ADVANCES IN JOINING TECHNIQUES USED IN DEVELOPMENT OF SPF/DB TITANIUM SANDWICH REINFORCED WITH METAL MATRICES*

J. E. Fischler
Douglas Aircraft Company
McDonnell Douglas Corporation
Long Beach, CA

ABSTRACT

Three- and four-sheet expanded titanium sandwich sheets have been developed at Douglas Aircraft Company, a division of McDonnell Douglas Corporation, under contract to NASA Langley Research Center. In these contracts, spot welding and roll seam welding were used to join the core sheets. These core sheets were expanded to the face sheets and diffusion bonded to form various type cells.

The advantages of various cell shapes and the design parameters for optimizing the wing and fuselage concepts are discussed versus the complexity of the spot weld pattern.

In addition, metal matrix composites of fibers in an aluminum matrix encapsulated in a titanium sheath were aluminum brazed successfully to the titanium sandwich face sheets. The strength and crack growth rate of the SPF/DB titanium sandwich with and without the metal matrix composites are described.

* The author would like to thank T. T. Bales and D. J. Maglieri, who served as technical monitors at Langley Research Center for their encouragement, support, and suggestions during the long development periods of the structural concepts described in this paper.

In addition, the author would like to thank the Douglas program director, R. D. FitzSimmons; the program manager, W. T. Rowe; those who fabricated the panels, N. R. Williams, M. Hayase, R. J. Walkington, R. C. Ecklund, and K. K. Yasui; those who designed, analyzed, and tested them, A. J. Dodd, R. N. Holmes, H. O. Beltran, P. S. Pavlovsky, R. Berg, E. L. Hayman, and C. C. Christianson; and those who did the material characterization, T. L. Mackay and P. S. Guthorn. Some assistance was also furnished by the Timet Corporation and D.W.A. Composite Specialties, Inc., suppliers of the titanium and metal matrix composite materials.

INTRODUCTION

A superplastic-formed/diffusion-bonded (SPF/DB) titanium sandwich, utilizing a unique method of spot welding core sheets that was developed at Douglas Aircraft Company, creates sandwich structure that can be tailored to the design loads. In this process, after spot welding the core sheets to the most optimum pattern for the loadings, the core is expanded and diffusion bonded to the doubler and face sheets to form a finished sandwich. The result is a very efficient sandwich construction with all the parts bonded by a very strong metal-to-metal diffusion bond. If built in production quantities, the process could provide significant weight and cost savings with proper designs.

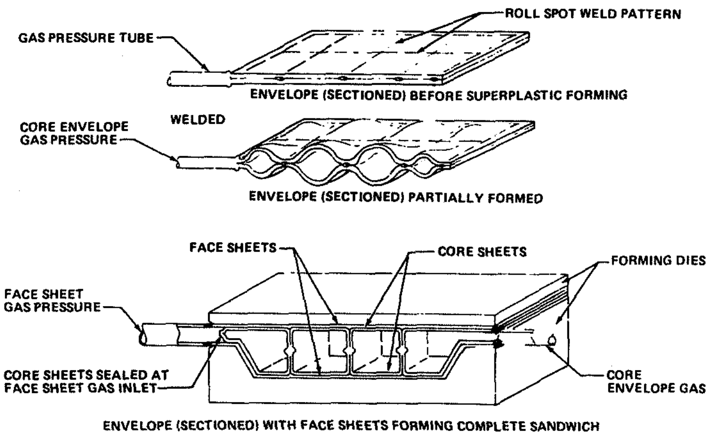
The panels utilized were: a 3- by 5-foot four-sheet SPF/DB titanium sandwich wing panel; a 3- by 3-foot, three-sheet SPF/DB titanium sandwich forward wing panel; an SPF/DB titanium sandwich primary structure wing panel with a DC-10 size access door; and a truss type, hat-stiffened, 3- by 5-foot primary structure fuselage panel, made by using the unique Douglas-developed, three-sheet roll seam welded sandwich concept, as well as smaller panels fabricated by aluminum brazing metal matrix composites to an SPF/DB titanium sandwich.

Static compression tests reveal that the SPF/DB titanium sandwich and the metal matrix composites brazed to the sandwich are structurally very efficient. Also, the SPF/DB titanium sandwich has a lower rate of crack growth starting from surface damage on one side.

Some of the problems of designing ultra-lightweight SPF/DB titanium sandwich are described briefly and some solutions presented in the following text.

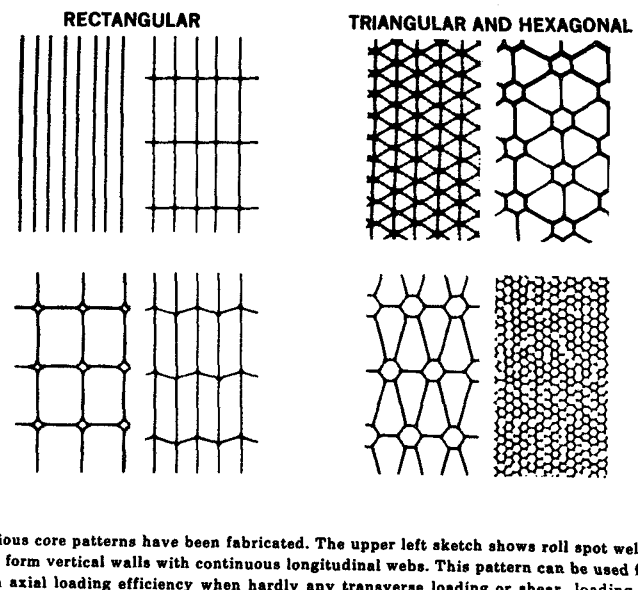
SPF/DB PHASES OF FABRICATION

FOUR-SHEET SANDWICH



The SPF/DB titanium sandwich developed at Douglas Aircraft Company is shown above. The top sketch illustrates the spot weld pattern made by the designer to meet the load requirements. These two core sheets, when partially formed from core envelope gas pressure, are shown in the middle sketch. Additional core pressure forces the pillow shape into vertical walls, and the core top and bottom surfaces are diffusion bonded to the outer face sheets. A very efficient titanium sandwich is formed in one operation.

CORE PATTERNS



Various core patterns have been fabricated. The upper left sketch shows roll spot welds that form vertical walls with continuous longitudinal webs. This pattern can be used for high axial loading efficiency when hardly any transverse loading or shear loading is present. The upper left-right pattern is used for typical aircraft structure when some transverse loading and/or shear loading is present. The upper right-left pattern is desirable when thin sheet shear buckling and axial loading are present. The upper right-right pattern is when higher axial loading, pressure loading (bending), and shear loading are present. The vertexes of the triangles are spot welded to form hexagonal shapes. These walls prevent thinning at the vertexes. The bottom left-left pattern has a diamond wall at the vertexes of the rectangular pattern for higher strength (by reducing thinning). The bottom left-right staggered transverse pattern was used to reduce the fatigue stress concentration factor. The bottom right-left pattern was developed to sustain high axial loads with high shear loadings. The bottom right-right pattern is an SPF/DB substitute for honeycomb sandwich.

