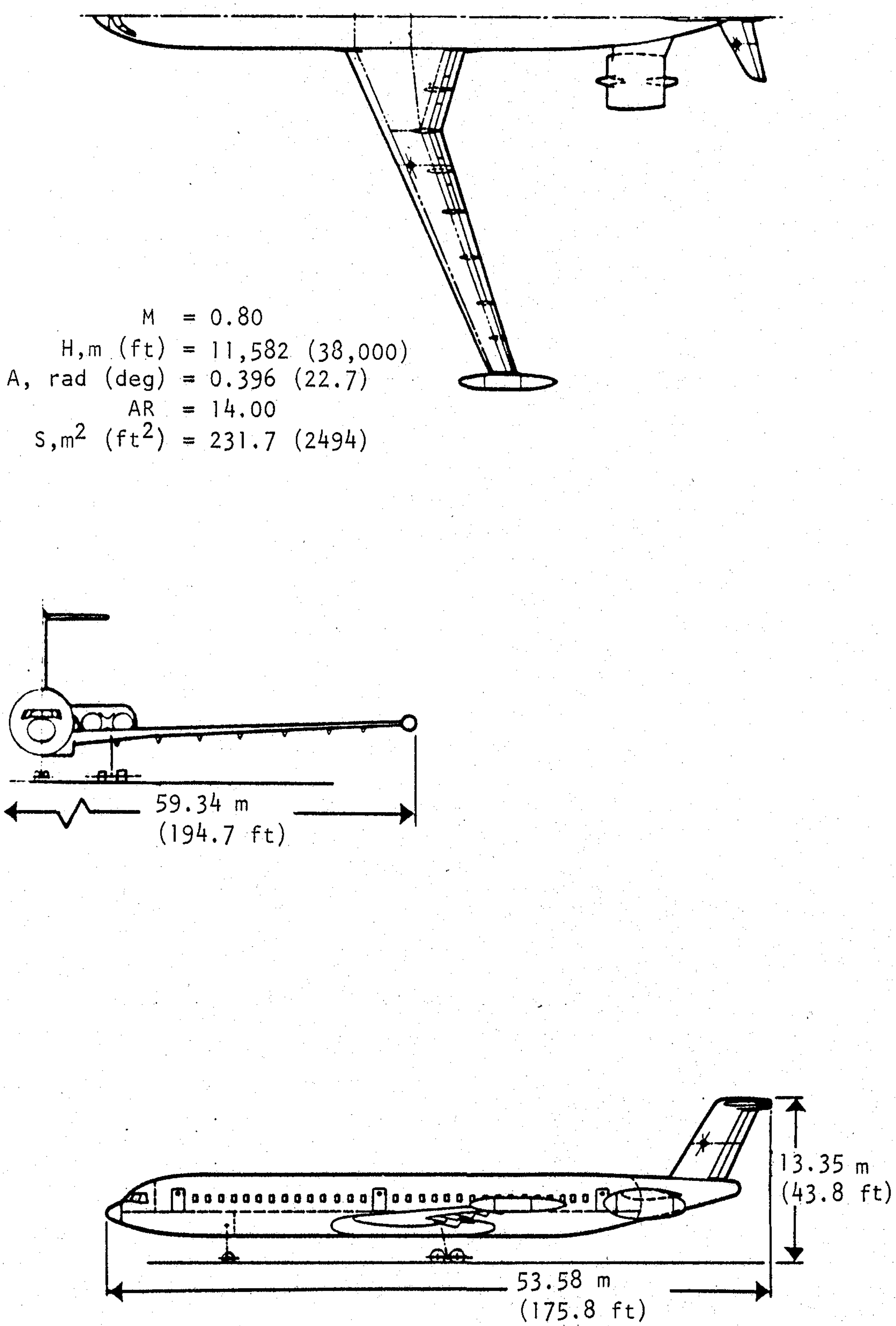


Figure 1. General arrangement, LFC-200-R

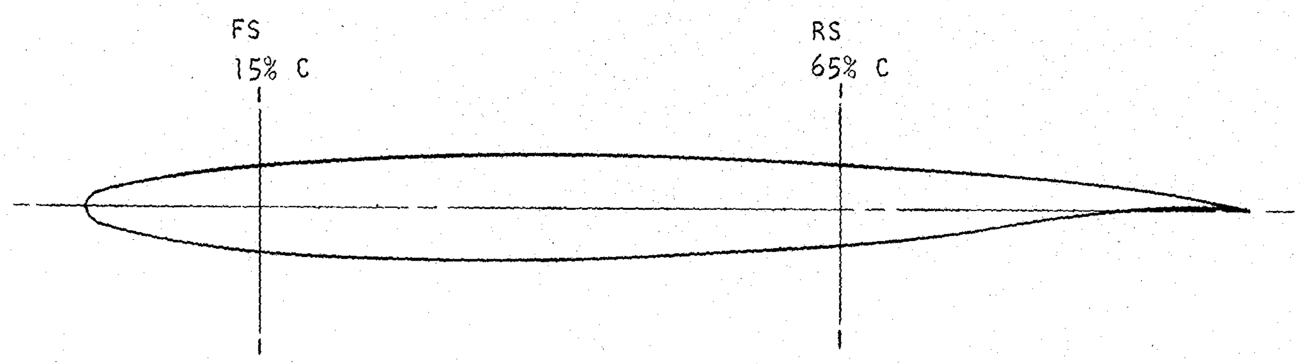


Figure 2.- Typical airfoil section.

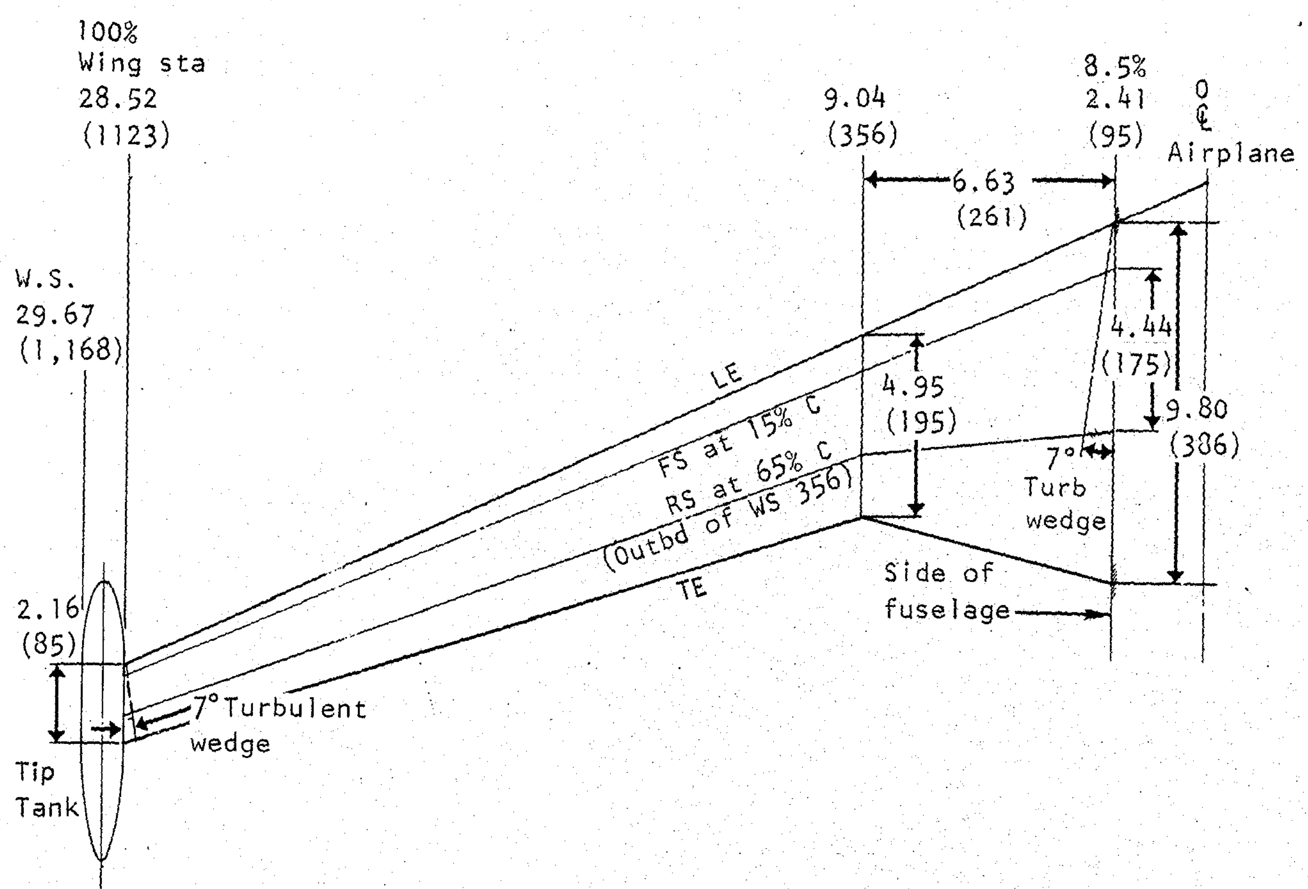
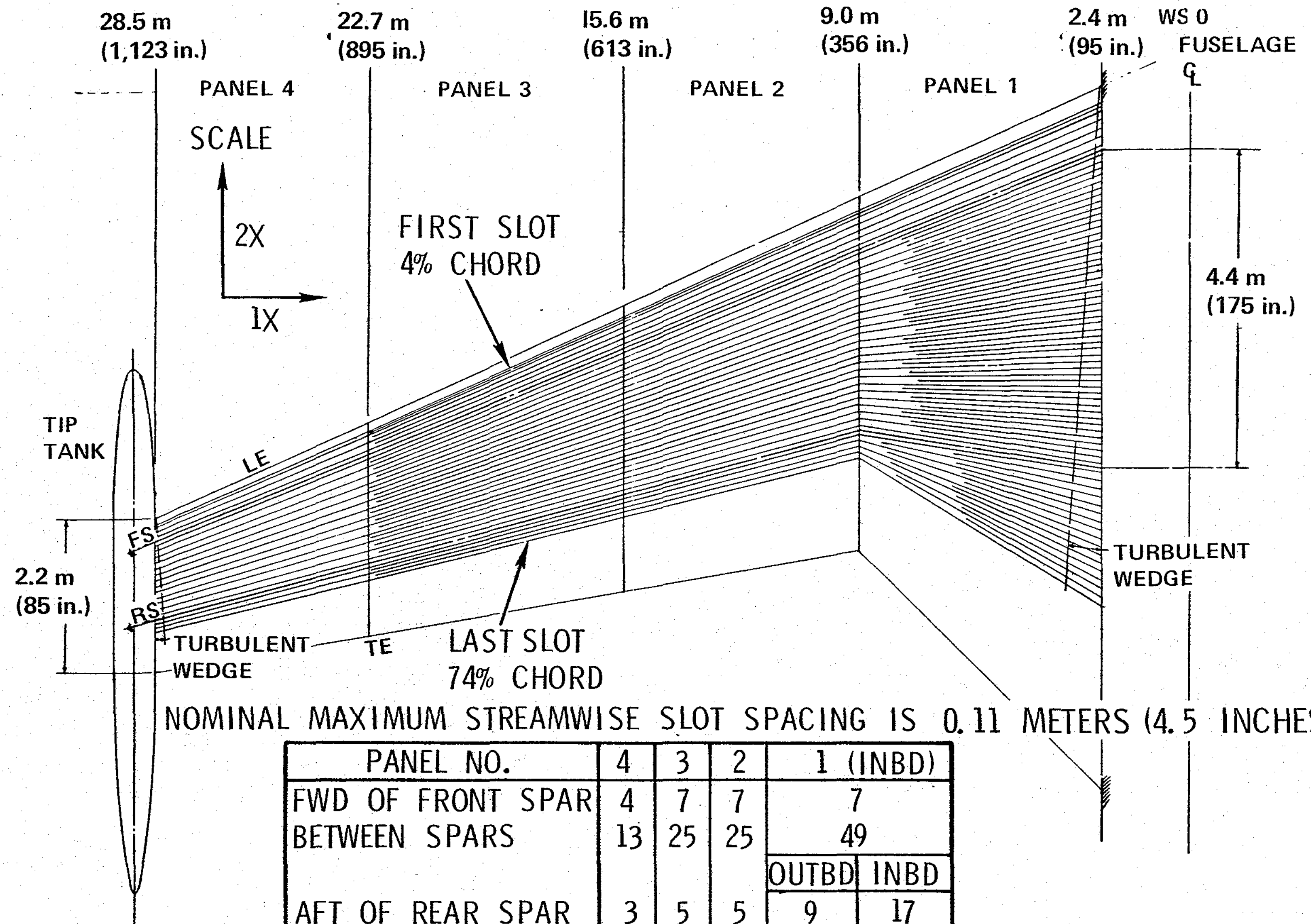


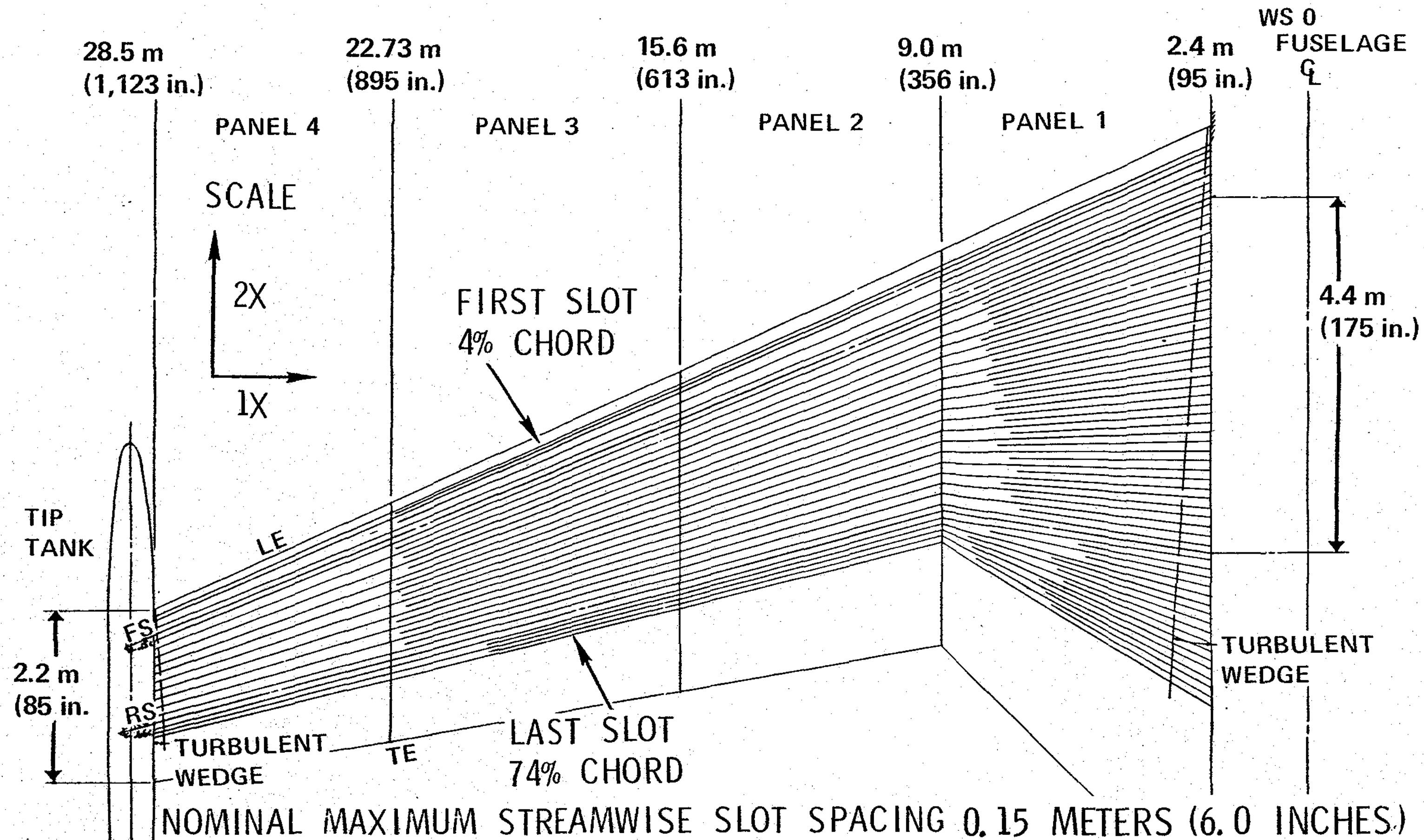
Figure 3.- LFC wing planform dimensions in meters (inches).



NOMINAL MAXIMUM STREAMWISE SLOT SPACING IS 0.11 METERS (4.5 INCHES)

PANEL NO.	4	3	2	1 (INBD)	
FWD OF FRONT SPAR	4	7	7	7	
BETWEEN SPARS	13	25	25	49	
				OUTBD	INBD
AFT OF REAR SPAR	3	5	5	9	17
TOTALS	20	37	37	65	73

Figure 4. Slot Spacing - Upper Wing Surface.



PANEL NO.	4	3	2	1 (INBD)	
FWD OF FRONT SPAR	3	5	5	7	
BETWEEN SPARS	10	19	19	37	
				OUTBD	INBD
AFT OF REAR SPAR	3	5	5	9	17
TOTALS	16	29	29	53	61

Figure 5.- Slot spacing - lower wing surface.

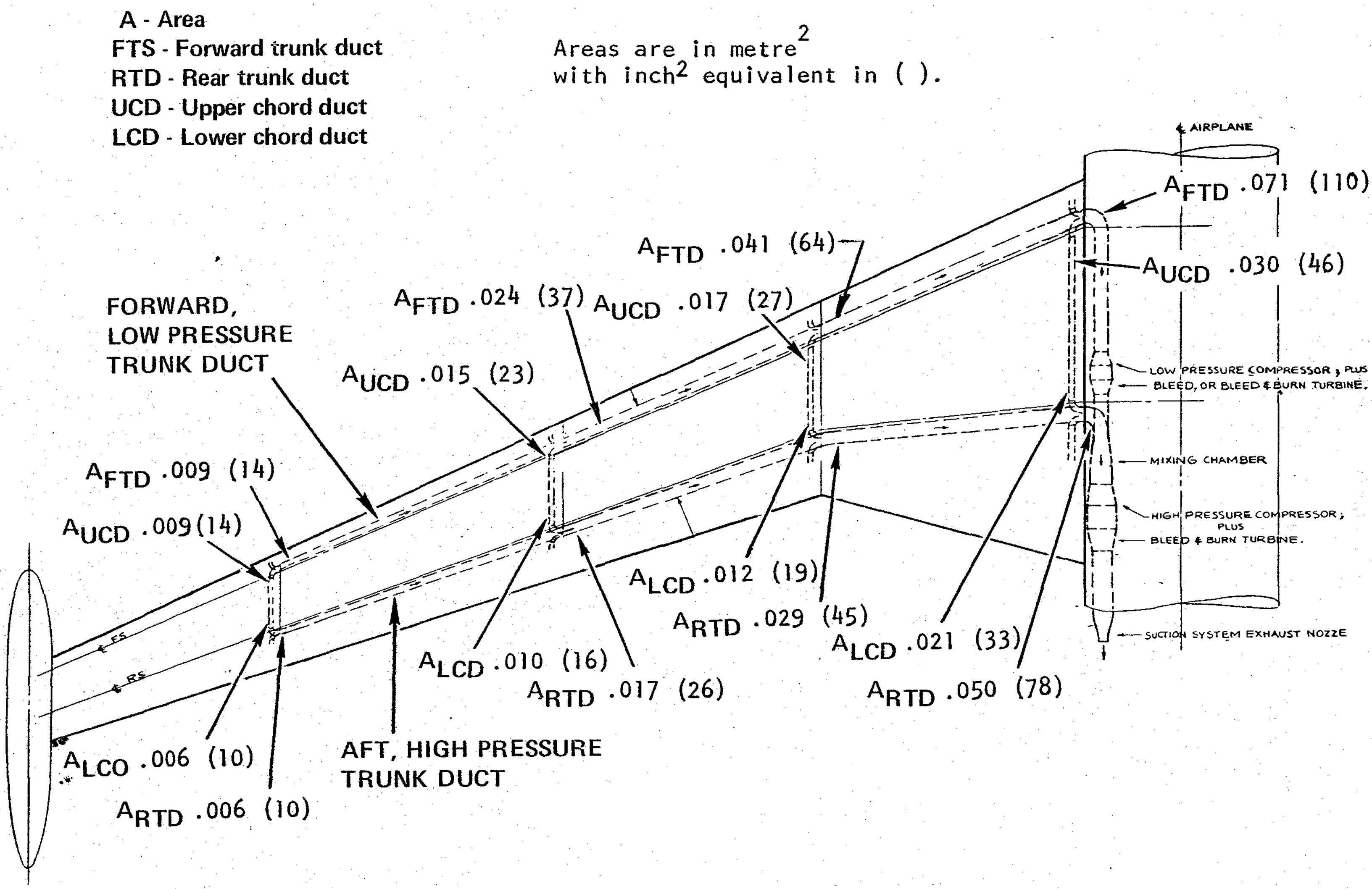


Figure 6.- Suction collector ducts and pumping system.