FABRICATION COMPLEXITY

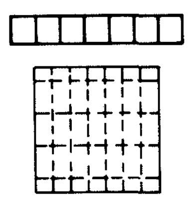
CORE TYPE	WELDING	PRESSURE CYCLE
STRAIGHT WEBS	1	1
RECTANGLES	2	2
TRIANGLES	3	8
INTERRUPTED RECTANGLES	8	6
ISOGRID	10	6
COLUMNS 1.27-CM (1/2-INCH) SPACING AND GREATER	4	1
1.90-CM (3/4-INCH) HEXAGONS	8	4
0.79-CM (5/16-INCH) HEXAGONS	10	5
SINE WAVE WEBS	10	2
STRAIGHT WEBS AND COLUMNS	2	3

- COMPLEXITY RATED ON 1-TO-10 SCALE

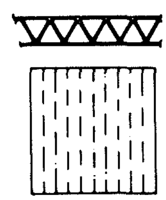
The complexity of fabricating various core patterns (which influences the cost) is based on the core type. The welding complexity is based on automated spot weld equipment that can easily go in straight lines but cannot be programmed for triangles, isogrid, and sine wave webs. These shapes must be scribed by hand. Future capital equipment could be programmed to automate the shapes. However, this would not be done unless a production quantity is desired.

CANDIDATE WING CONCEPTS

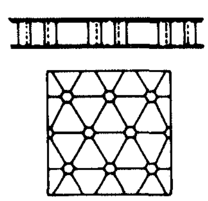
SPF/DB SANDWICH



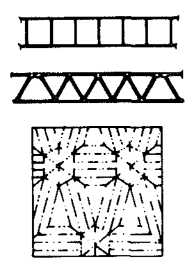
RECTANGLE CORE



SINGLE-TRUSS CORE



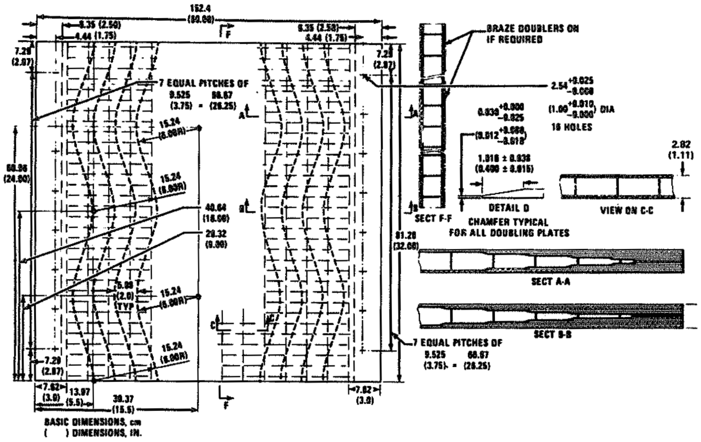
ISOGRID CORE



COMBINED CORE

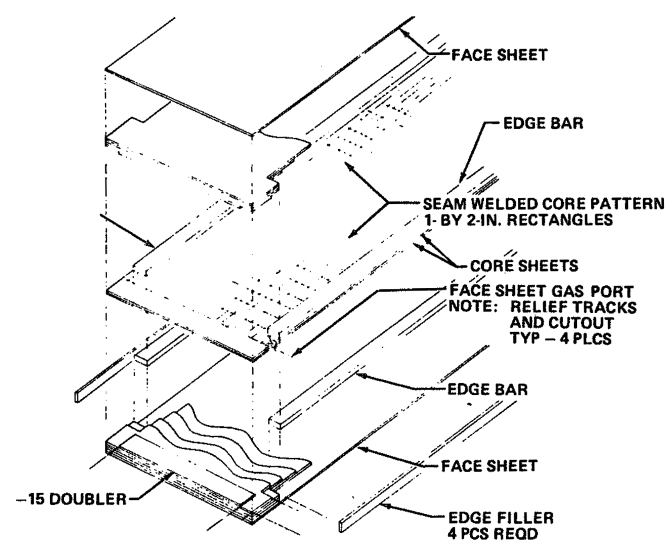
The candidate core patterns for the primary wing of a supersonic transport are shown. Only one pattern can be selected. Analysis indicates that the upper left rectangular core will be the best compromise for weight and cost.

FATIGUE PANEL RECTANGULAR CORE SANDWICH



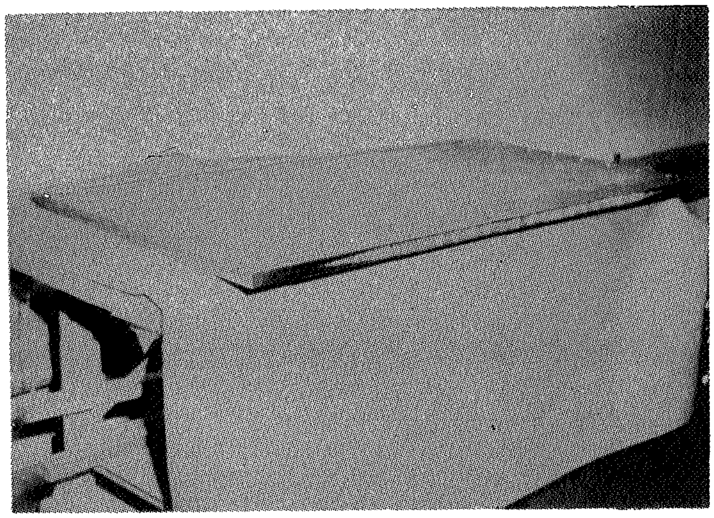
The wing fatigue panel design is shown. Sheets of titanium, chamfered to avoid stress risers, are placed over the two rectangular spot welded core sheets and formed in one "blow" to the panel final shape.

3- BY 5-FOOT WING TEST PANEL
LAY-UP DETAIL



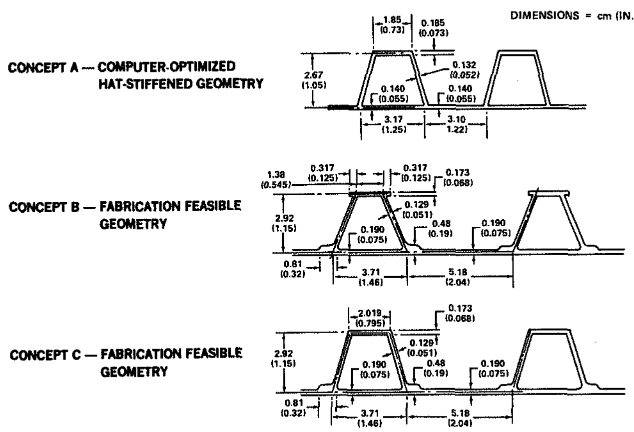
The lay-up details of the wing panel are shown. The edge bars are compressed and provide the side restraint to prevent the core sheets from pulling out when the core sheet forming pressure is applied.

3- BY 5-FOOT WING PANEL PRIOR TO TESTING



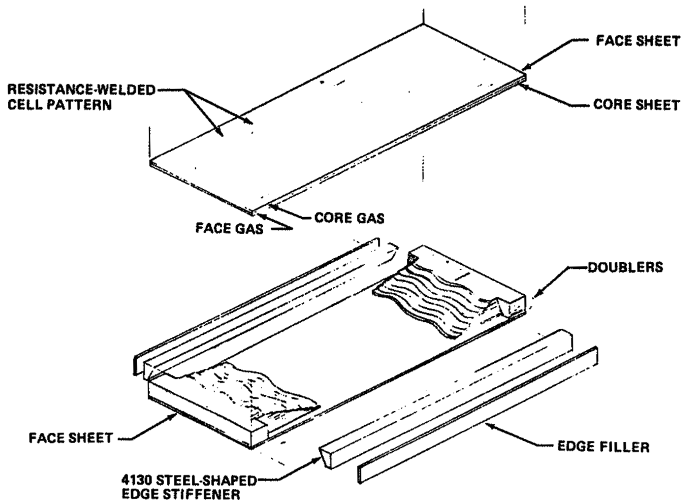
The wing fatigue panel is machine finished and prepared for testing.

HAT-STIFFENED GEOMETRY



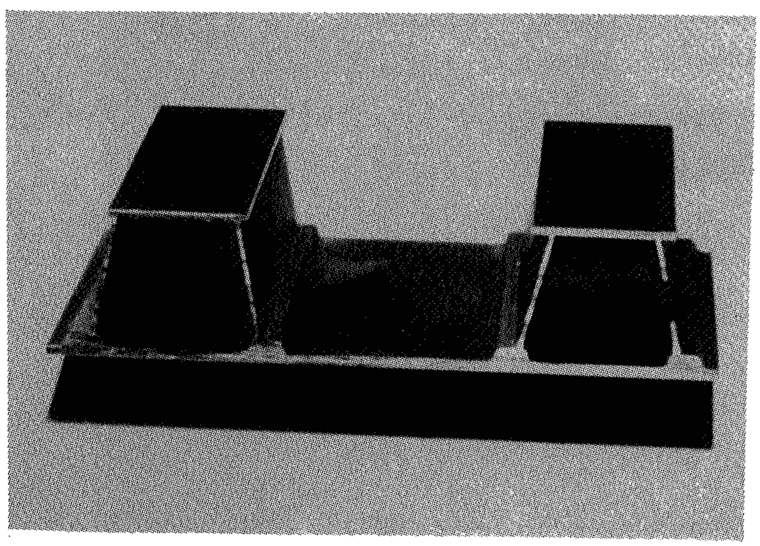
The hat-stiffened geometry desired for the fuselage was obtained by a computer-optimized program. The results are shown in Concept A. Using a three-sheet process developed at Douglas Aircraft Company, Concept B can be fabricated by roll seam welding two sheets together (at the 0.19-inch dimension), then blowing one sheet to form the web and upper skin and caps. The sheet between the caps is cut off, leaving a stringer with a high moment of inertia. Concept C was also considered if the cutouts of Concept B could not be fabricated. Available forming pressure and restraint fixture strength influenced the fabrication of feasible geometry.

3- BY 5-FOOT FUSELAGE PANEL
ASSEMBLY SCHEMATIC



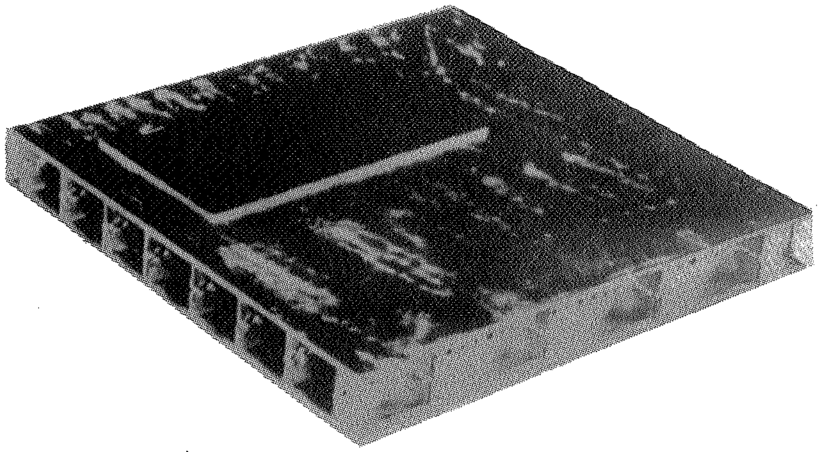
The assembly schematic for the fuselage panel is shown. The core sheet is blown down to the doublers to form the hat-stiffened pattern. The difference in pressure between the alternate small and large cells results in the required truss angle.

EDGEWISE COMPRESSION (1.4) SPECIMEN NY DIRECTION



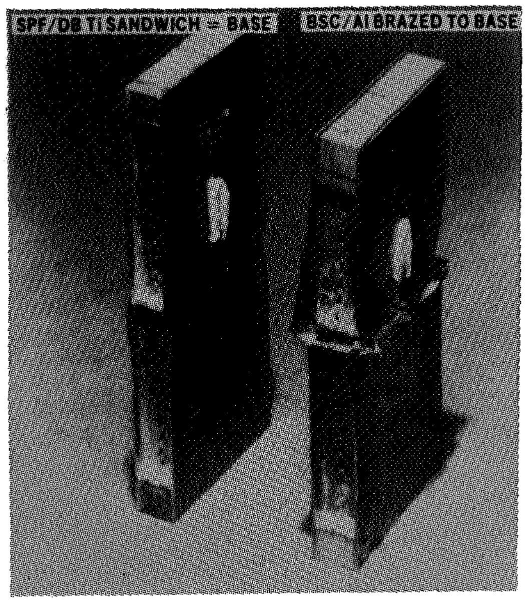
A small section of the completed panel for the "three-sheet" fuselage is shown. The high structural efficiency in compression of this specimen has been verified in test.

SPF/DB EXPANDED SANDWICH WITH BRAZED METAL MATRIX COMPOSITE



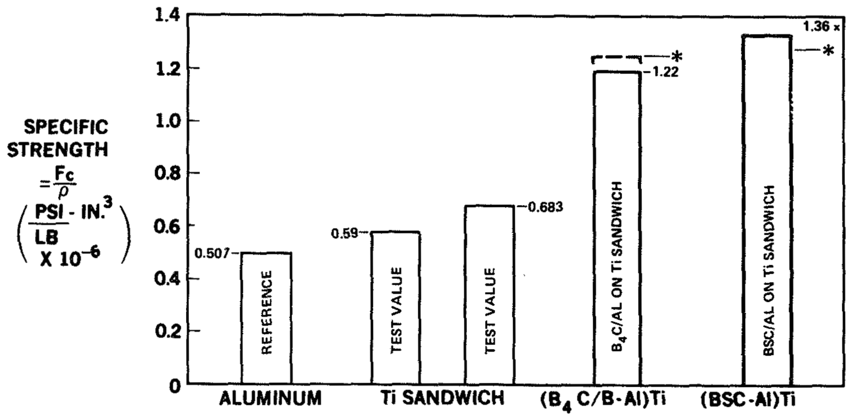
A titanium SPF/DB sandwich is shown as the base sandwich with an aluminum metal matrix brazed to it. The brazed panel was excised with a similar sized small compression panel shown in the next figure.