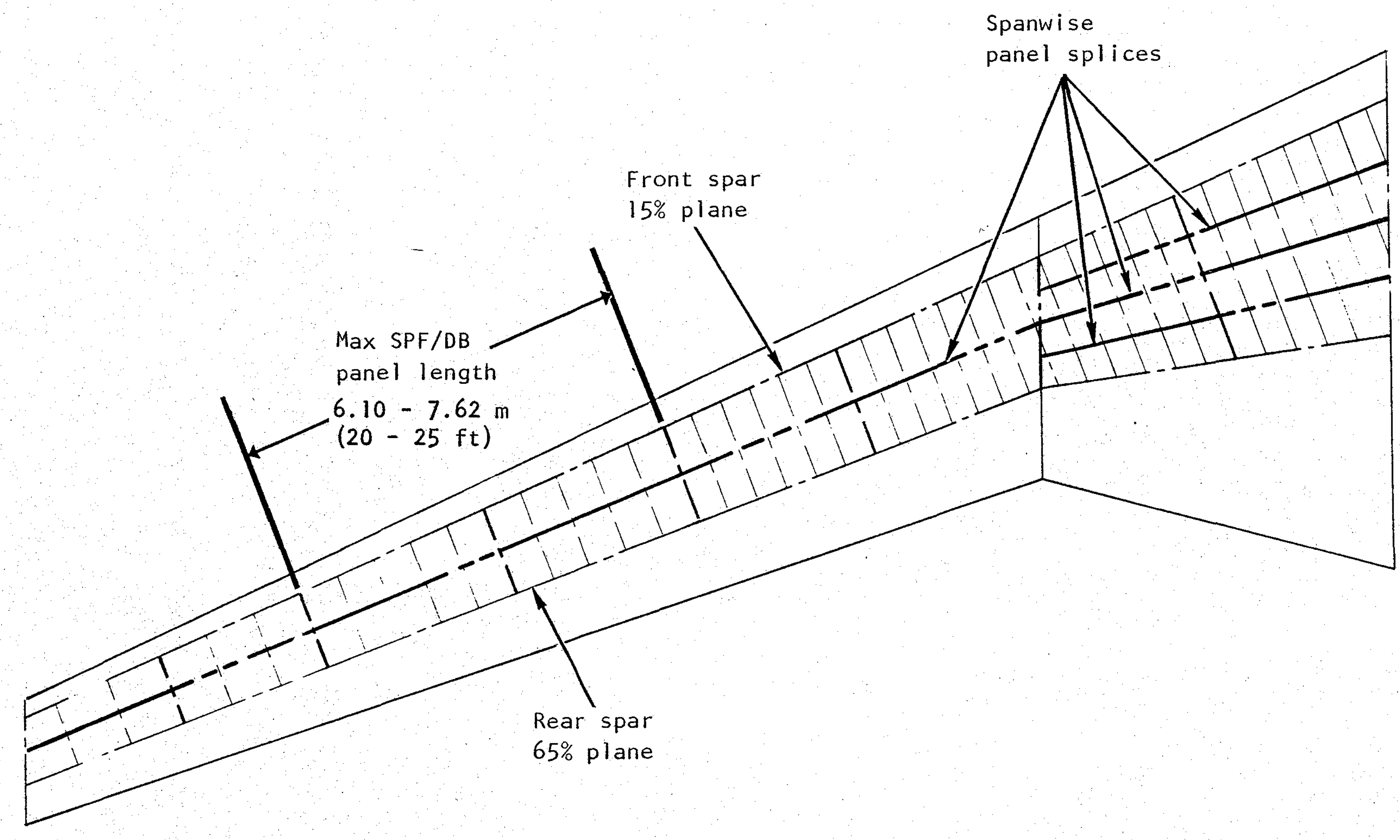


Figure 7. Wing Diagram Showing Constraints.

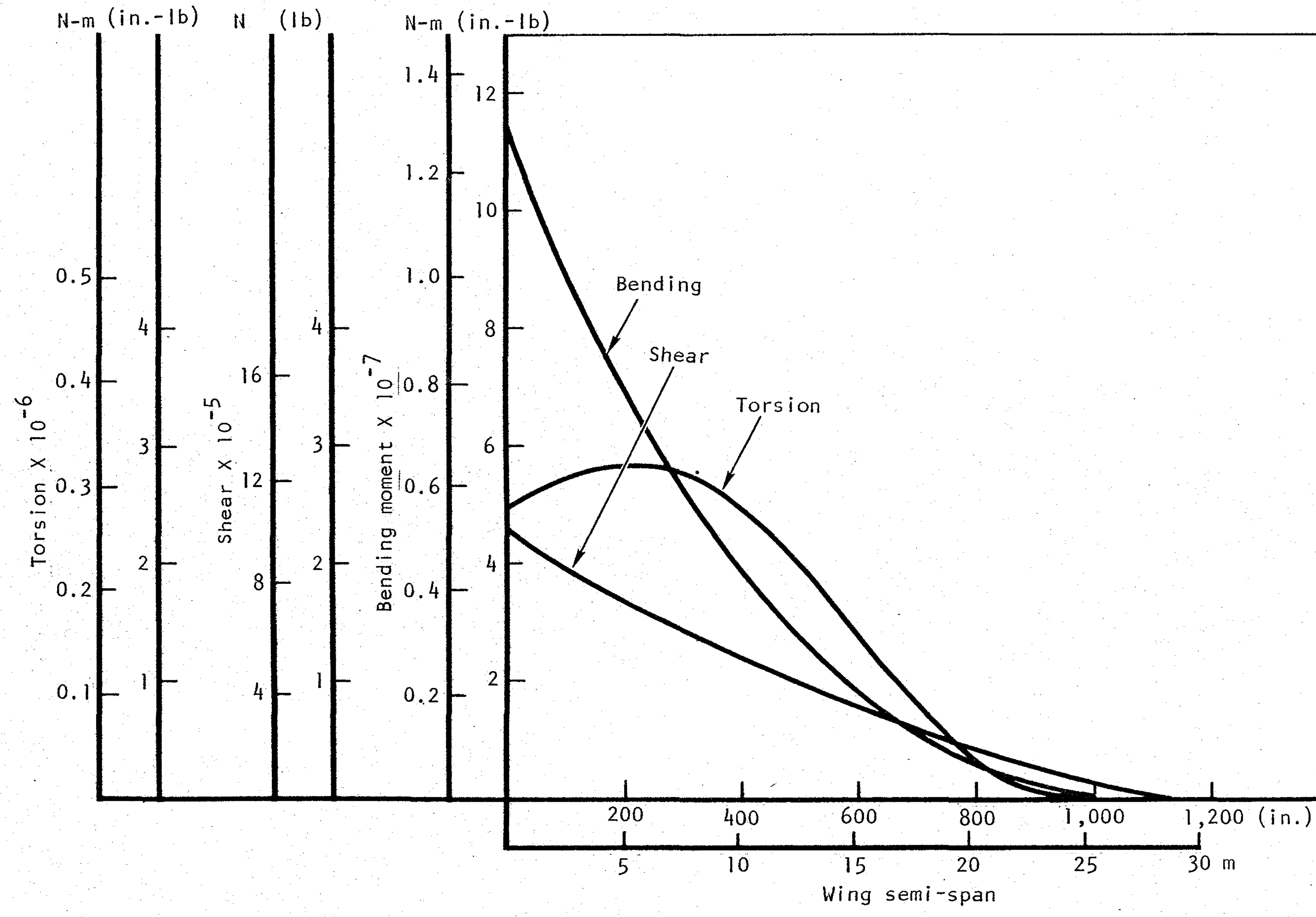


Figure 8.- Wing loads - 2.5 G flaps up limit.

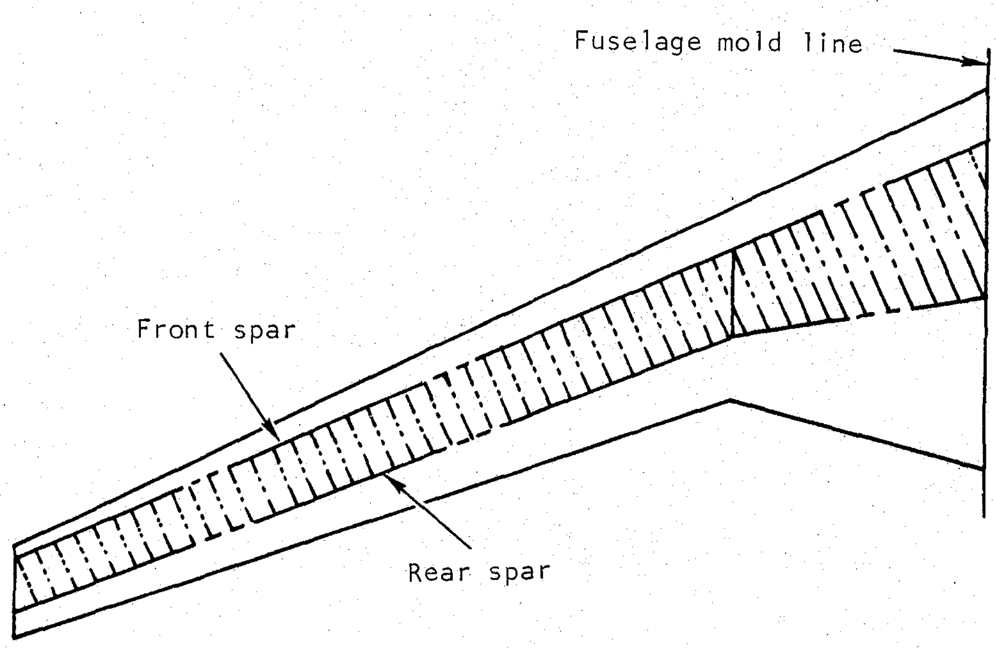


Figure 9.- Multirib configuration.

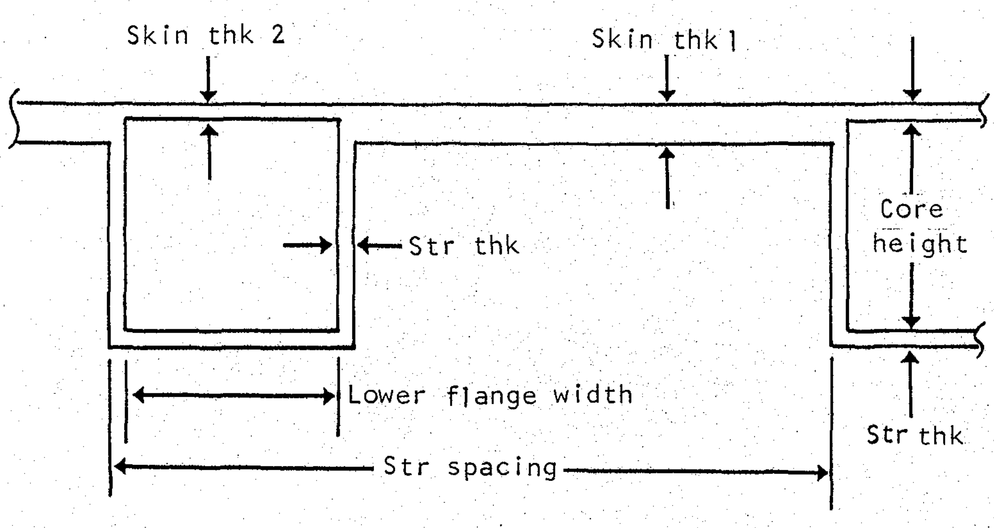


Figure 10.- Integral hat/stringer configuration used in multirib SWEEP program.

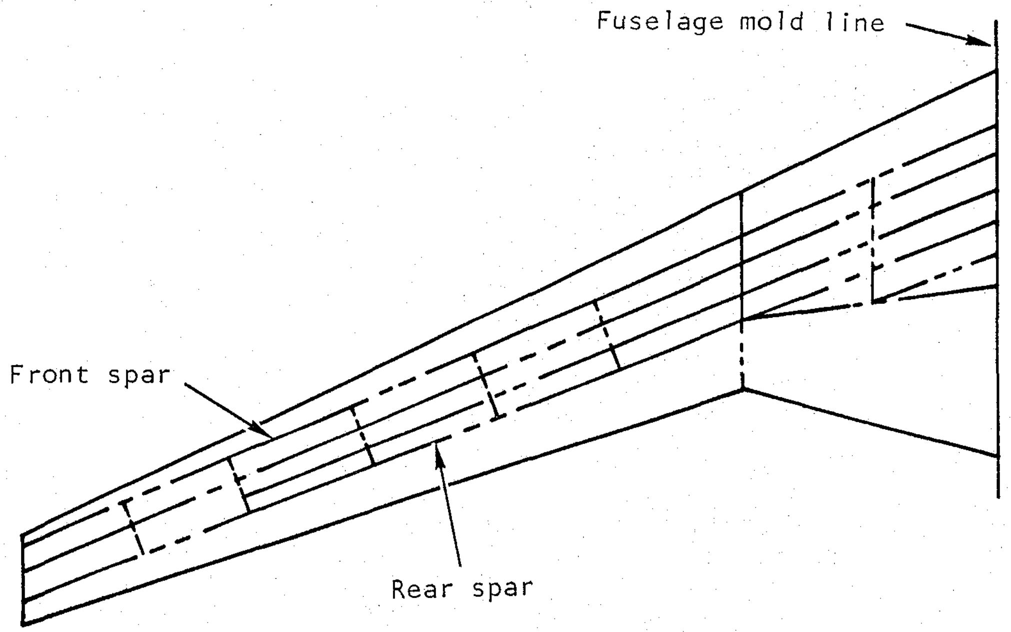


Figure 11.- Multispar configuration.

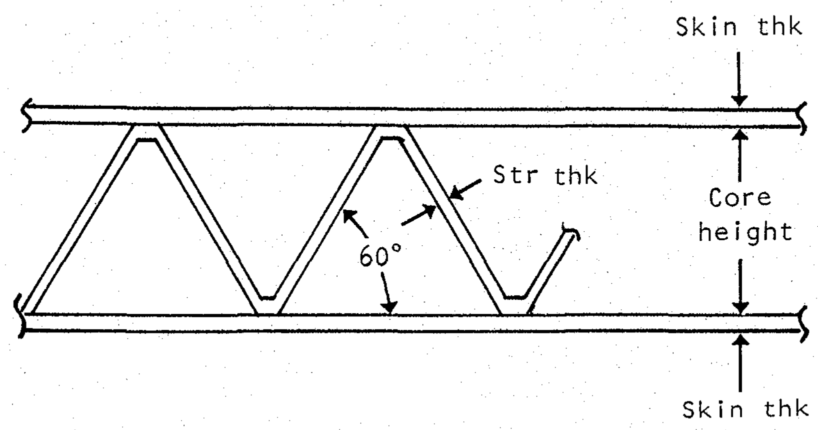


Figure 12.- Truss-core sandwich panel used in multispar SWEEP program.

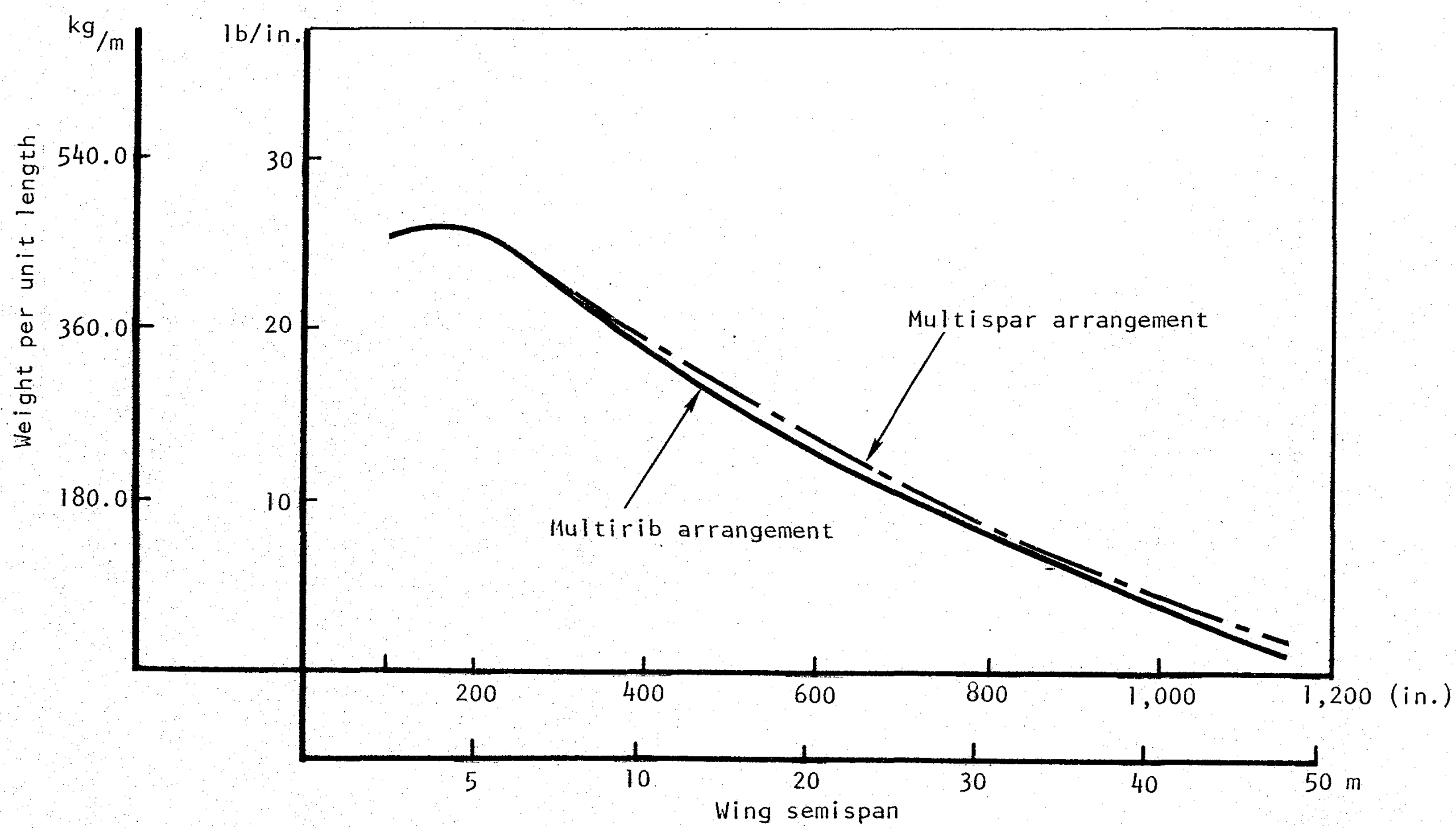


Figure 13.- Total wing weight distribution.

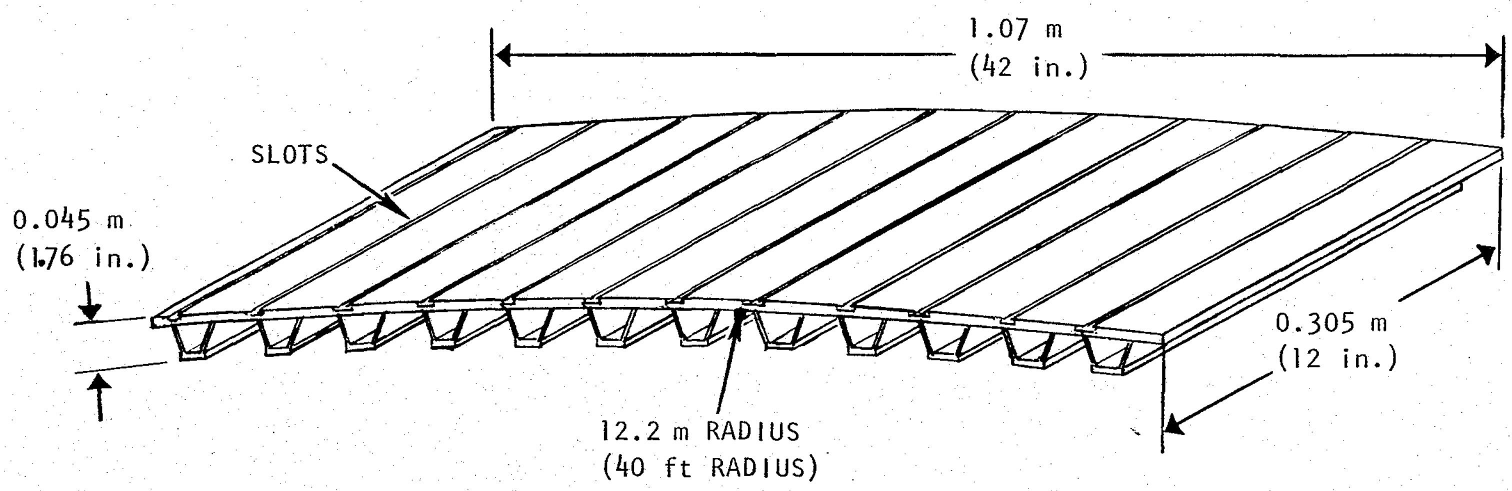


Figure 14.- Selected feasibility concept.