EDGEWISE COMPRESSION TEST SPECIMENS



The base SPF/DB titanium sandwich is shown on the left. The similar sized panel with the metal matrix composite brazed to it is shown on the right. The local buckling mode of failure is shown on the left. The metal matrix panel has approximately the same shape. However, the failure occurs at a higher load. The failure could be from bending of fibers or web shear, or failure of the braze, or any combination of these.

SPF/DB TITANIUM SANDWICH AND MMC TEST RESULTS

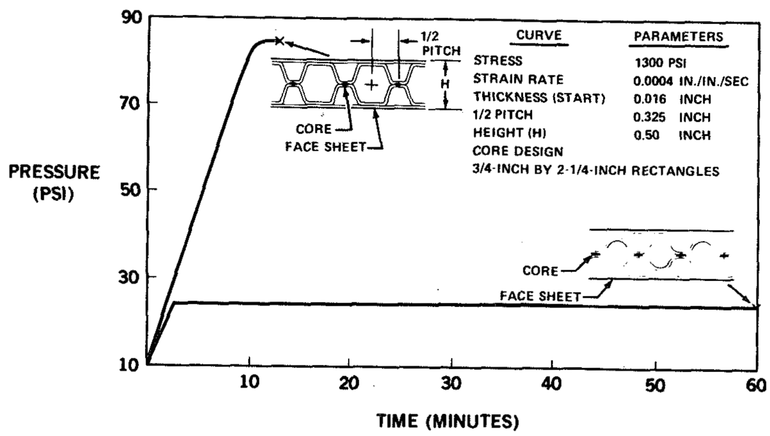


*ASSUMING NO BRAZE FAILURE AT ROOM TEMPERATURE (ROM)

A comparison of the critical short column compression stress divided by density is shown for sandwich structures at room temperature. Adding the metal matrix continuous fibers in an aluminum matrix significantly increases the specific strength.

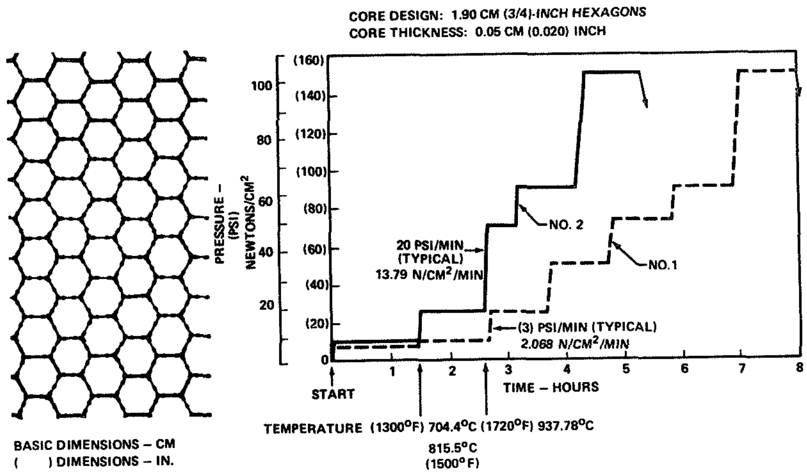
SUPERPLASTIC FORMING PROGRESS; CALCULATED CURVE VERSUS CONSTANT PRESSURE

(U.S. UNITS)



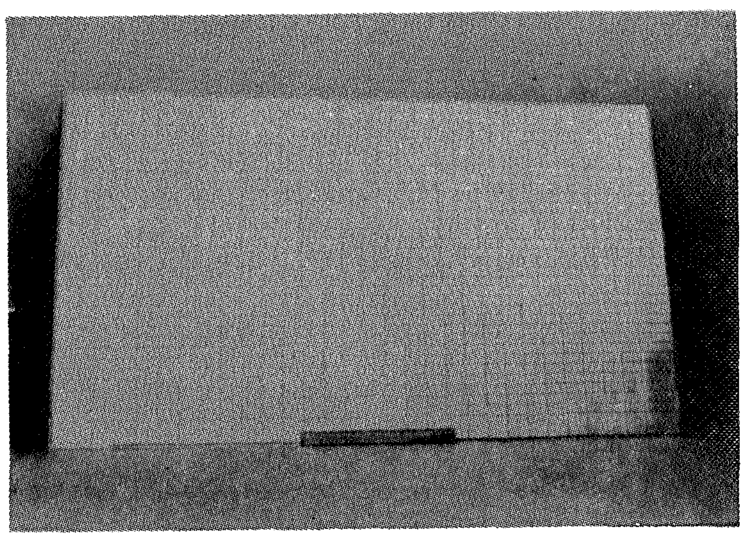
With the spot weld spacing and geometry as shown, a desirable constant strain rate can be achieved with the pressure as shown and the calculated result produces cells that have reached the face sheets after a short time. Then, the pressure can be increased to form the rectangular corners. The lower curve shows that the reduced pressure will not form the rectangular cells, even after a long time.

REDUCED CYCLE TIME INNOVATIONS



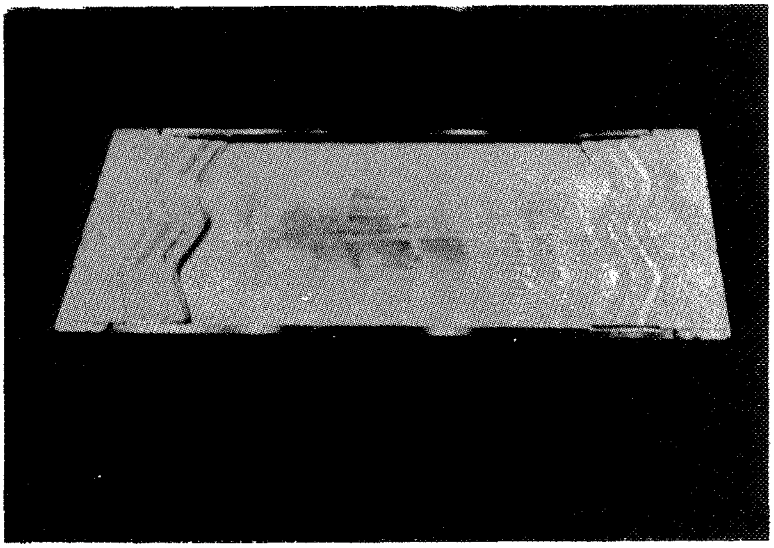
Hexagonal cells have been created for the SPF/DB sandwich using the pattern on the left. Early forming at 1,300°F with higher pressure is one way to reduce the cycle time. Too much pressure at low temperatures could cause thinning and failure. Computer programs were created to prevent this.

WELDED CORE ASSEMBLY FOR 3- BY 5-FOOT WING PANEL



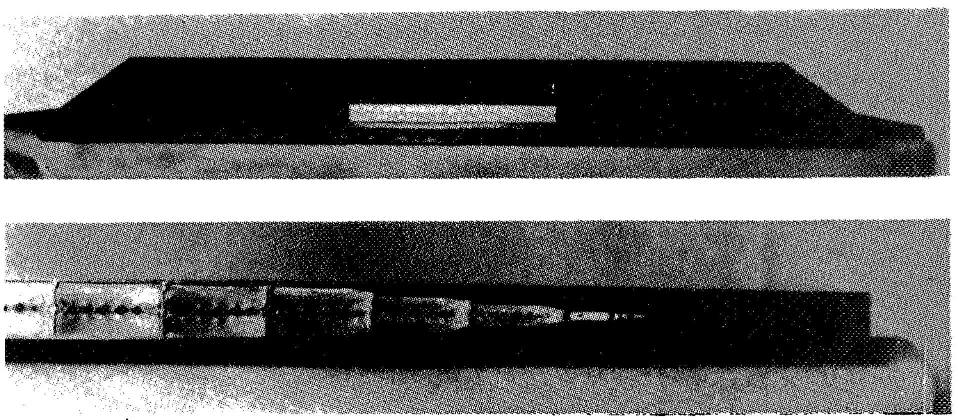
The spot weld pattern for the core sheets for 1- by 2-inch cells is shown for a 3- by 5-foot wing panel.

FACE SHEET AND DOUBLER ARRANGEMENT — WING



The internal end machined doublers (for one side) are shown.

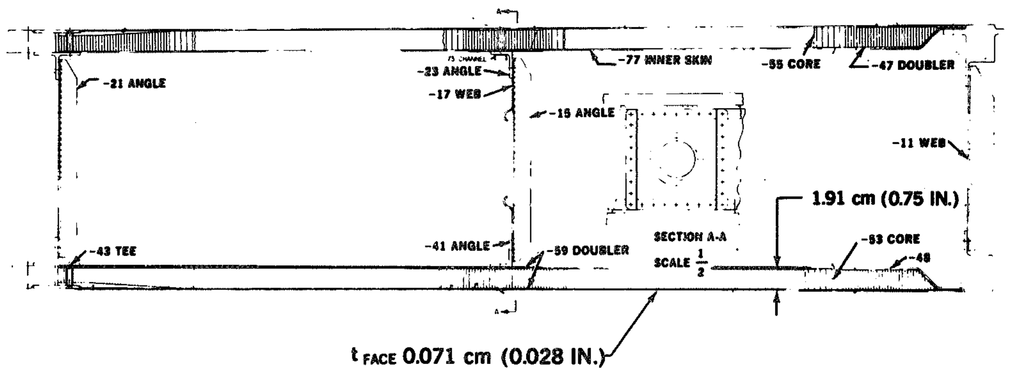
3- BY 5-FOOT WING PANEL AFTER MACHINING



The edge view of the SPF/DB panel shows the final machined doublers, all from initial flat sheets, which have been formed in one blow. This is how the SPF/DB process holds the fabrication costs down.

-1 BOX ASSEMBLY — Al BRAZED Ti HONEYCOMB

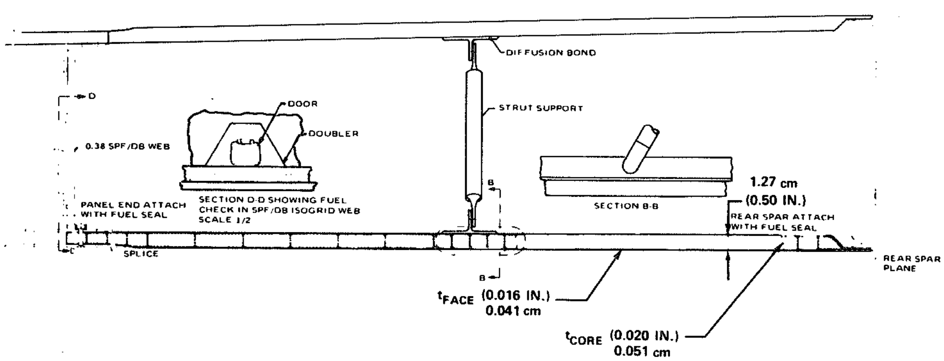
WING BASE CONFIGURATION



An aluminum brazed titanium honeycomb wing panel box is shown as the "base" conventional structure. It should be noted that fabrication must include the machining of the end doublers, the machined end densified core, the many fasteners, and the brazing of the sandwich panel.

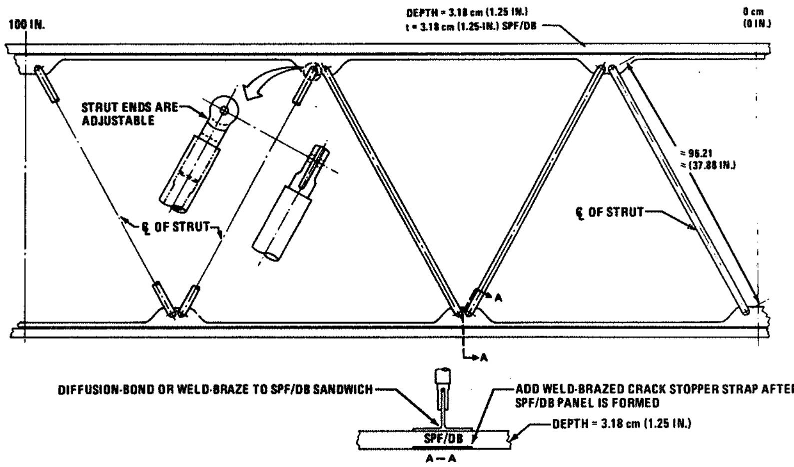
-501 BOX ASSEMBLY — SPF/DB SANDWICH Ti CONCEPTS

RECTANGULAR CELL WITH FUEL CELL ACCOMMODATIONS



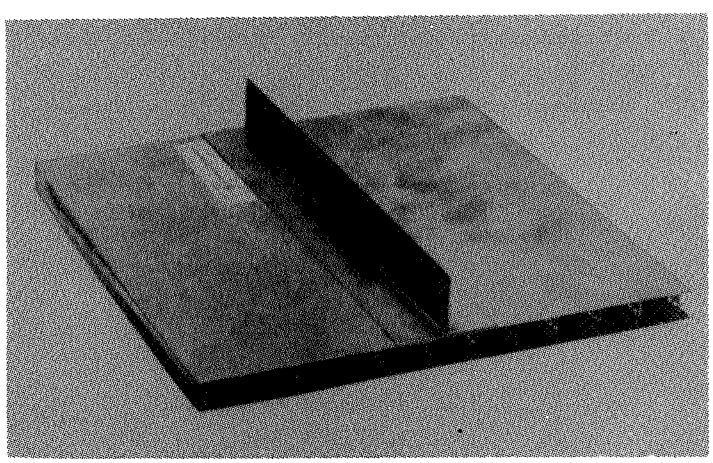
The SPF/DB sandwich box is shown. End doublers are incorporated in the wing panels. A tee spar cap is diffusion bonded to the wing panels and strut tubes are used for the intermediate spar. The major spars are of isogrid SPF/DB sandwich construction, as shown in Section D-D.