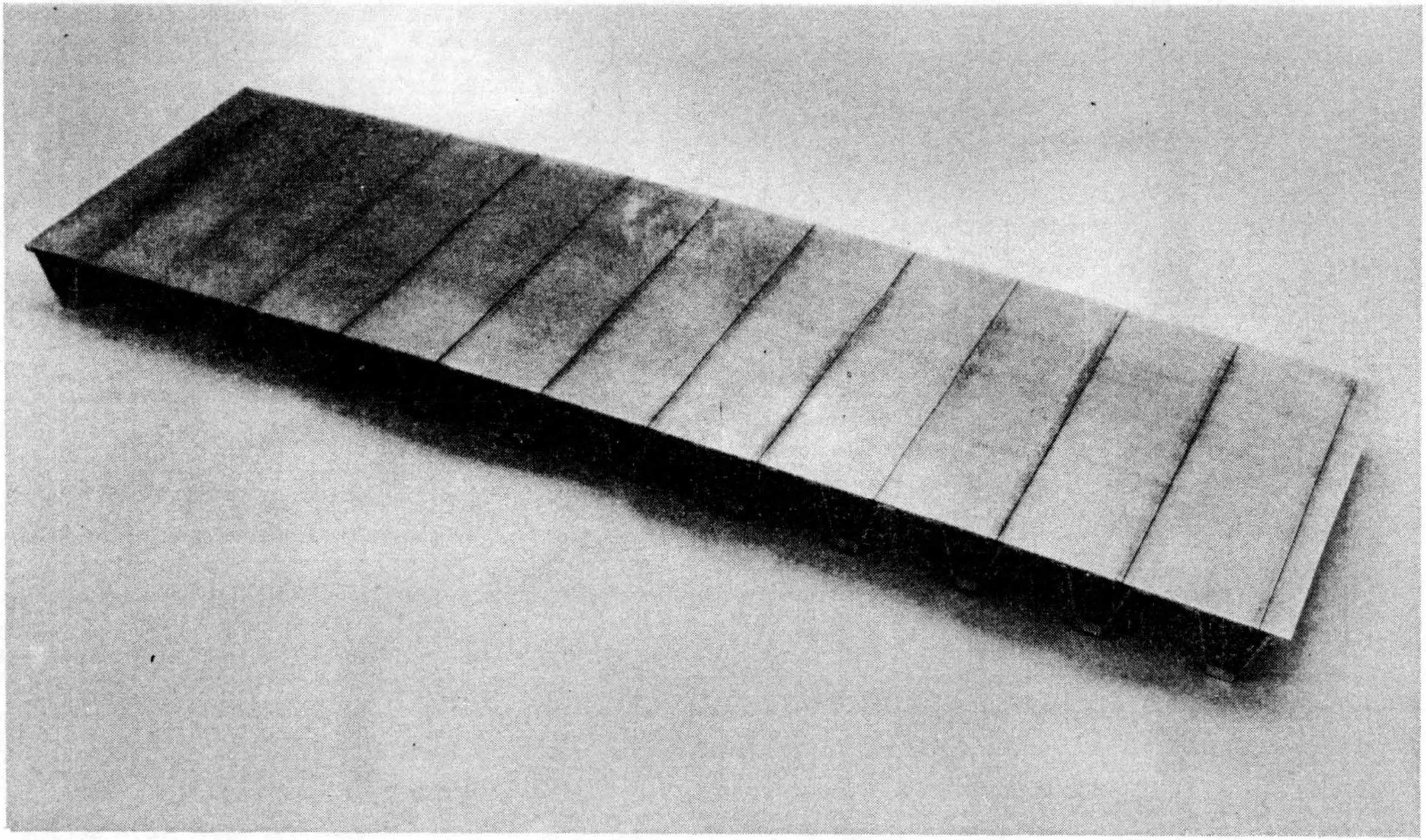


Figure 15.- Feasibility Panel, Moldline Surface

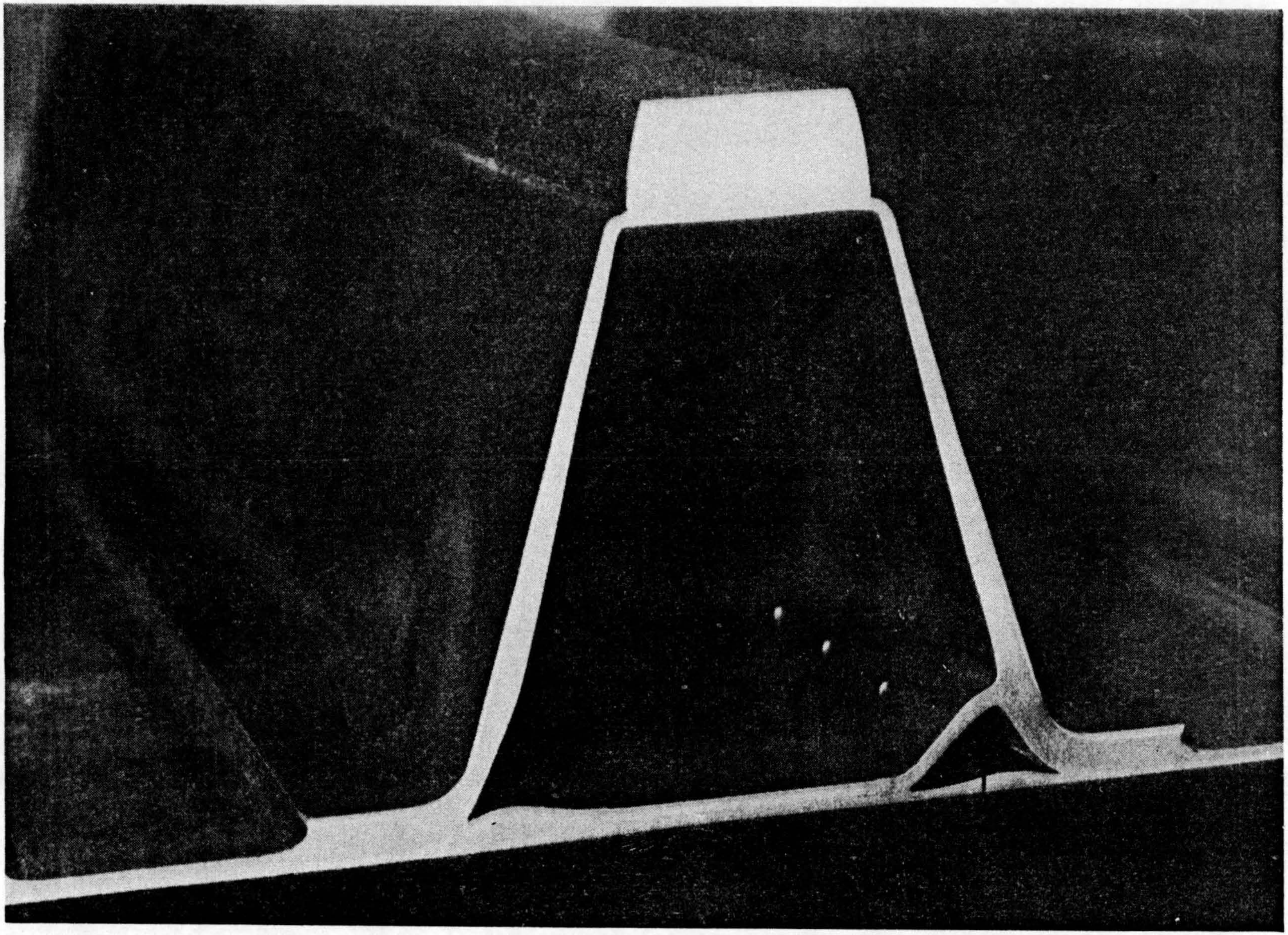


Figure 16.- Plenum and Metering Holes in Feasibility Panel

Figure 17.- Stringer-slot arrangement - upper surface.

Figure 18.- Stringer-slot arrangement - lower surface.

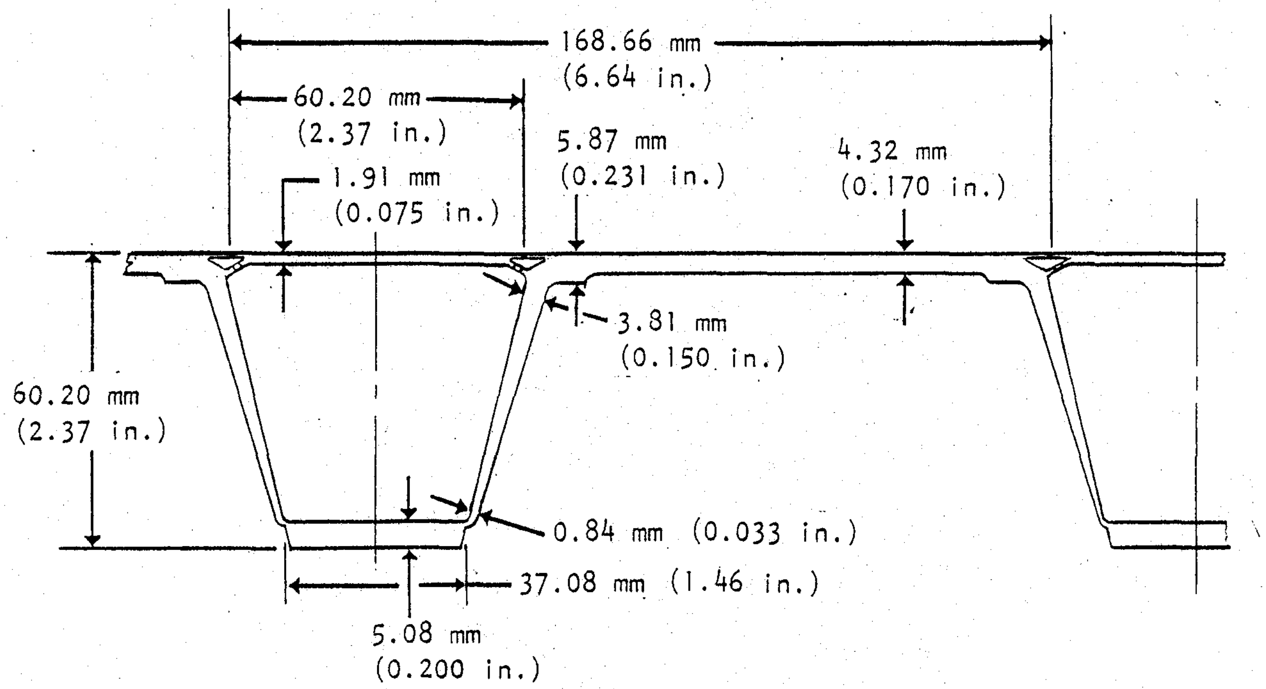


Figure 19.- Upper cover stringer at wing station 2.41 m (95 in.).

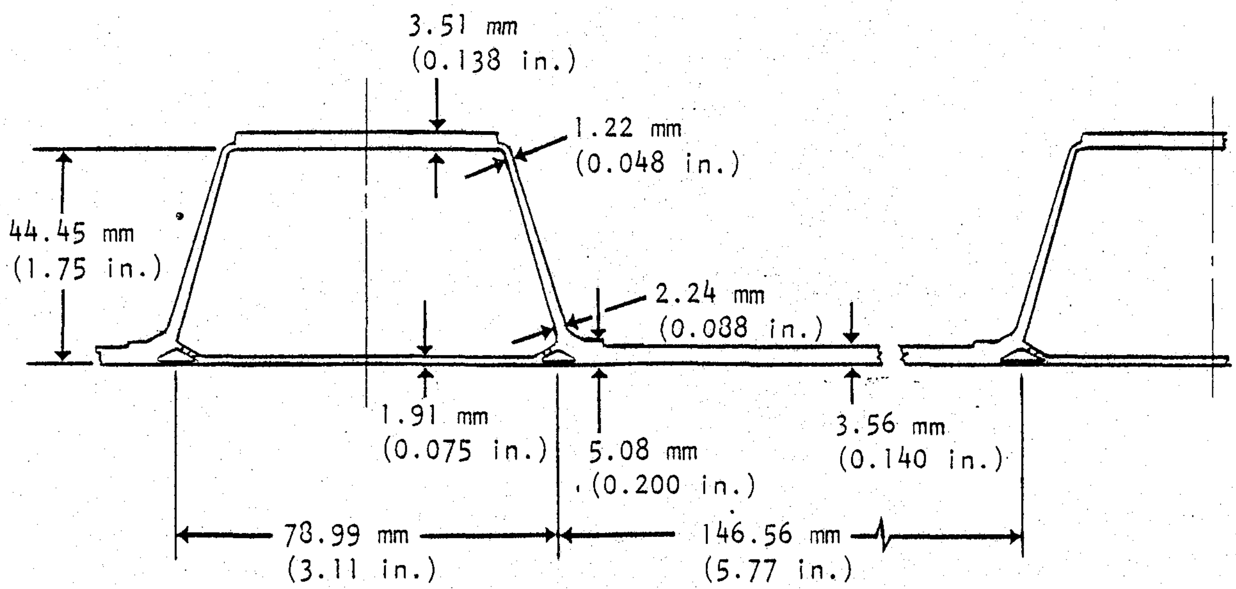
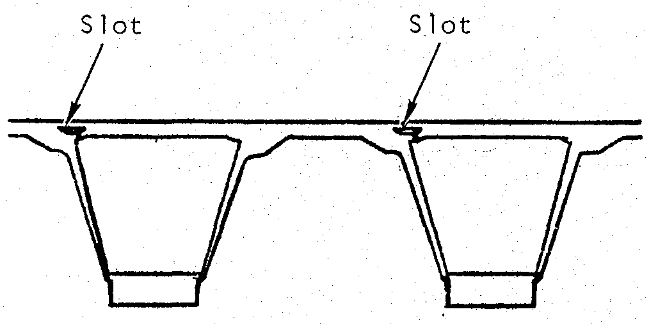
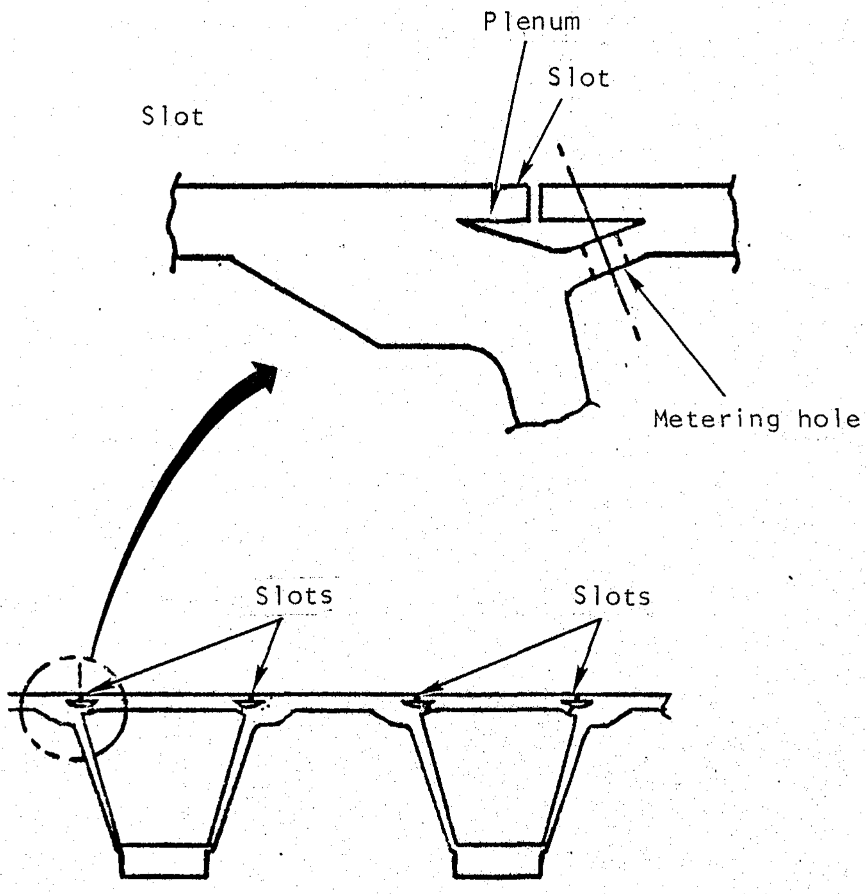


Figure 20.- Lower cover stringer at wing station 2.41 m (95 in.).



a. One slot per hat section



b. Two slots per hat section

Figure 21.- Hat-stiffened semisandwich concept for increasing number of slots.

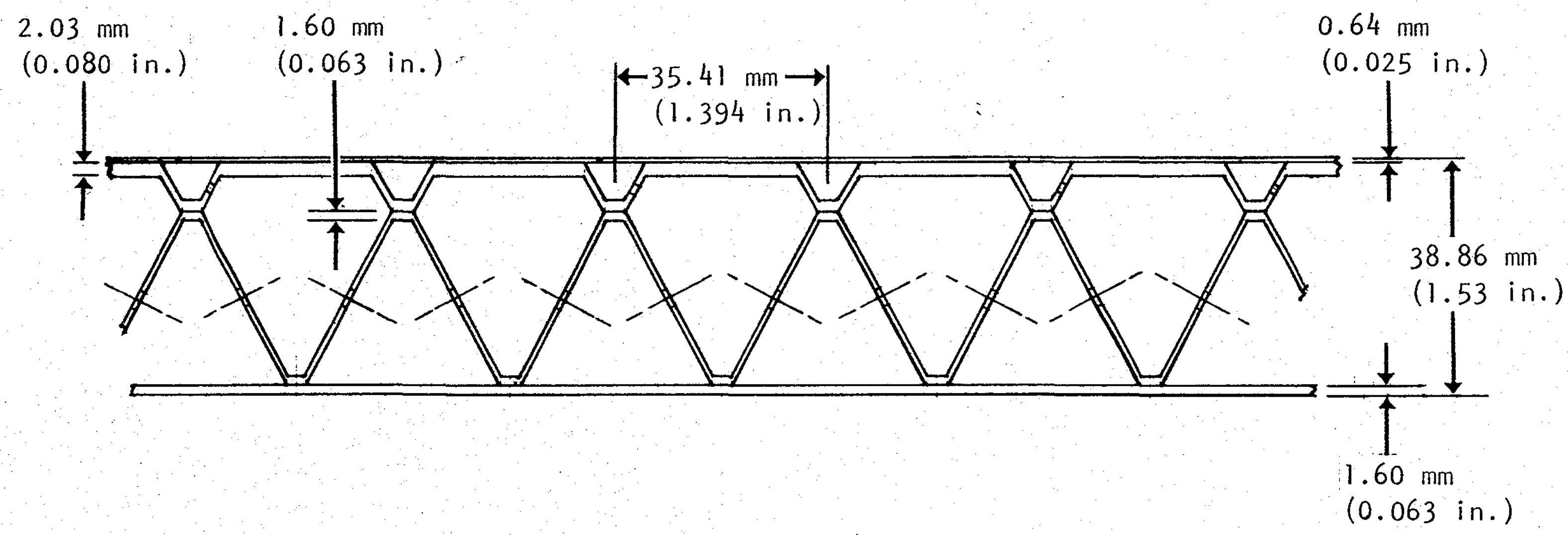


Figure 22.- Modified truss core sandwich integral LFC slot.

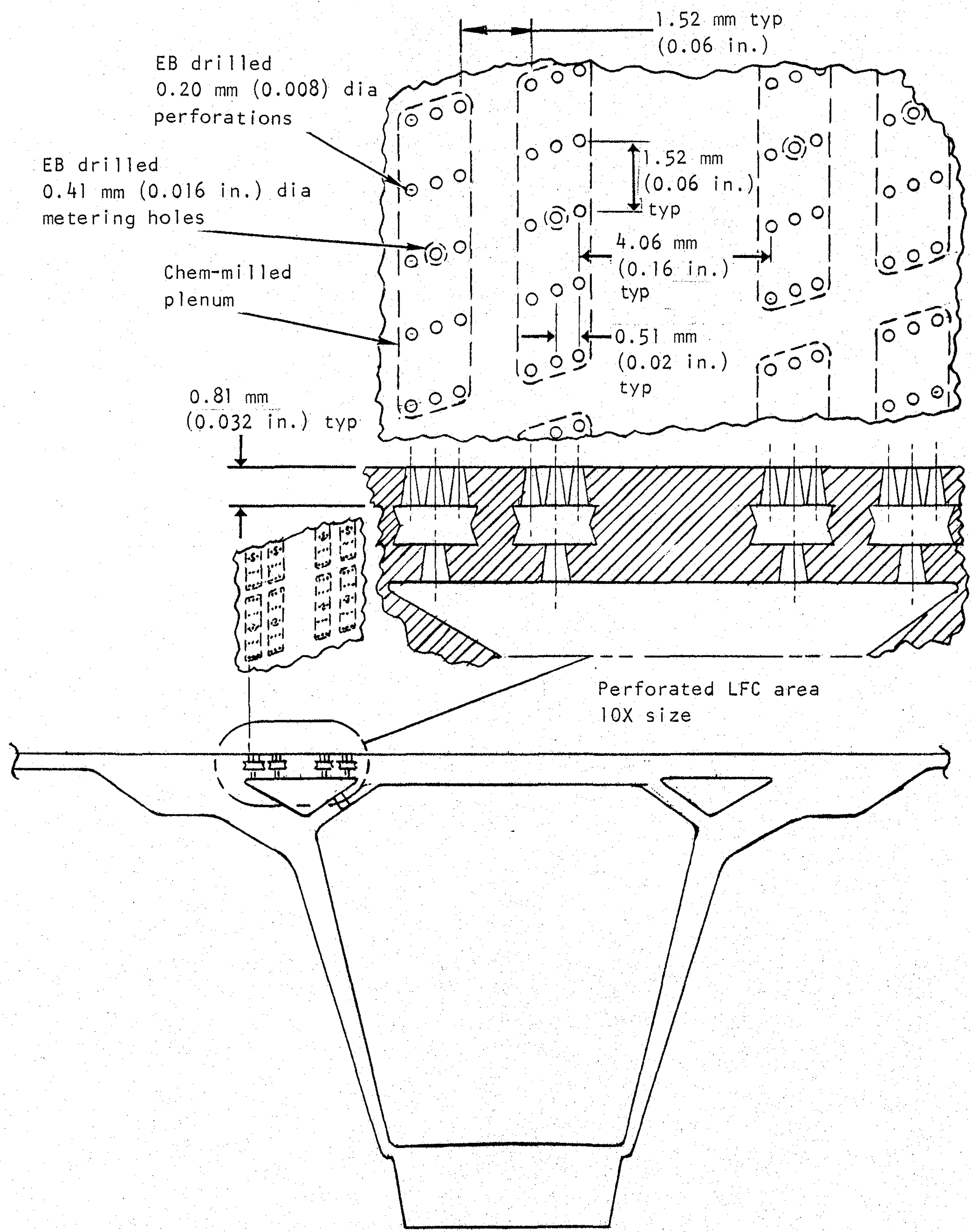


Figure 23.- Typical stiffener integral perforated LFC.

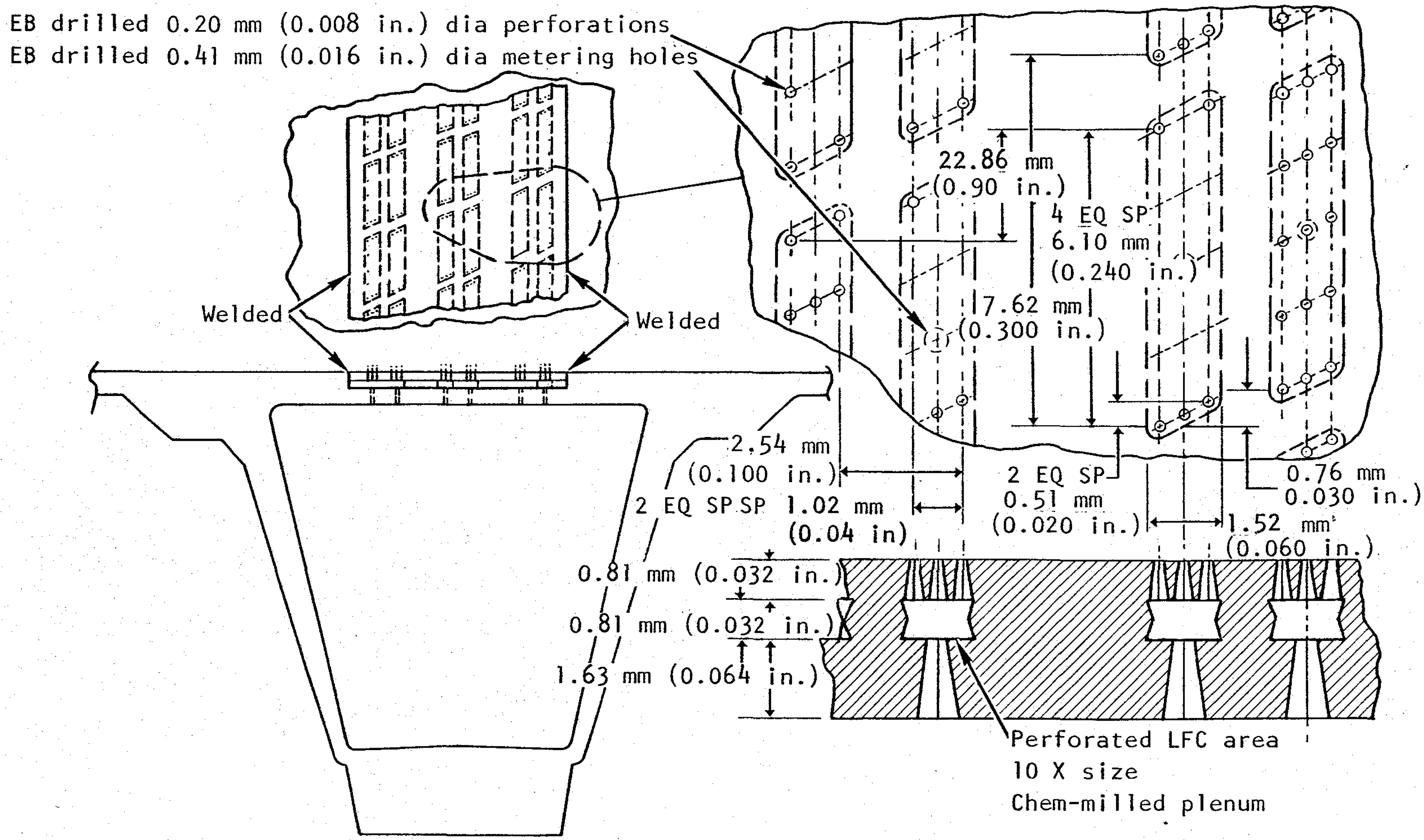


Figure 24.- Typical stiffener - separate-perforated LFC strip.

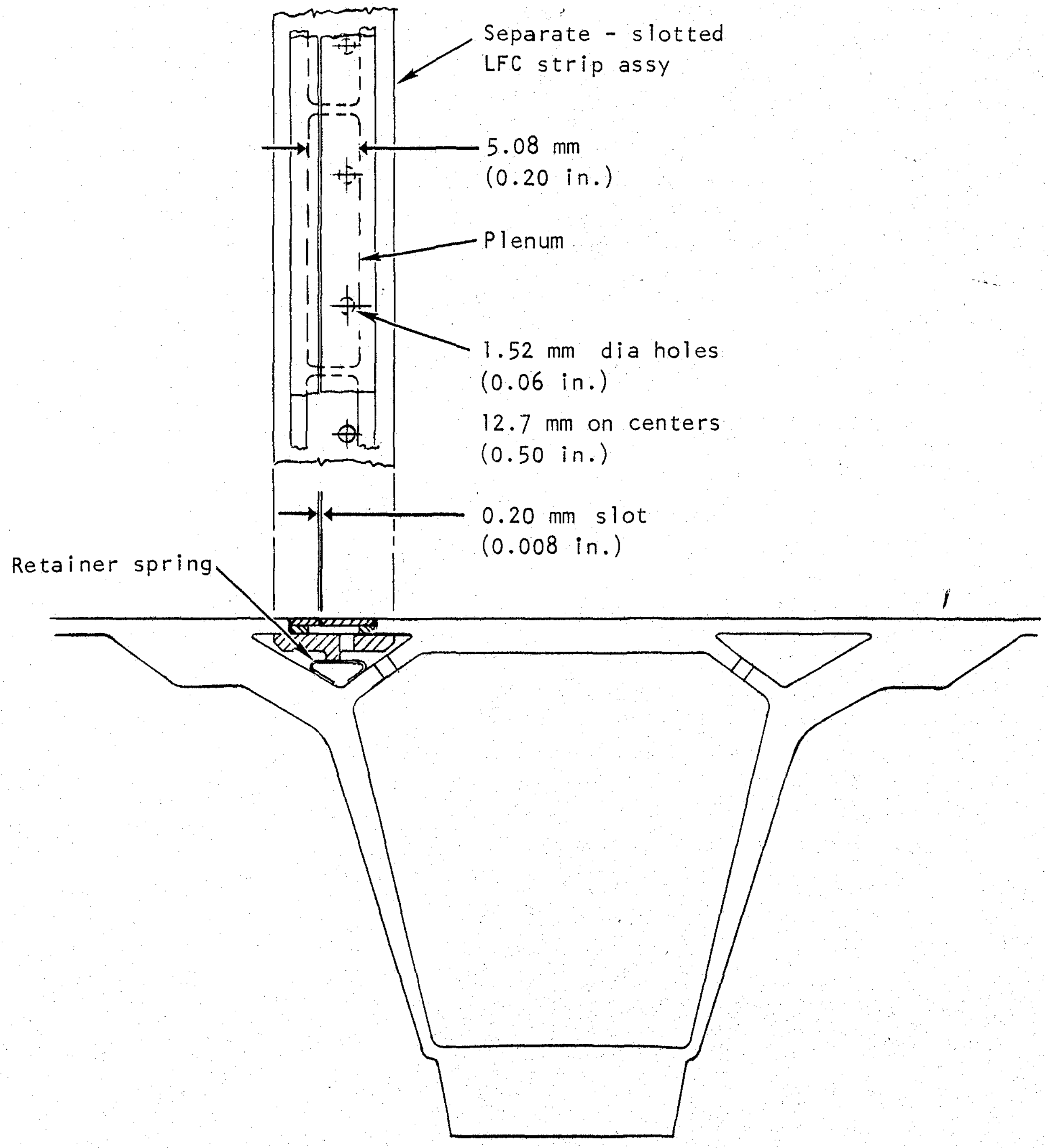


Figure 25.- Typical stiffener - separate-slotted LFC strip.

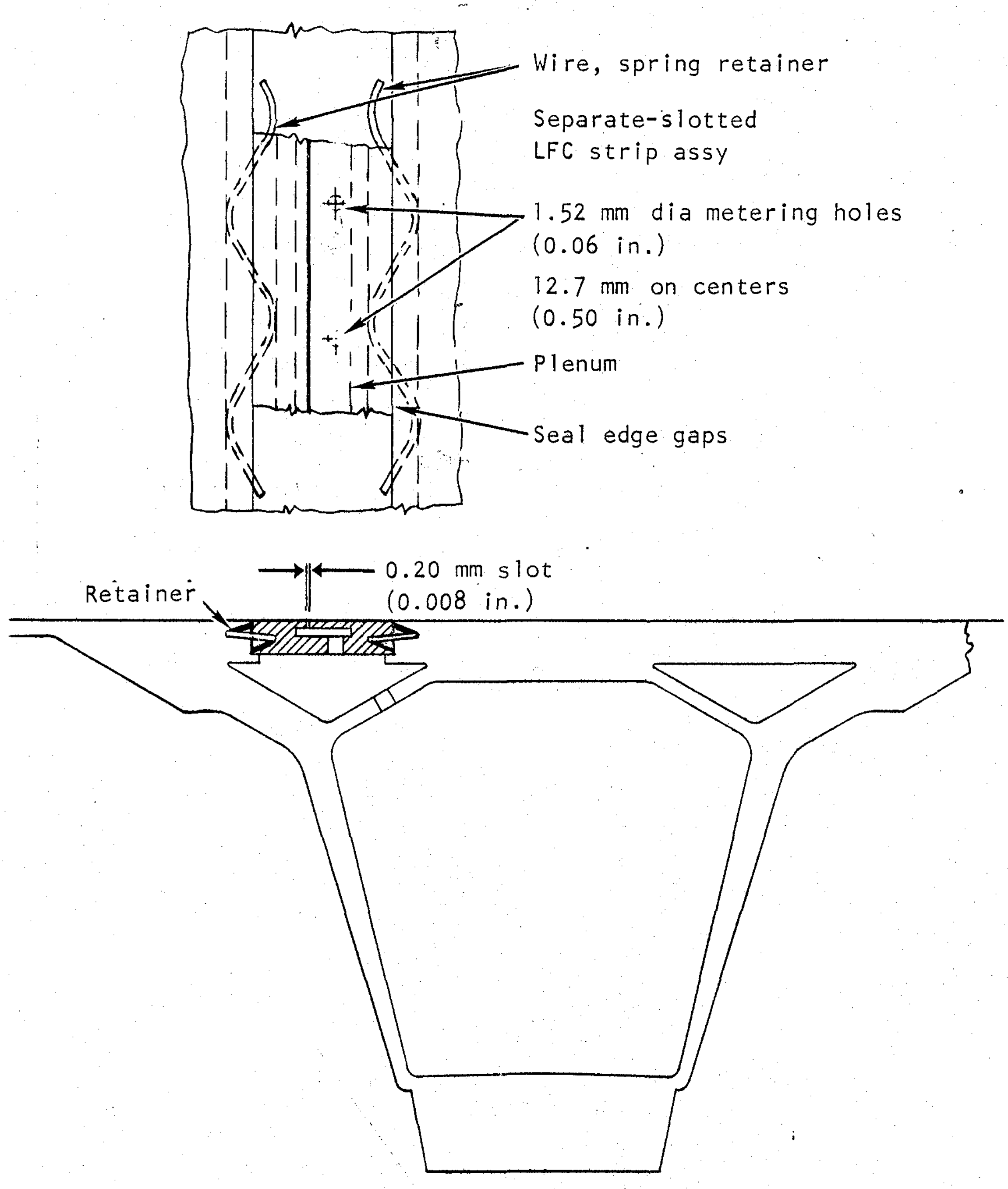


Figure 26.- Typical stiffener - separate LFC strip, wire spring retainer.

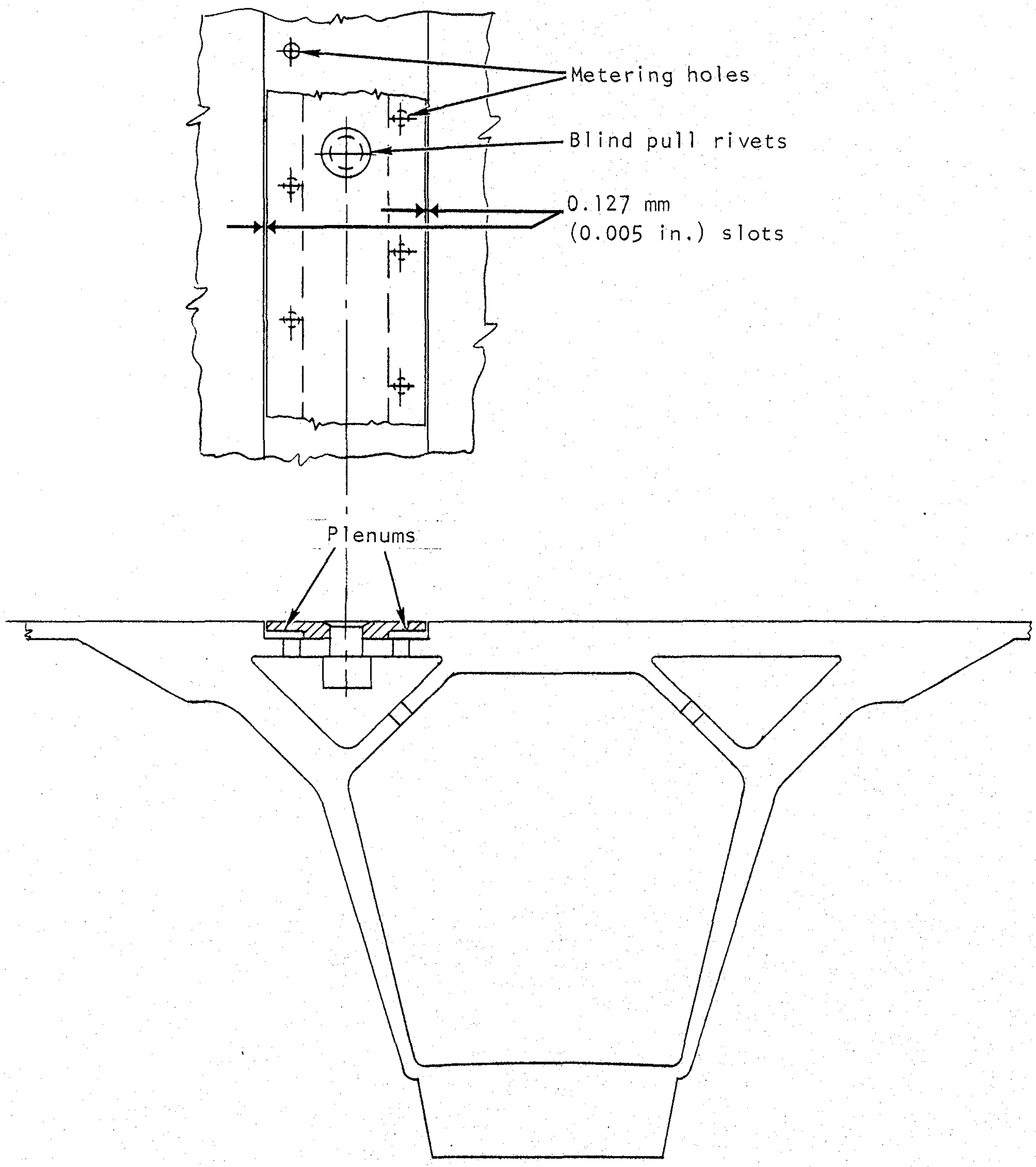


Figure 27.- Typical stiffener - separate LFC strip, mechanically attached.

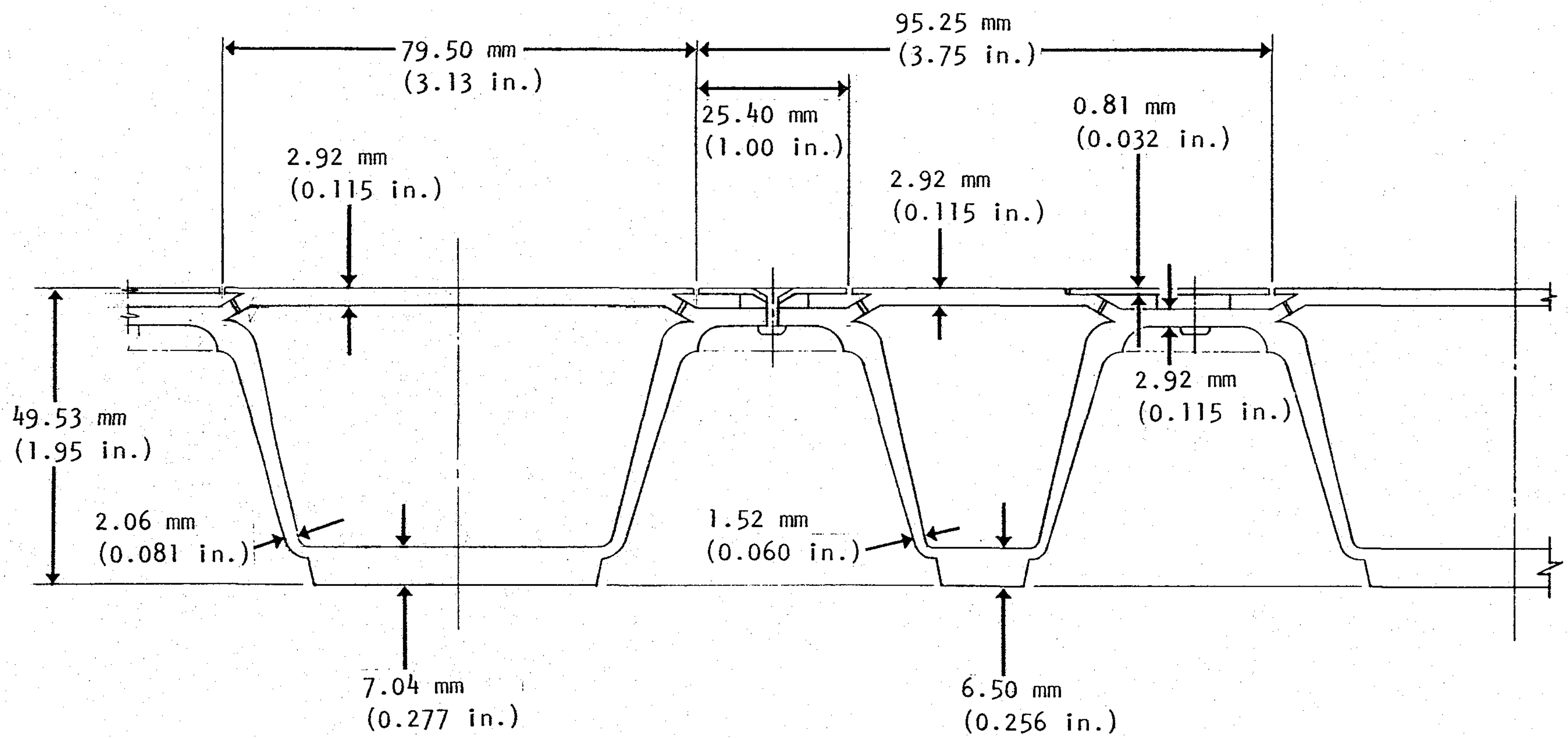


Figure 28.- Upper cover stringers at wing station 9.04 m (356 in.) alternate arrangement.

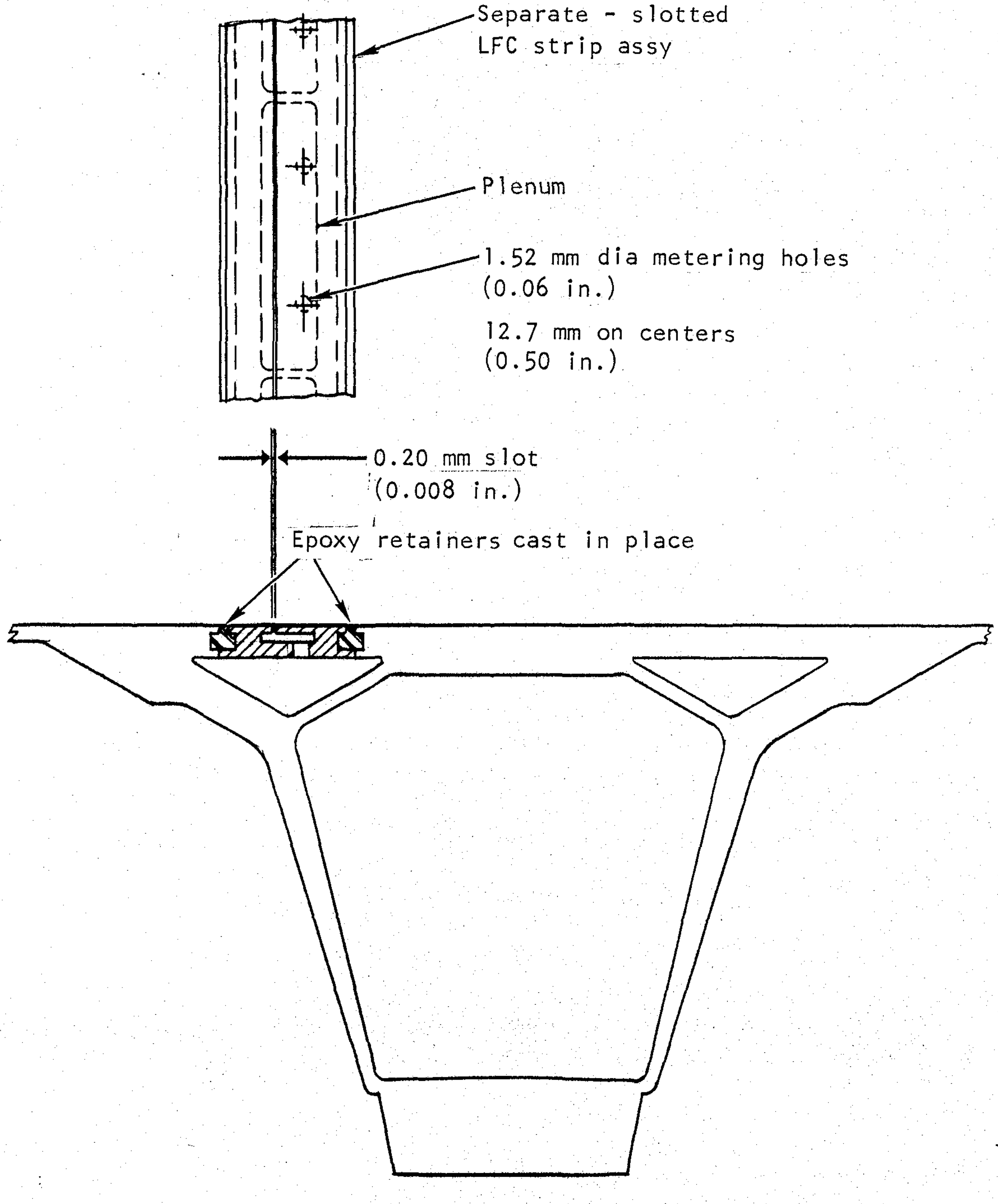


Figure 29.- Typical stiffener - separate LFC strip, epoxy retainer.