WING SPAR — TUBE STRUTS ATTACHED TO TEE SPAR CAP AND SPF/DB COVER PANELS



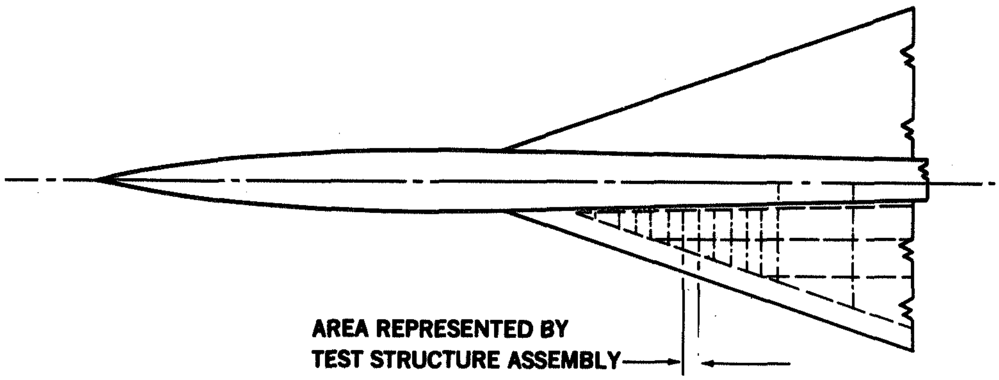
The intermediate spar details are shown. The strut end fittings are adjustable for quick installation of the struts at the holes in the spar cap tees.

SPF/DB SANDWICH PANEL WITH INTEGRAL DOUBLERS AND ATTACHED TEE



This panel with the tee spar cap was fabricated in one "blow." The tee was set in the die on the face sheet and when all parts were heated, the core sheets were blown to the face sheets and pressure was applied at SPF temperatures to diffusion bond all the parts.

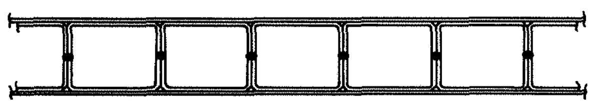
FORWARD WING STRUCTURE



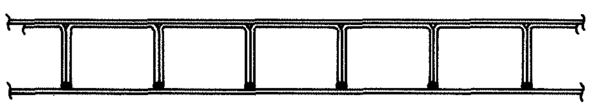
The forward wing structure of a supersonic transport wing has lightly loaded structure. Minimum-weight panels can be formed in this area using the SPF/DB titanium sandwich process.

WING PANEL DETAIL

OPTIMUM GAUGES FOR MINIMUM WEIGHT



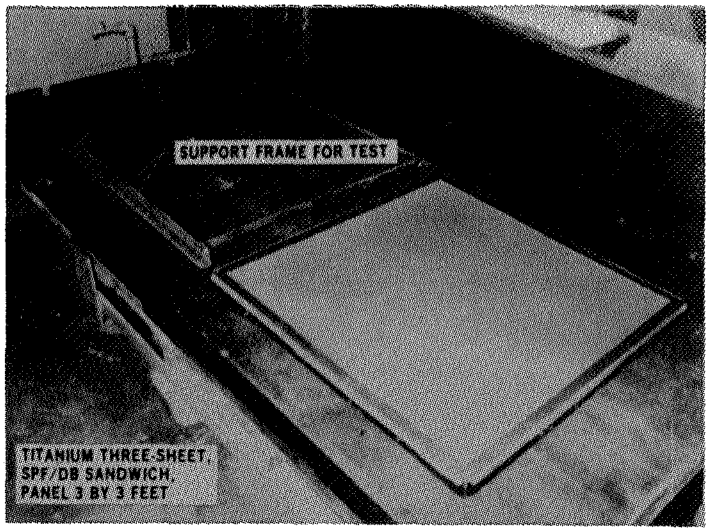
4-SHEET CONSTRUCTION
2 FACE SHEETS OF 0.016
2 CORE SHEETS OF 0.008



3-SHEET CONSTRUCTION
1 TOP FACE SHEET OF 0.013
1 BOTTOM FACE SHEET OF 0.016
1 CORE SHEET OF 0.008

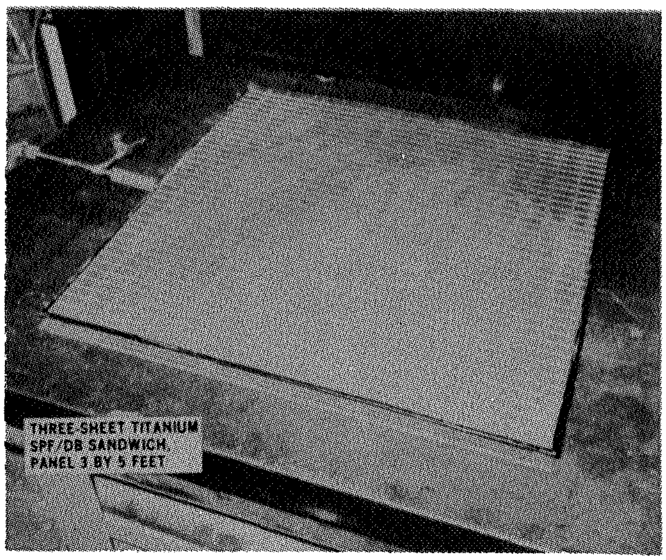
To obtain minimum wing panel weight, a four-sheet construction and a three-sheet construction were considered. The three-sheet construction was chosen since it is lighter in weight when the available minimum core gage is the critical parameter.

OUTER SKIN SIDE, FORWARD WING



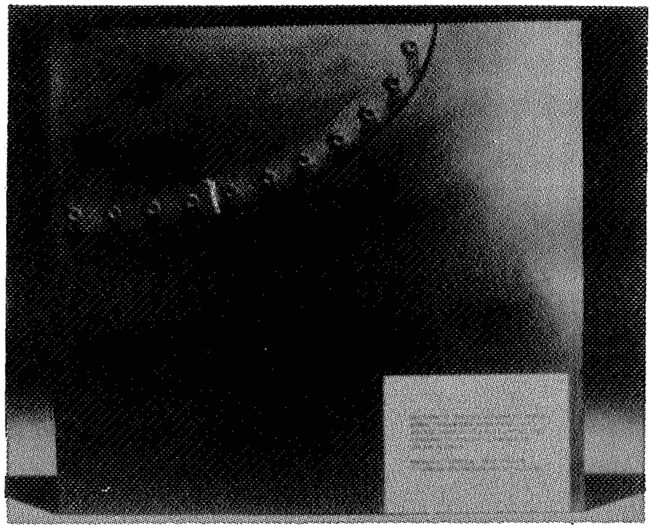
A three-sheet SPF/DB titanium sandwich was fabricated for the forward wing. The *smooth side that faces the* outer skin is shown on the bottom right. The upper left is a frame for testing the panel.

INNER SKIN SIDE, FORWARD WING



The inner skin side shows the spot welds of the single core sheet to the inner face sheet. Sufficient compression buckling of these panels is available so the slight amount of "eyebrowing" is not objectionable.