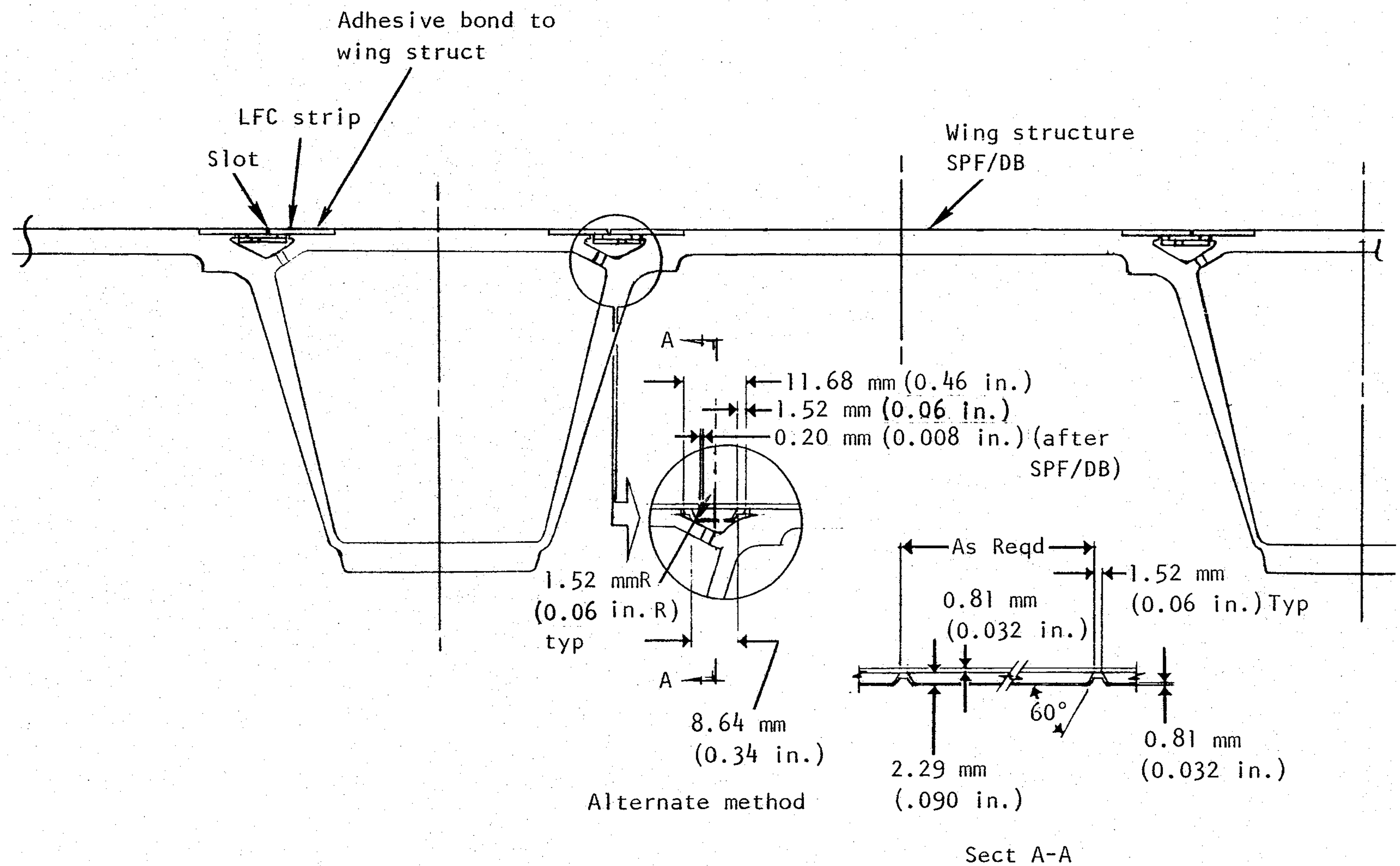


Figure 30.- Typical stiffener - separate-slotted LFC strip-bonded.

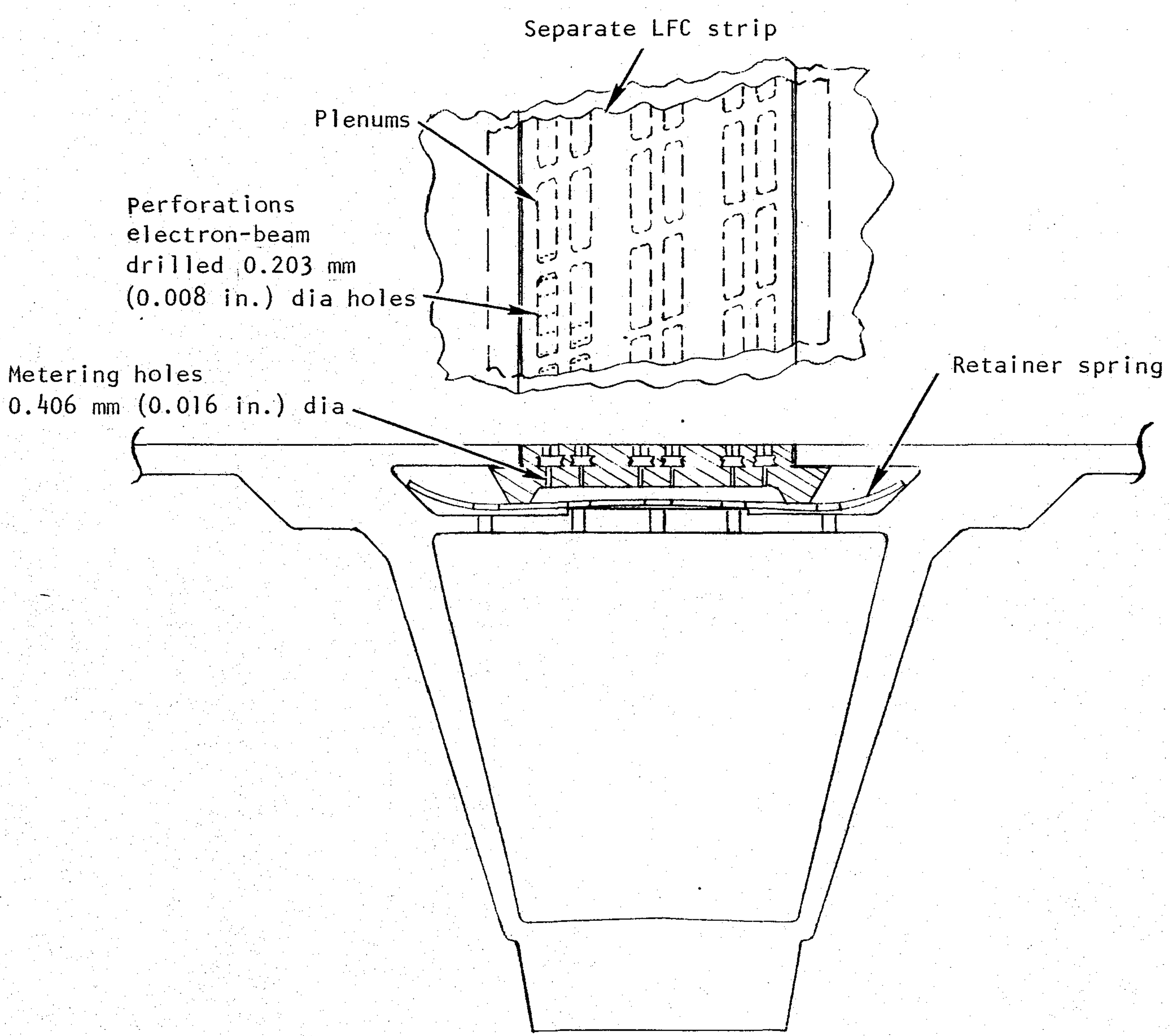


Figure 31.- Typical stiffener - separate-perforated LFC strip-spring retainer.

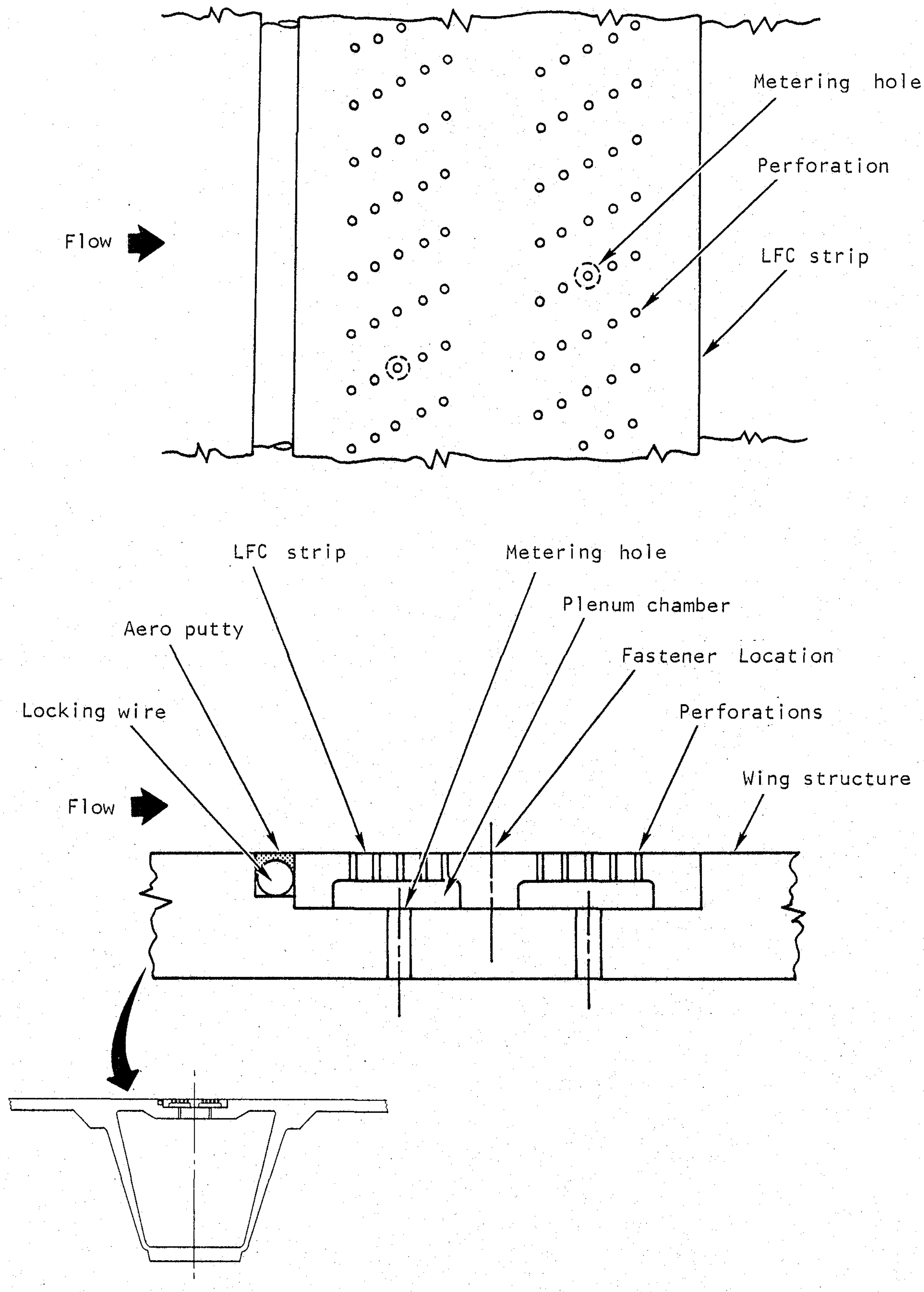


Figure 32.- Replaceable perforated strip insert for suction LFC wing.

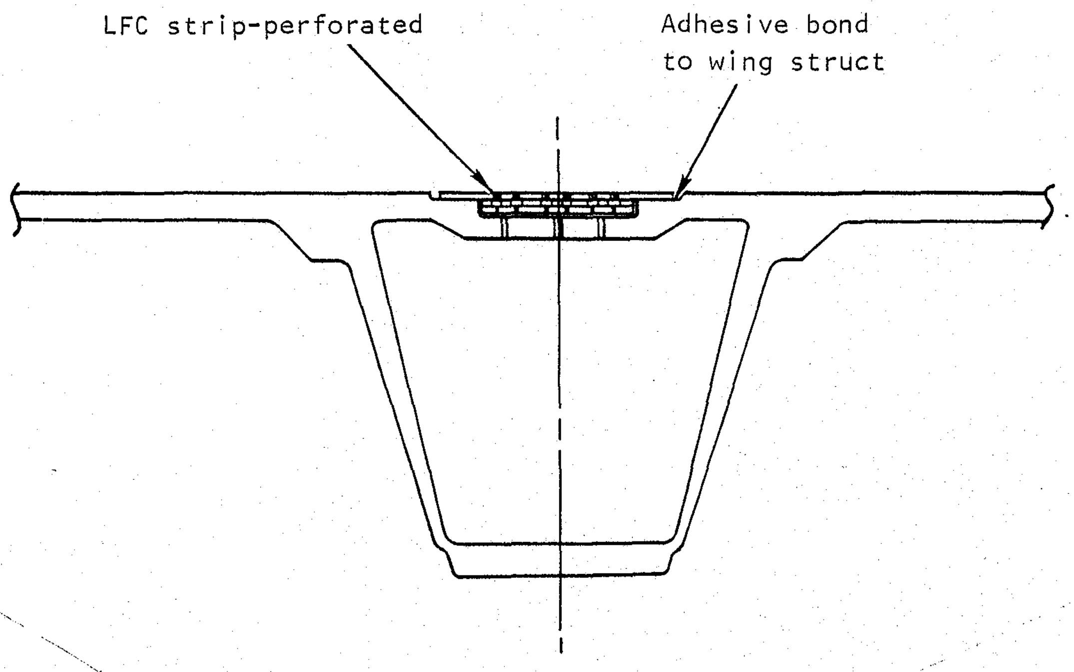


Figure 33.- Typical stiffener - separate perforated LFS strip-bonded.

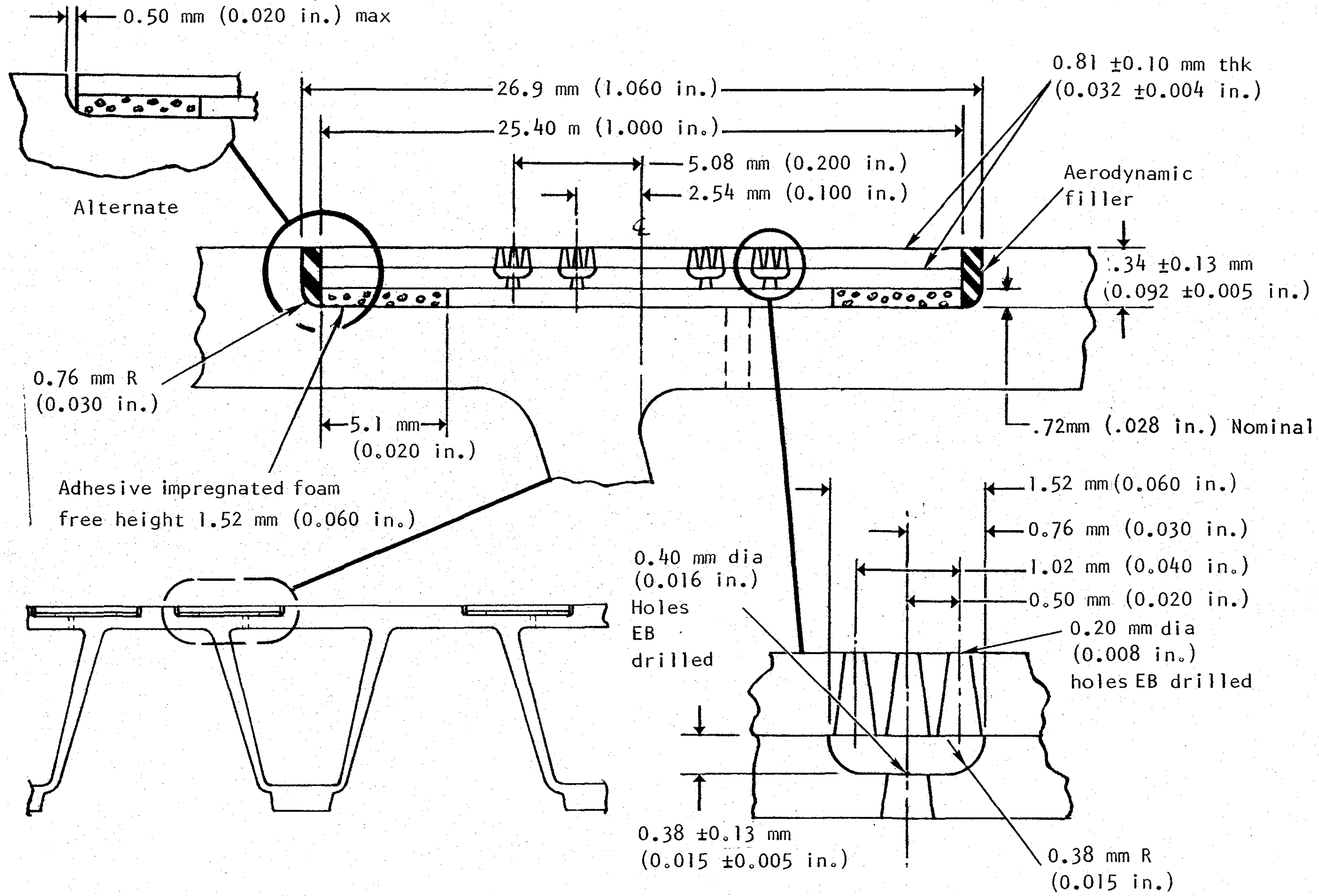


Figure 34.- Replacable, perforated LFC strip installation.

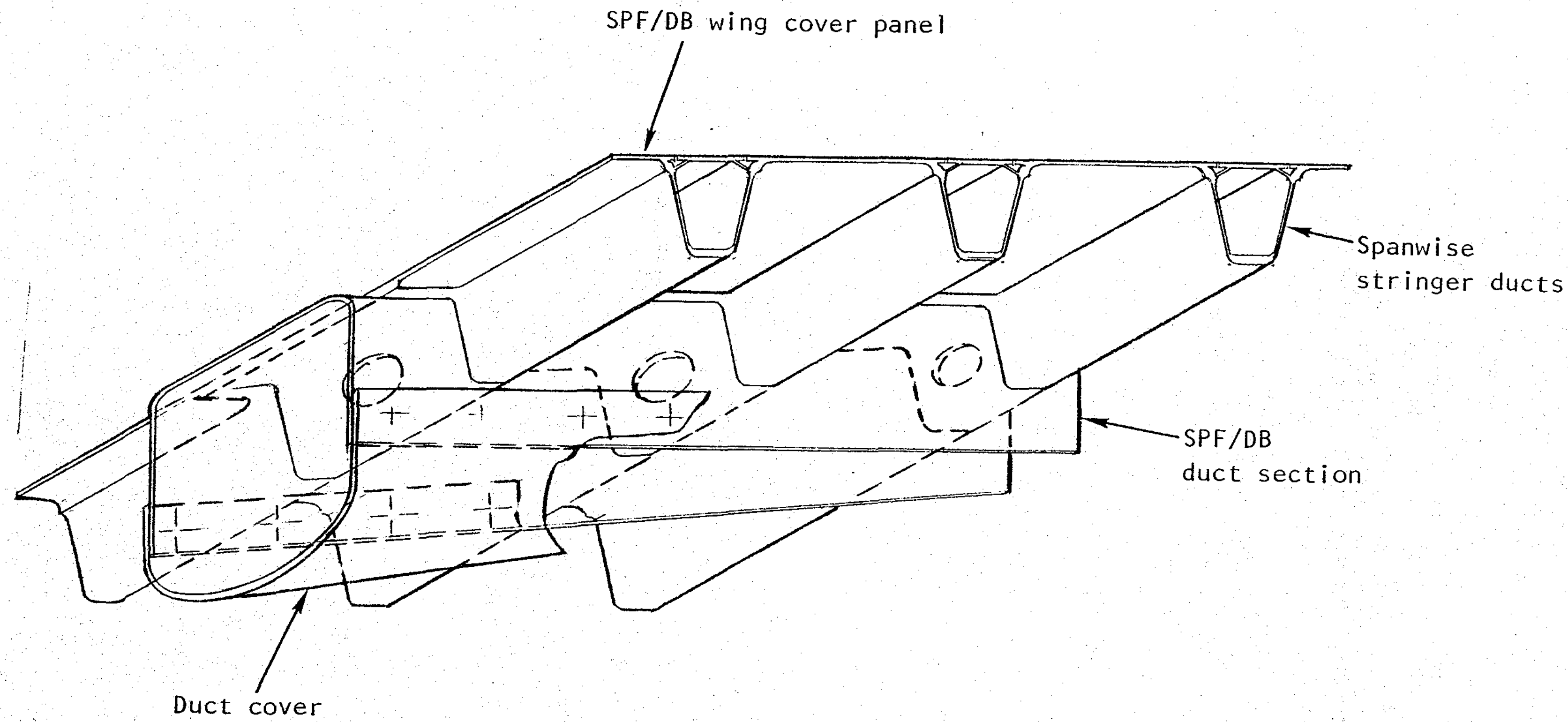


Figure 35.- Integral chordwise duct - SPF/DB concept.