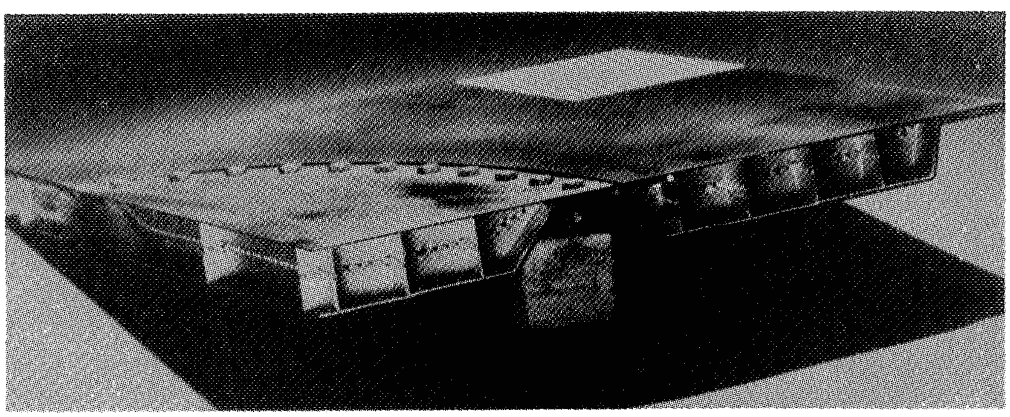
SECTION OF SPF/DB Ti SANDWICH WING ACCESS PANEL



One-fourth of a 3- by 3-foot panel with a DC-10 size access door is shown after being compression tested to the design ultimate axial loading of 204,000 pounds. This panel is a typical supersonic primary wing structure.

SECTION OF WING TEST PANEL WITH ACCESS DOOR

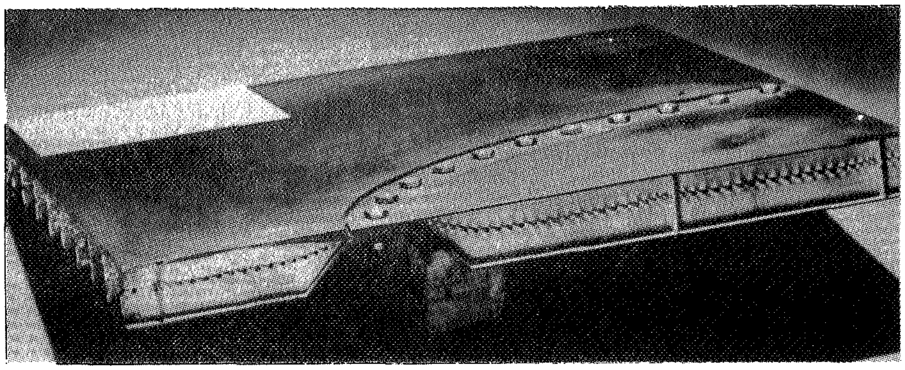
SPF/DB TITANIUM SANDWICH AFTER ULTIMATE LOADING VIEW SHOWING AXIAL LOADED CELLS



The view in this picture shows the more closely spaced axial loaded cells after testing to ultimate load.

SECTION OF WING TEST PANEL WITH ACCESS DOOR

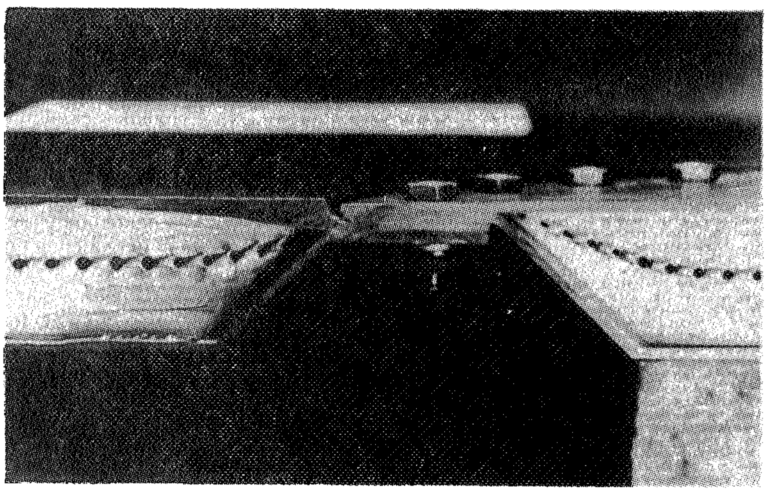
SPF/DB TITANIUM SANDWICH AFTER ULTIMATE LOAD VIEW SHOWING TRANSVERSE LOADED CELLS



This view shows the more lightly loaded transverse cells in the wing test panel with the access door. The panel was tested only in the axial direction to ultimate loading. To reduce the cost, no countersunk holes or countersunk bolts were used. However, multilayer sheets were diffusion bonded to provide sufficient thickness for a countersink.

SECTION OF WING TEST PANEL WITH ACCESS DOOR

SPF/DB TITANIUM SANDWICH AFTER ULTIMATE LOADING LOAD CARRY-THROUGH DETAILS



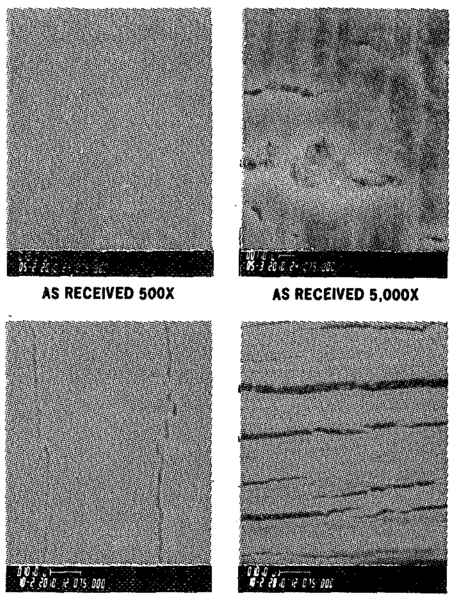
A close-up is shown of the joint between the wing panel and access door. The two core sheets are "blown" to the many layers of doublers necessary for load carry-through.

ULTRALIGHT SANDWICH

PROBLEM	SOLUTION
NONUNIFORM MATERIAL THICKNESS	SELECTED CORE STOCK WITH MATCHING GAGE AND UNIFORM THICKNESS
TEMPERATURE NONUNIFORMITY	REVISED HEATER DESIGN TO MINIMIZE EDGE EFFECT OF TEMPERATURE
CORE DEPTH AND CELL CONFIGURATION	DEVELOPED TIME, TEMPERATURE, AND PRESSURE CYCLES TO ACCOMMODATE CONFIGURATION
LEAKS • EXCESSIVE STRAIN/STRAIN RATE BRITTLENESS	EXPERIMENTED WITH CYCLE AND MINIMUM GAGE
POOR FLOW-THROUGH CLEAVAGE	ELIMINATED LEAKS
SURFACE CONTAMINATION	SELECTED CONTAMINATION-FREE STOCK
POOR AVAILABILITY OF PROPER MATERIAL SIZE — WIDTH AND GAGE	MILL PROBLEM — WILL IMPROVE WITH INCREASED USAGE

The problems associated with designing and fabricating ultralight sandwich SPF/DB titanium structures are listed. Also, on the right, some possible solutions are suggested.