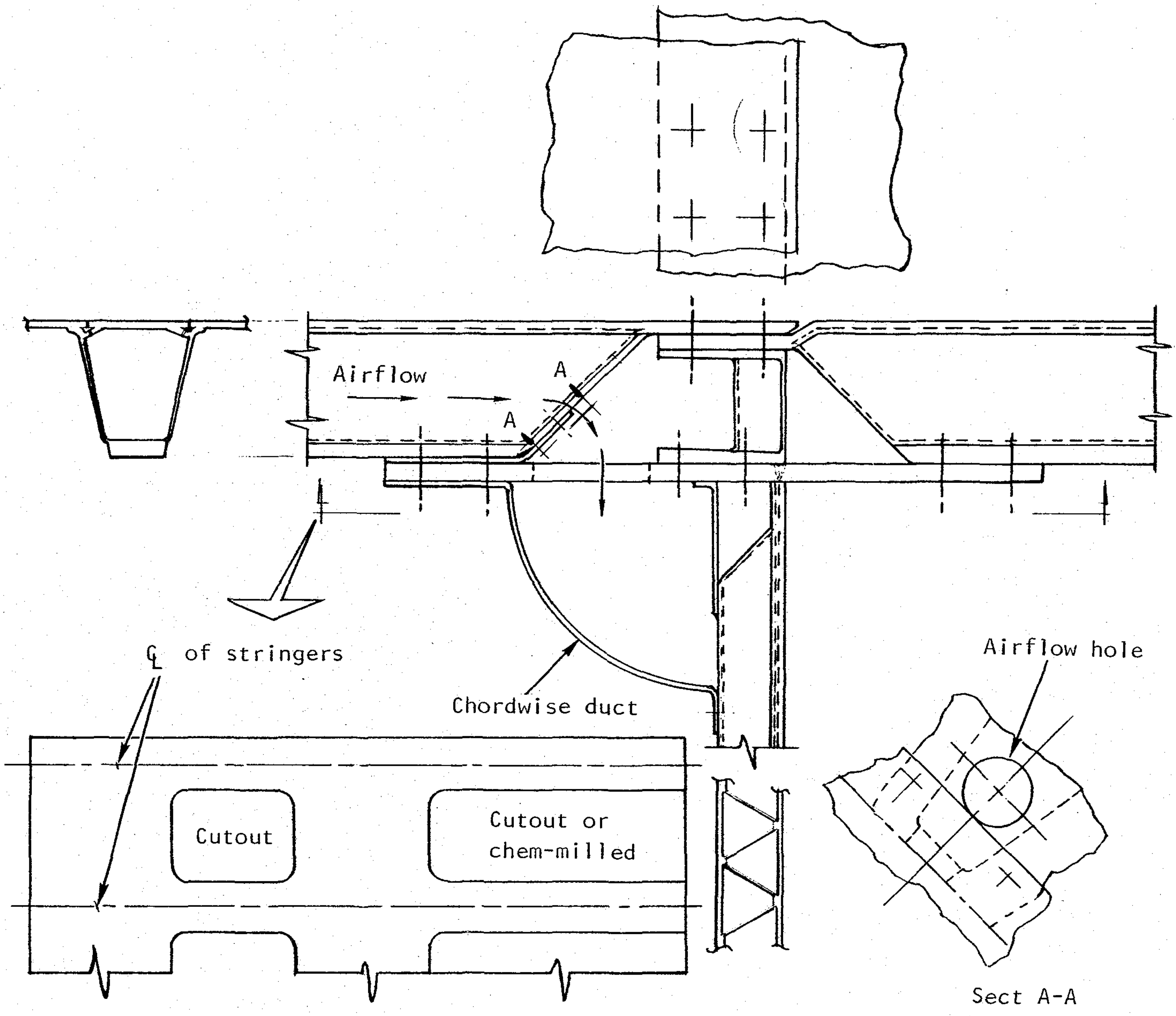


Figure 36.- Integral chordwise duct - mechanically fastened.

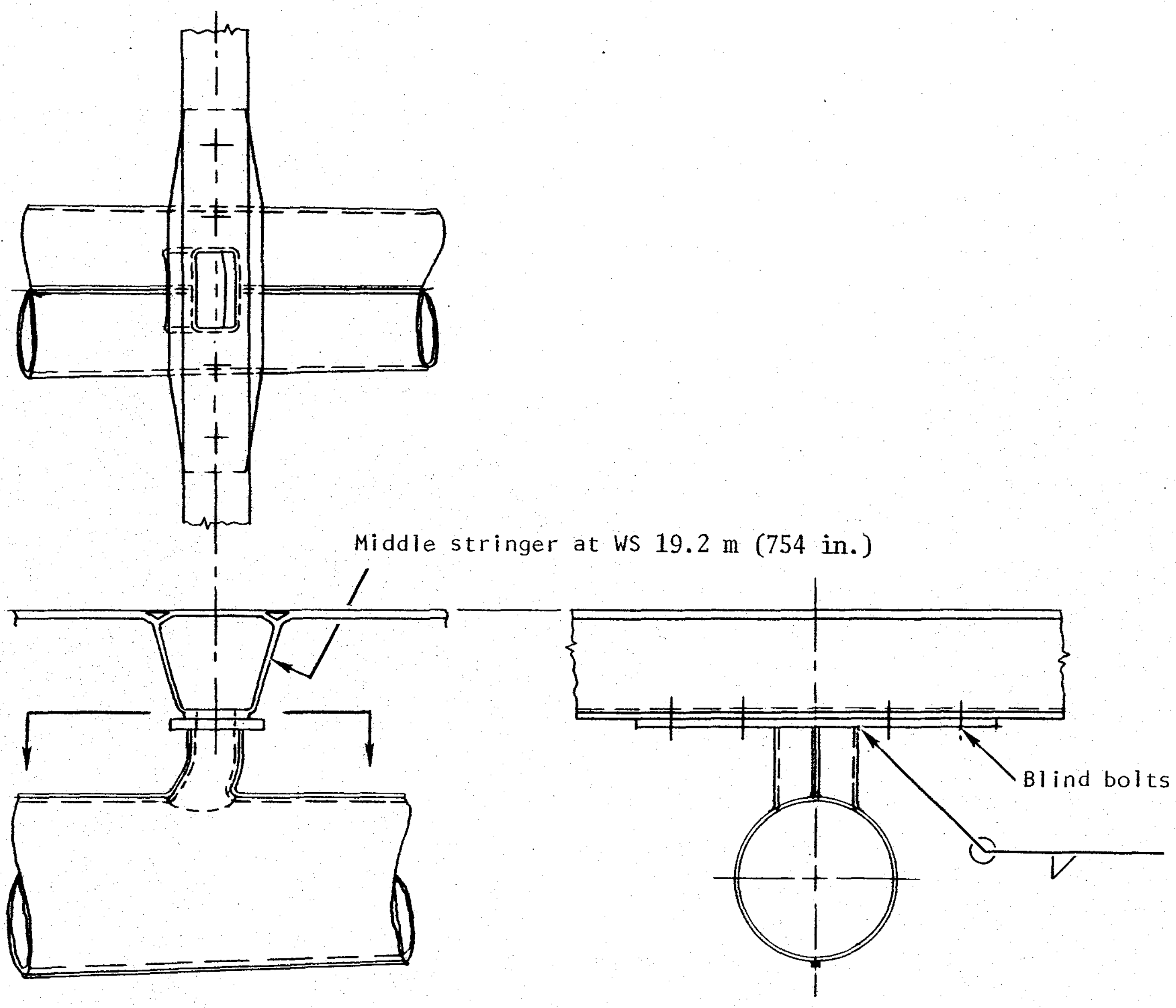


Figure 37. Separate chordwise duct - stringer bottom interface.

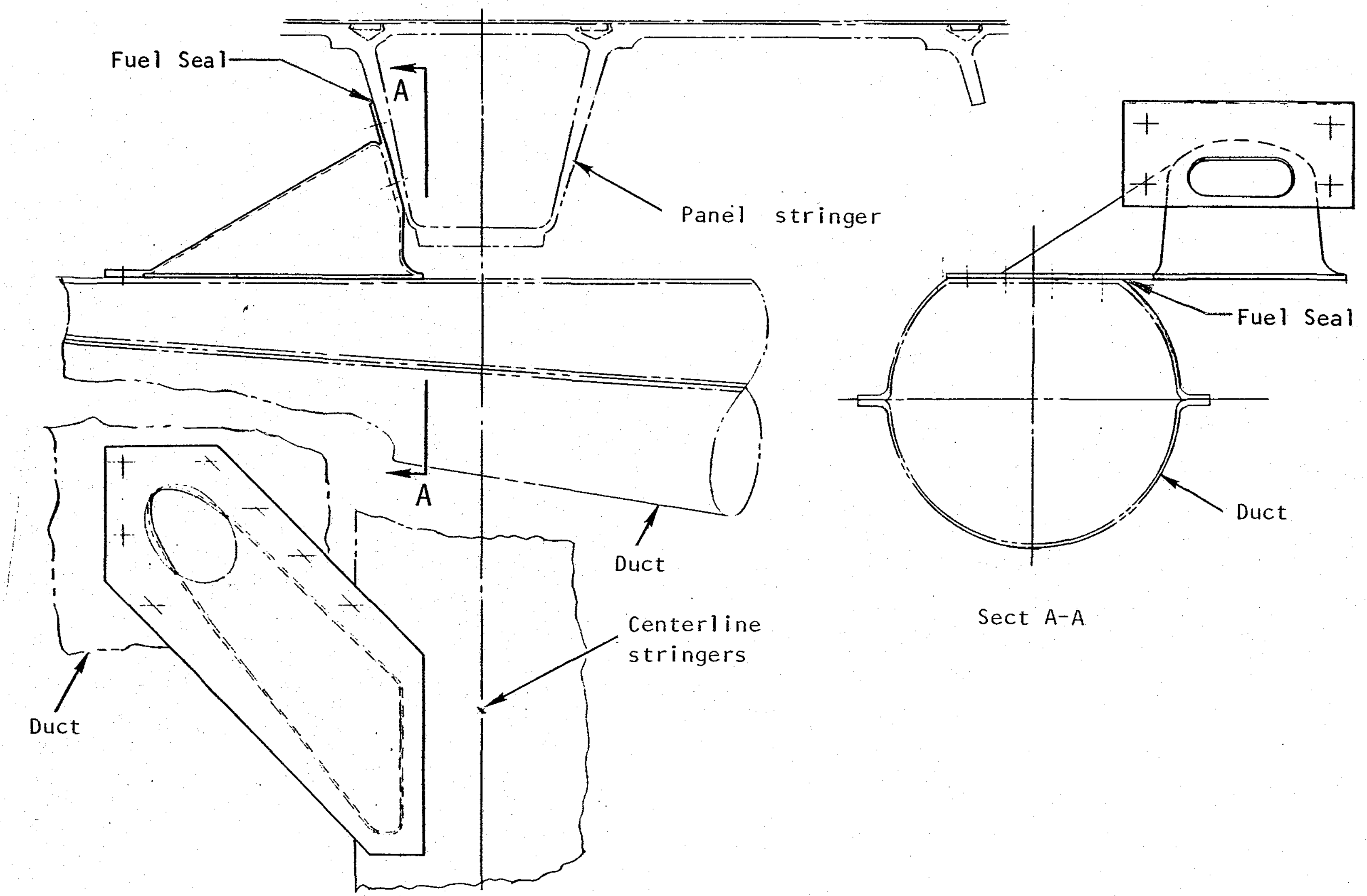


Figure 38. Separate chordwise duct - separate transfer duct.

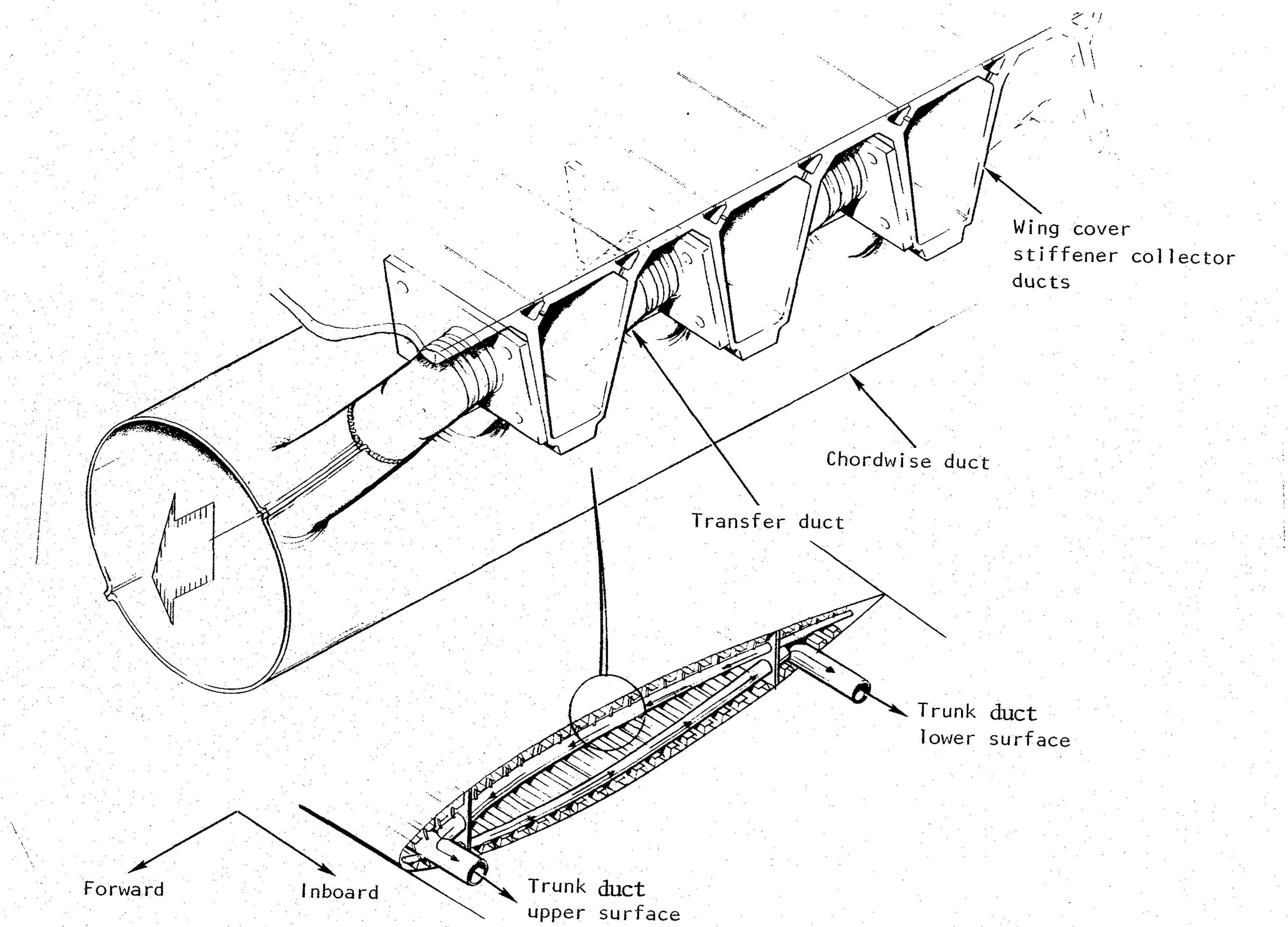


Figure 39.- Separate chordwise duct - flex duct concept.

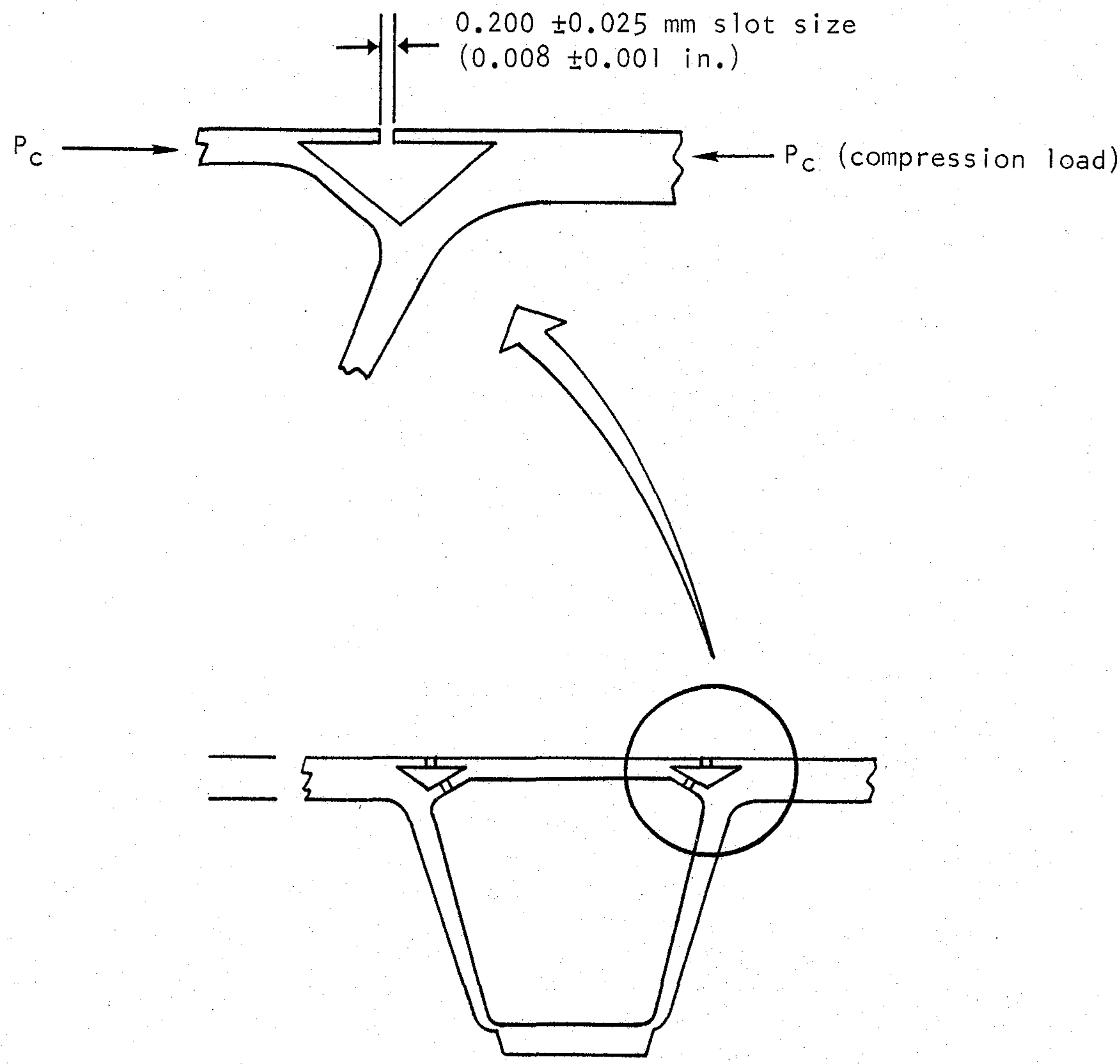


Figure 40.- Typical integral plenum and slot configuration.

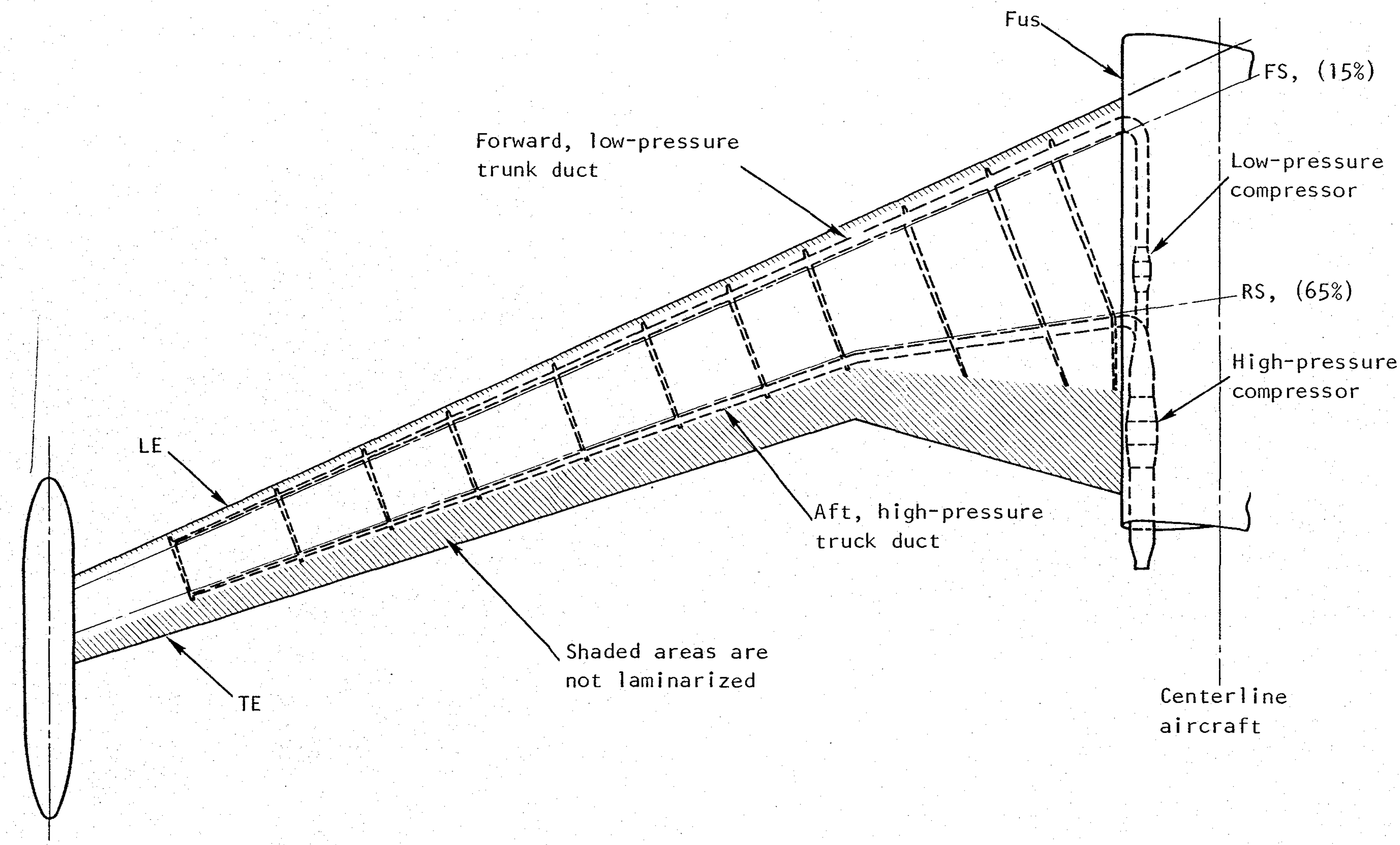


Figure 41. Multiple chordwise LFC duct system.

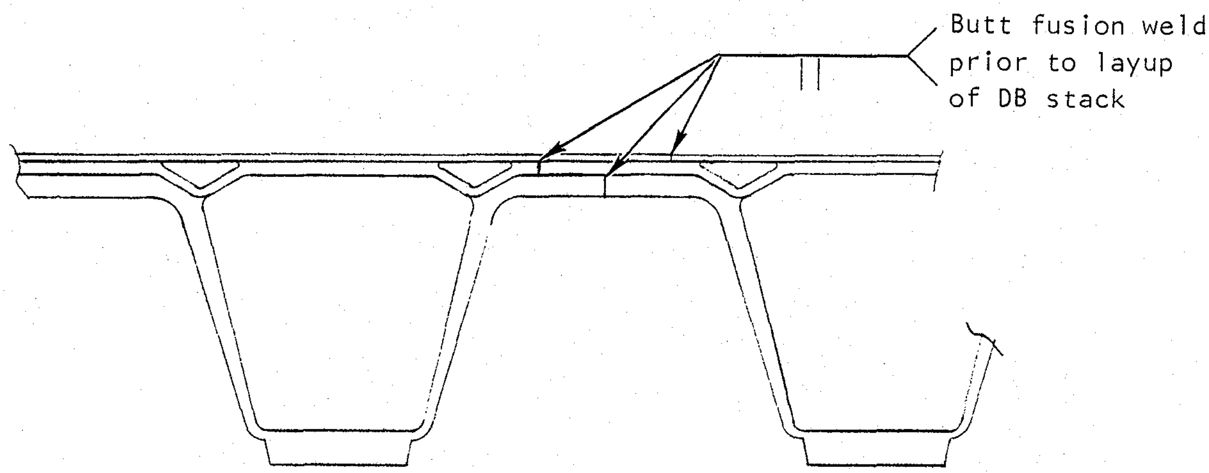


Figure 42. Pre-SPF/DB weld joint concept.

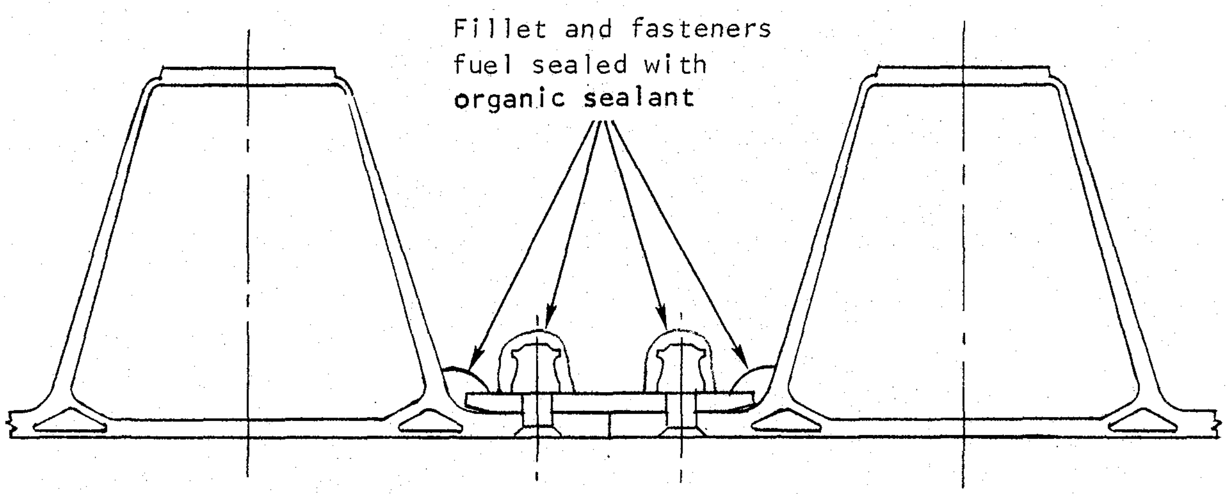


Figure 43. Butt joint - spanwise panel splice.

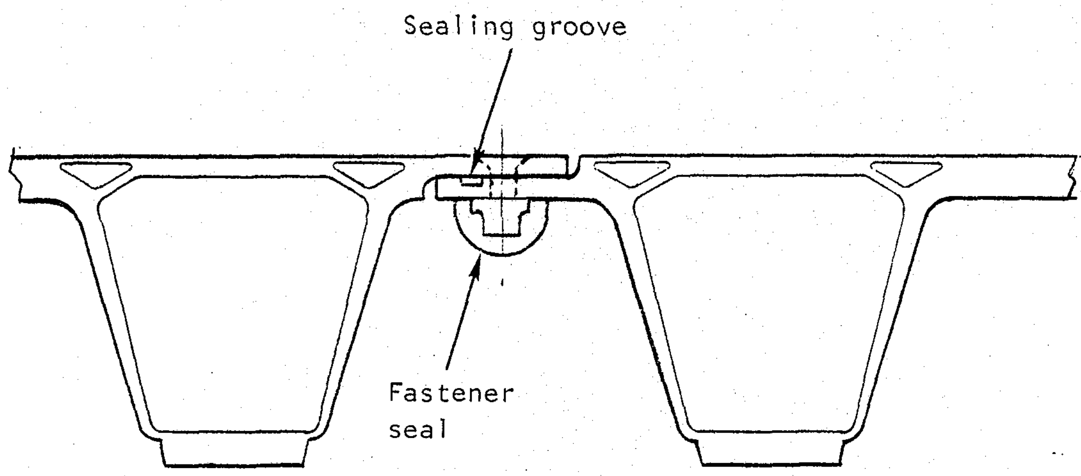


Figure 44. Overlap joint - spanwise panel splice.

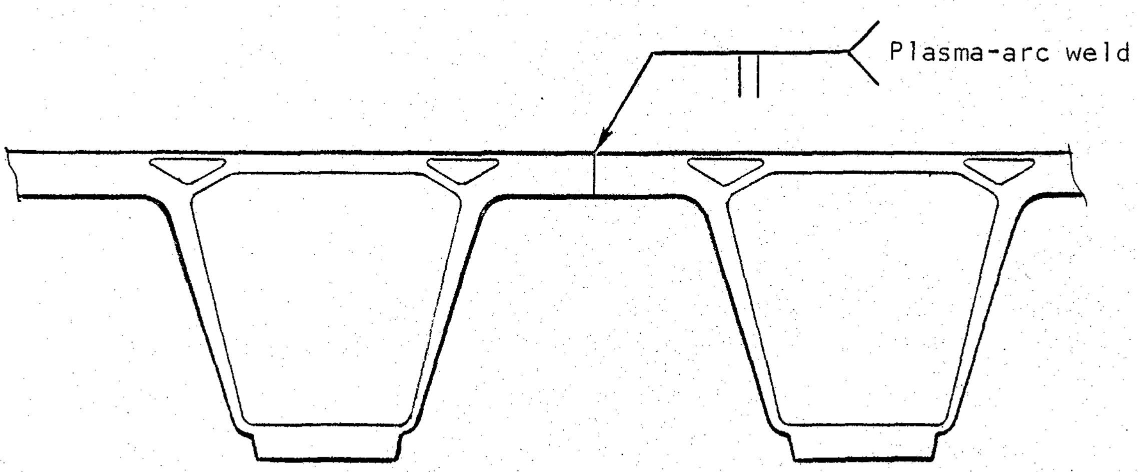


Figure 45. Wing panel welded spanwise splice concept.

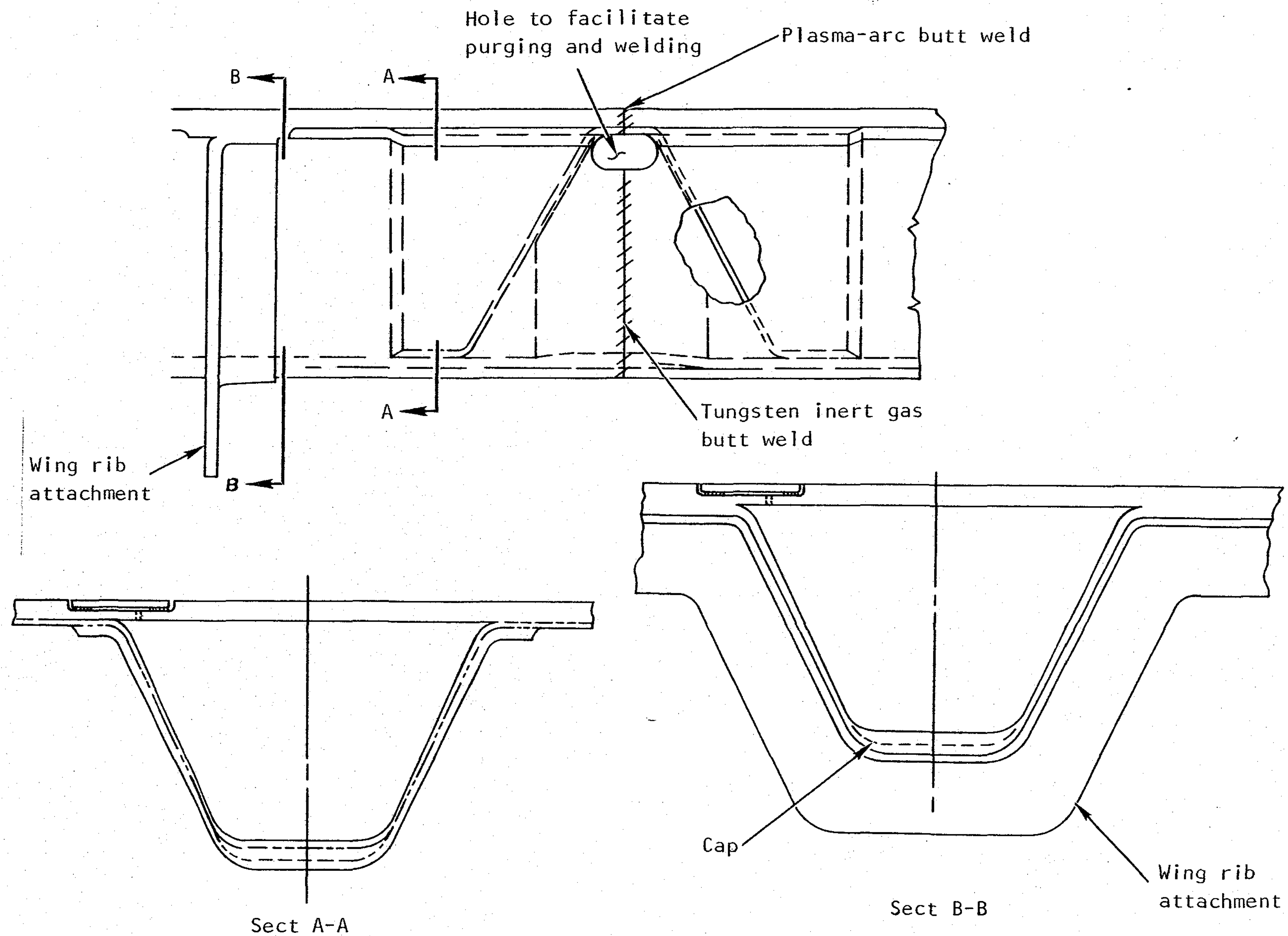


Figure 46. Wing upper cover - chordwise panel splice concept.

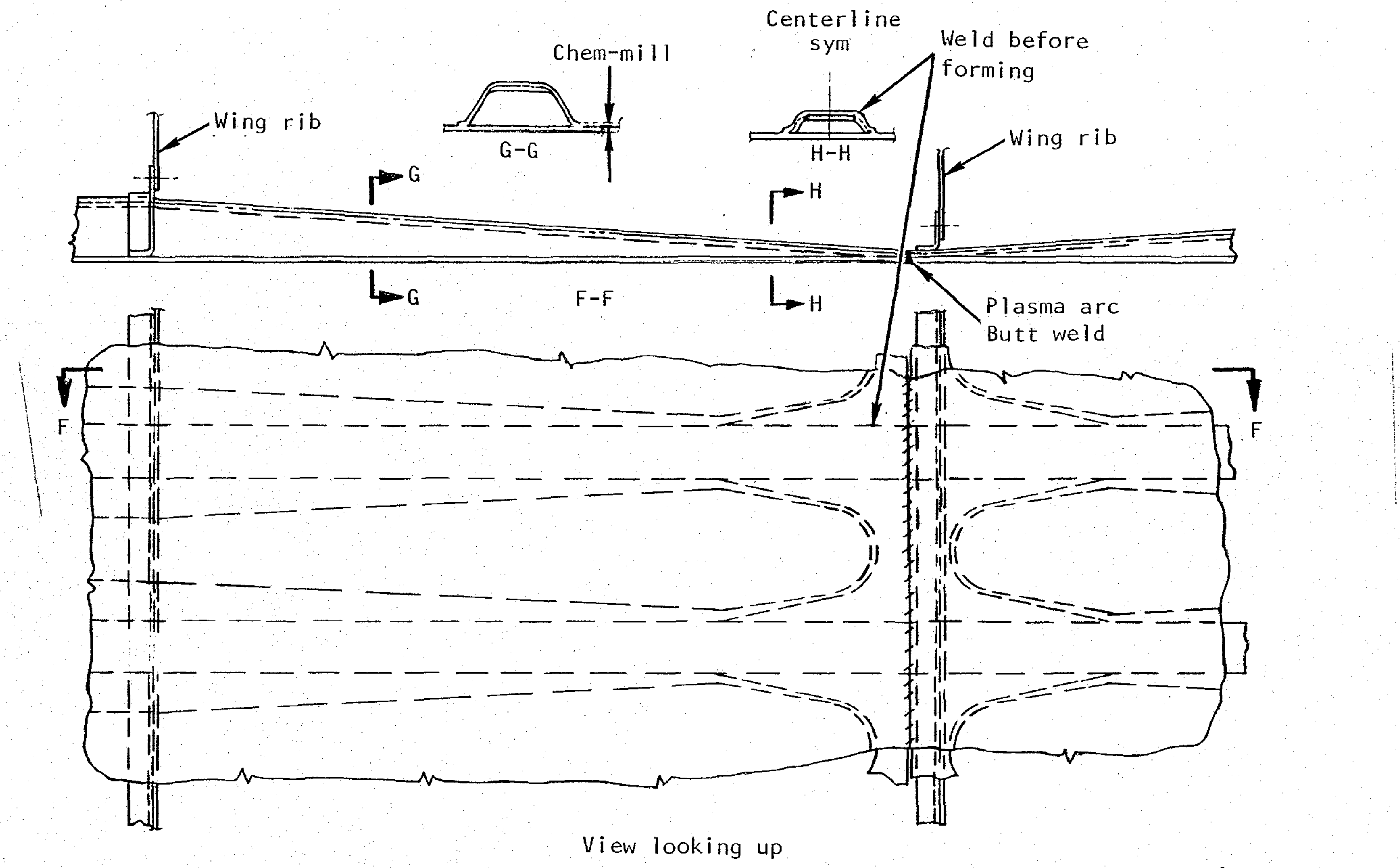


Figure 47.- Wing lower cover - chordwise panel splice concept.

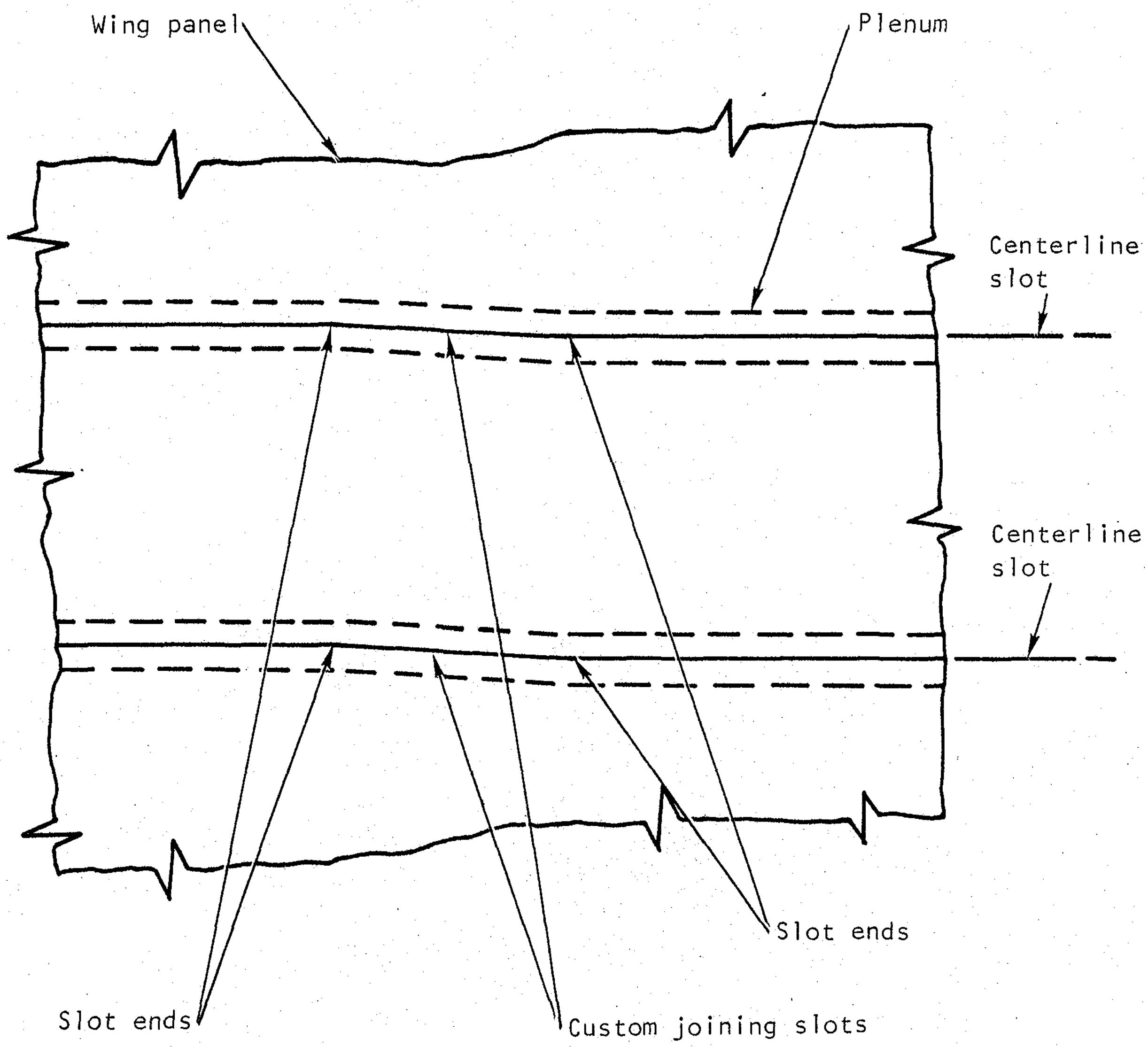


Figure 48.- Wing panel slot splice concept.

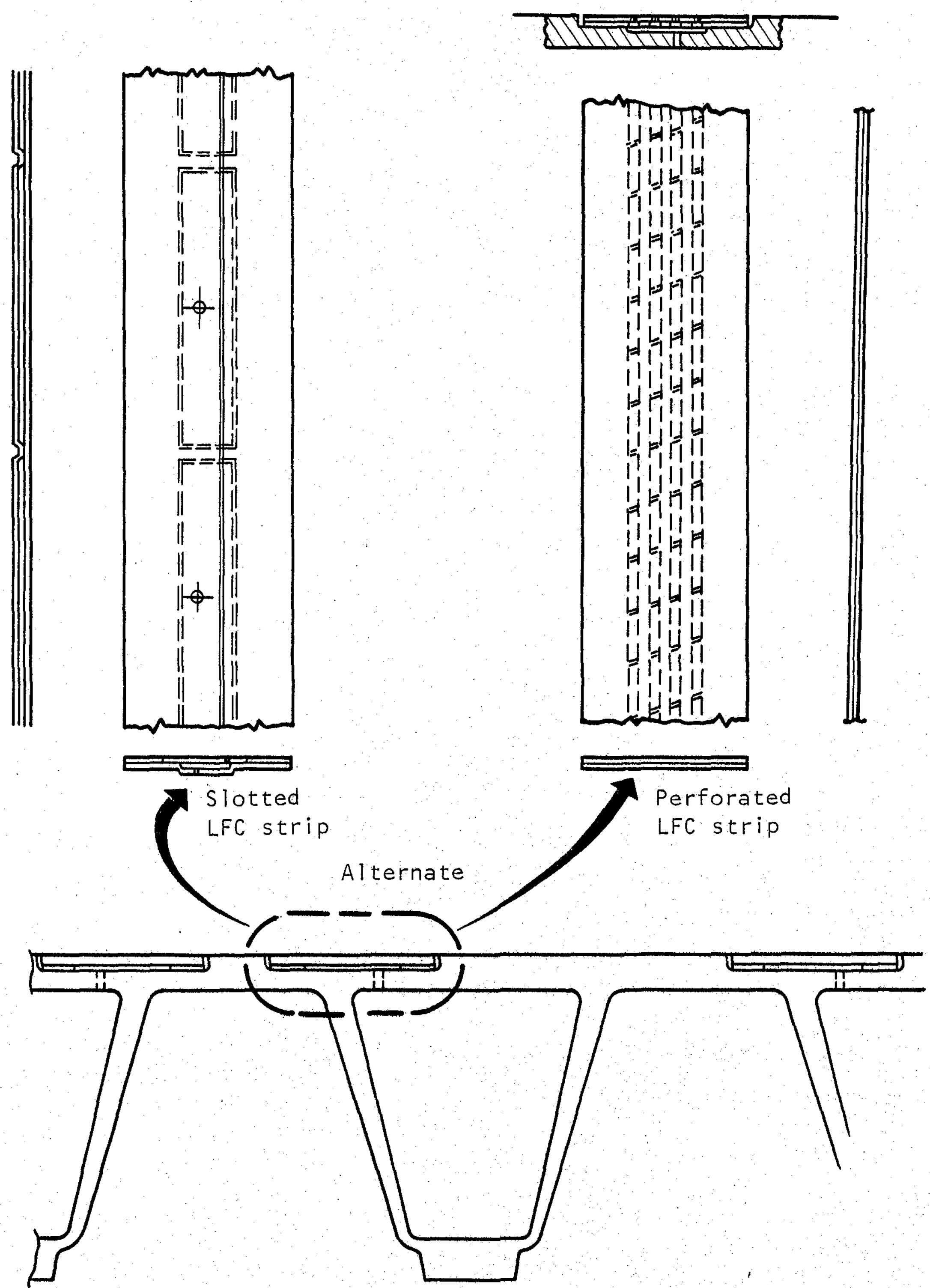


Figure 49.- Separate LFC strips.

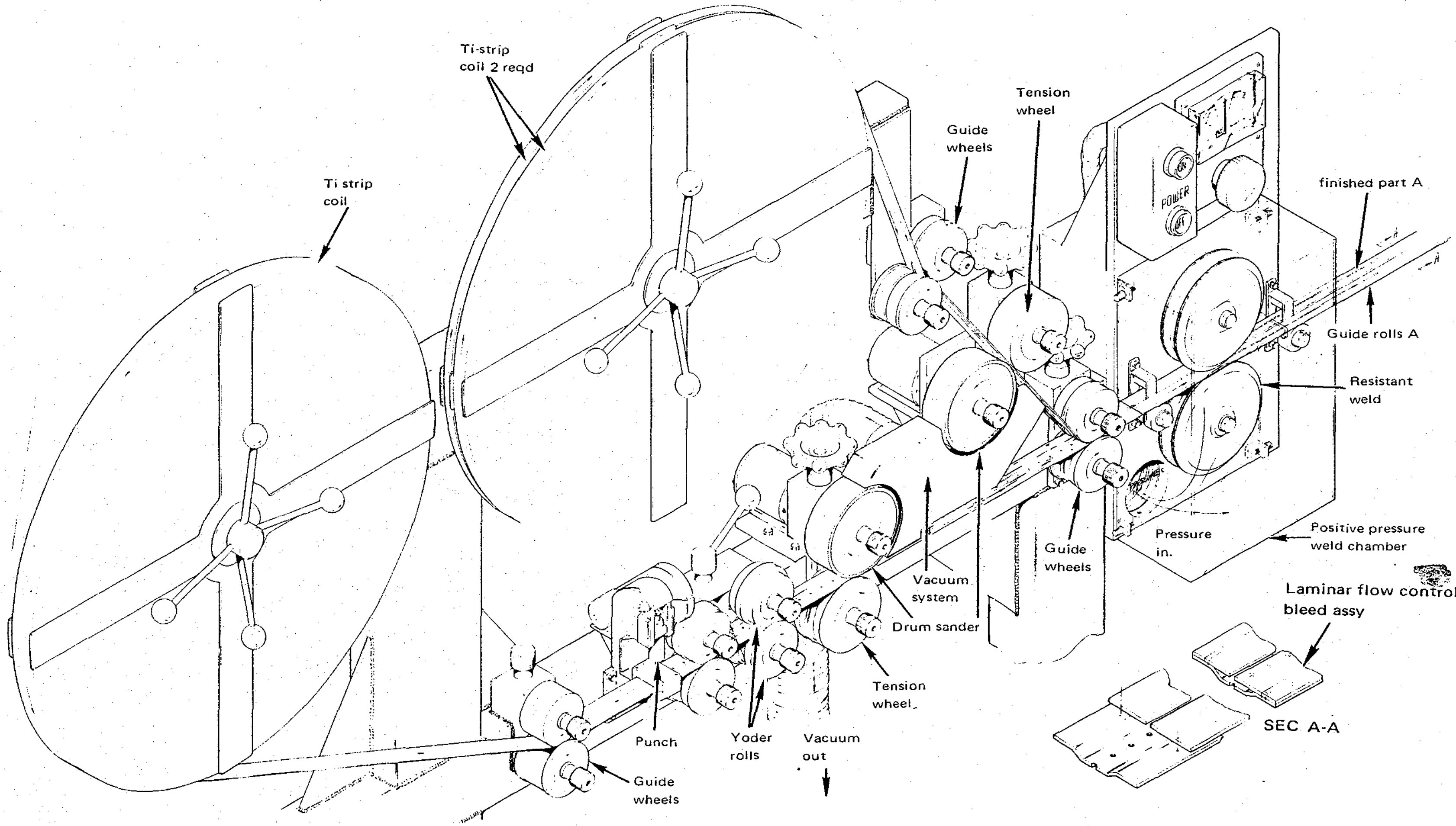


Figure 50. - Production fabrication concept - LFC slotted strip.

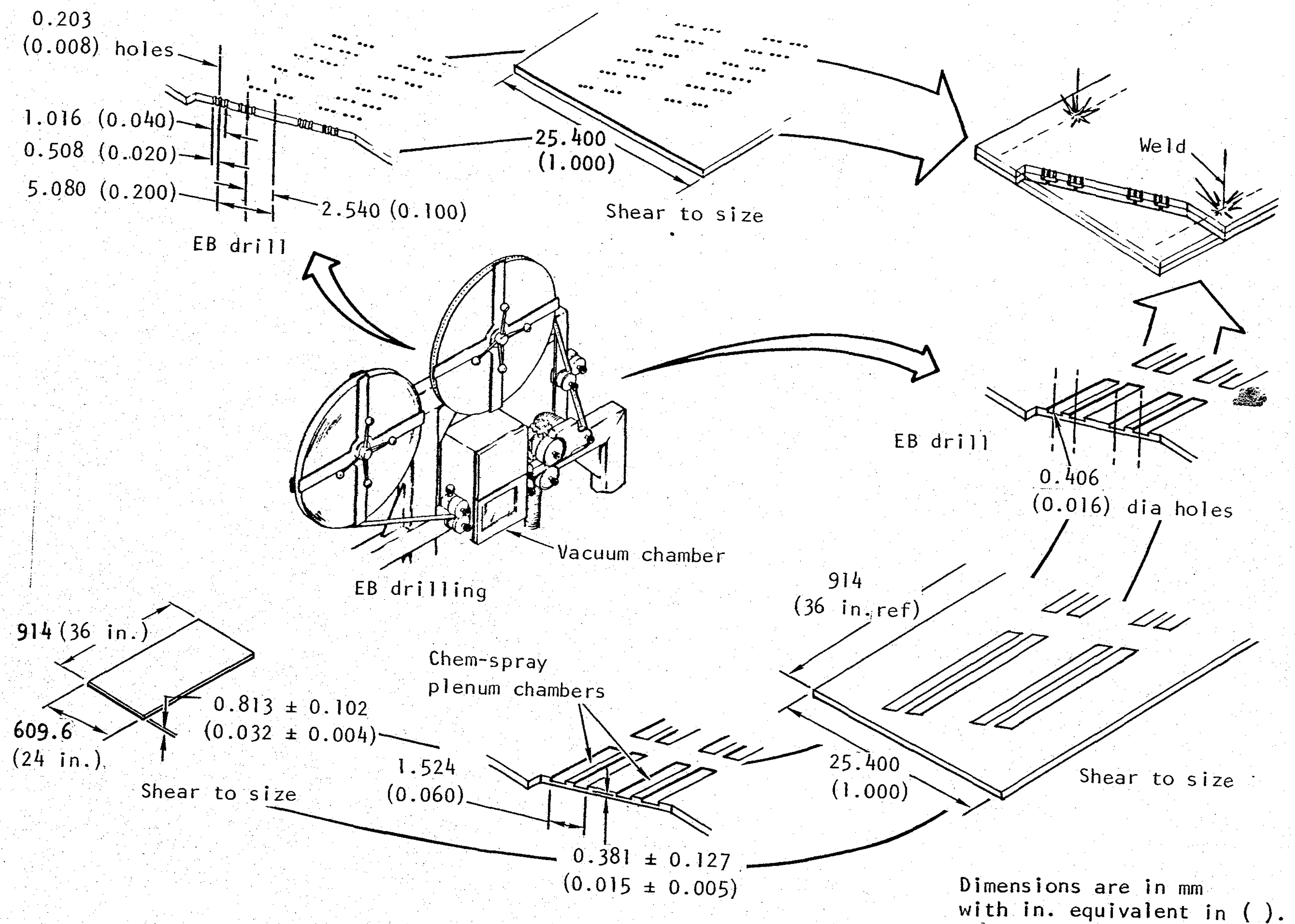


Figure 51. Production fabrication concept - LFC perforated strip.

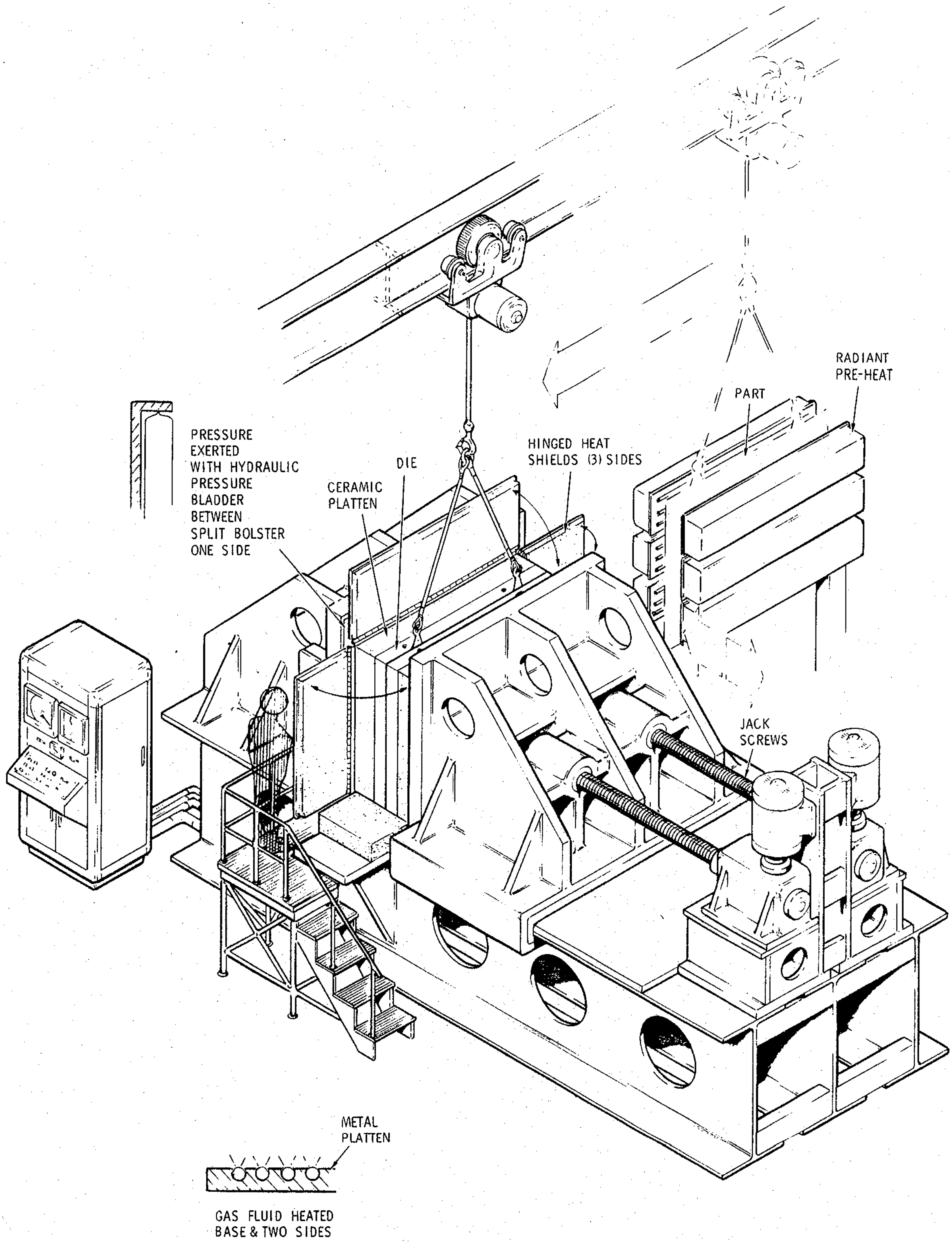


Figure 52. - Production SPF/DB fabrication concept - LFC wing panel.

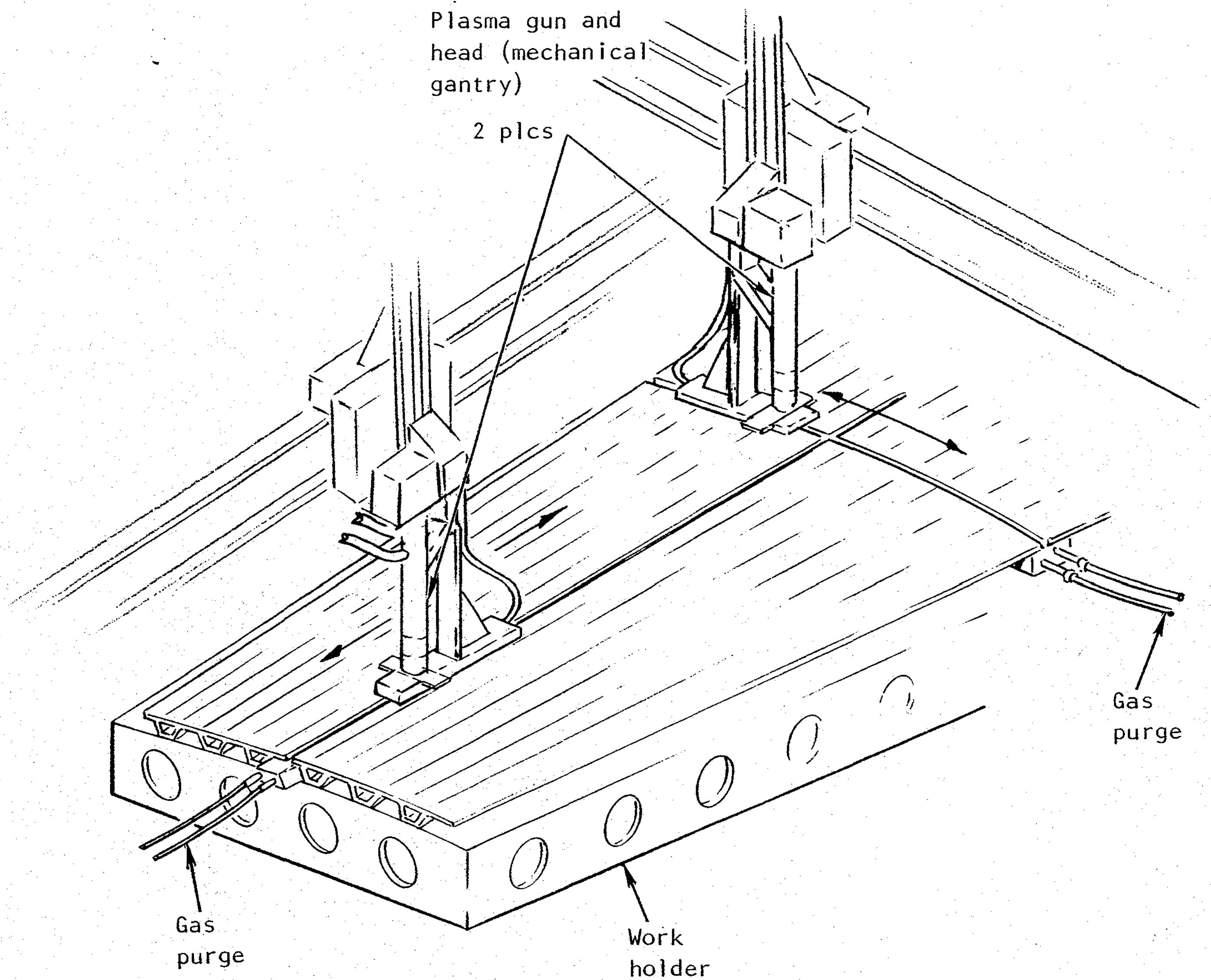


Figure 53. - Wing panel joining concept - plasma-arc welding.

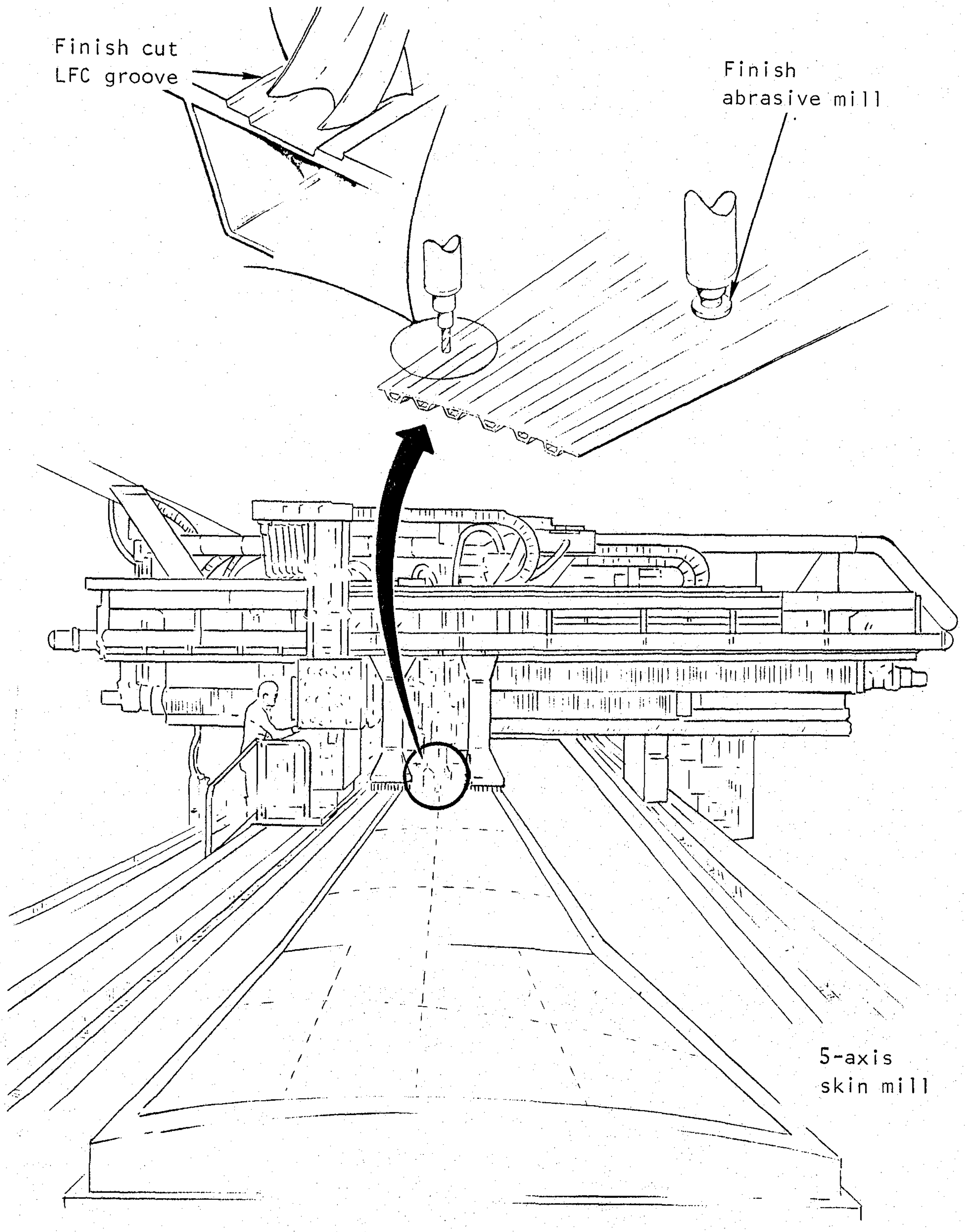


Figure 54. - Wing panel - mold line surface machining.

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16. Abstract

This analytical and conceptual design program was conducted to develop concepts and approaches for applying superplastic forming/diffusion bonding (SPF/DB) technology to the problems of design, fabrication, operation, and maintenance of wings for LFC transport aircraft.

Alternate concepts and design approaches were developed for suction panels and techniques were defined for integrating these panel designs into a complete "LFC 200R Wing." The design concepts and approaches were analyzed to assure that they would meet the strength, stability and internal volume requirements. Cost and weight comparisons of the concepts were also made.

Problems of integrating the concepts into a complete aircraft system were addressed. Developed were: methods for making splices, both chordwise and spanwise; fuel tight joints and internal duct installations. Manufacturing problems such as slot alignment, tapered slot spacing, production methods and repair techniques were addressed.

An assessment of the program, in terms of lessons learned and conclusions reached, was made and used to develop recommendations for additional research in the development of SPF/DB for LFC wing structure.

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