SURFACE CONDITION OF 8-MIL FOIL

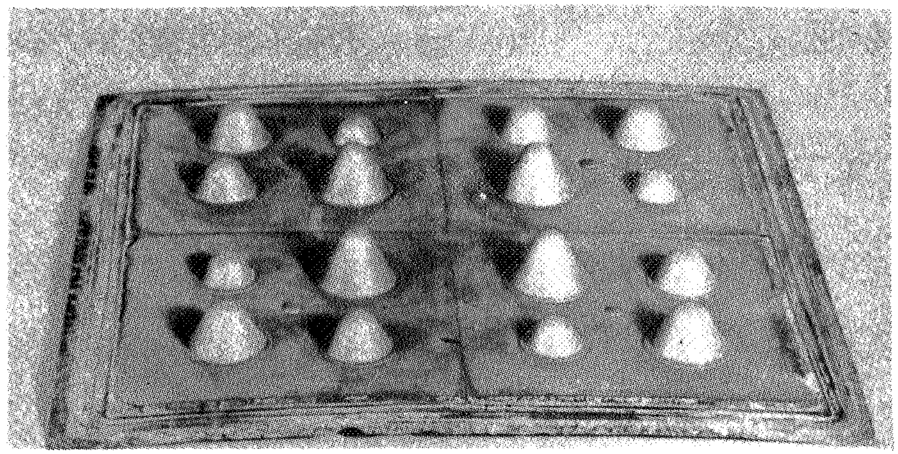


AS RECEIVED 500X — AS RECEIVED 5,000X

AS RECEIVED (BENT) 1,000X — AS RECEIVED (BENT) 1,000X

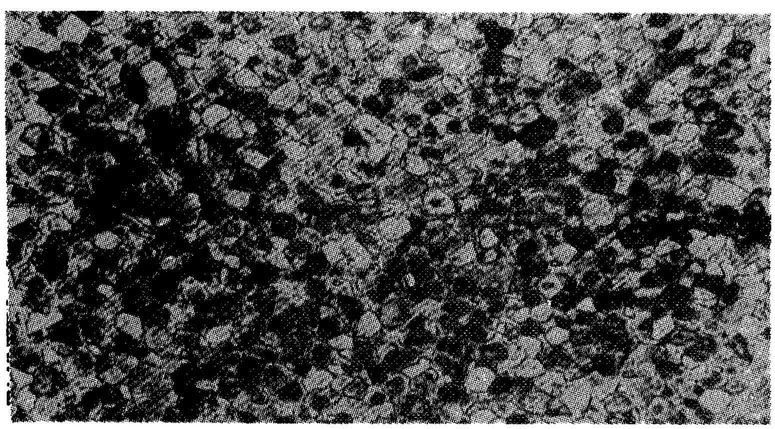
The poor nonuniform condition of 8-mil foil that was considered for ultra-lightweight SPF/DB sandwich panels is shown above. Notice that at 1,000X and 5,000X magnification, the material is not very uniform. Eight-mil foil is made by rolling heavier thicknesses down. The cost and material condition could be carefully controlled if large amounts are needed.

8-MIL CONE TESTS



Cone tests on 8-mil foil show how severely the thickness and material properties vary when superplastically formed. Core thicknesses were increased to prevent failure due to excessive thinning.

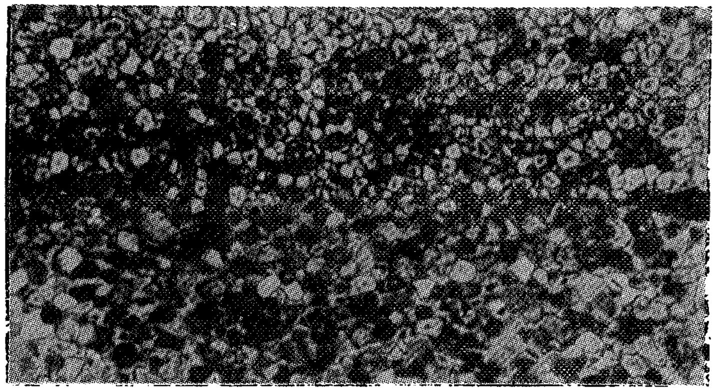
DIFFUSION BOND AT EDGE OF CLEAVAGE CORE TO CORE



NEG LW-240 MAGNIFIED 300X

The core-to-core diffusion bonding looks excellent. At the right center is the edge of the cleavage. It is difficult to distinguish the original boundary of the thicknesses to the left of the cleavage.

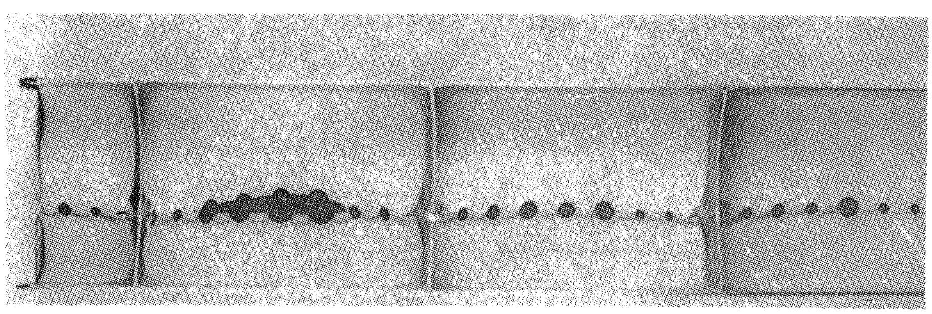
DIFFUSION BOND AT EDGE OF CLEAVAGE
CORE-TO-FACE SHEET



NEG LW-239 MAGNIFIED 300X

The core-to-face sheet diffusion bonding is good, but not as good as the core-to-core bonding. The difference shown in grain size is due primarily to the larger elongation of the core compared to the face sheet and some temperature differences. However, to the left of the cleavage, the grains seem to intermingle and it is difficult to distinguish the boundary of the original thicknesses.

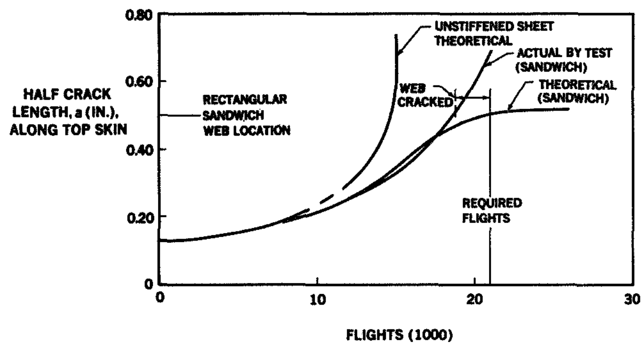
CORE FAILURE DUE TO EXCESSIVE STRAIN RATE



Excessive strain/strain rate brittleness can occur to cause the core failure shown. The best pressure-temperature-time cycle, with the poor surface conditions and nonuniform material thicknesses for minimum gage material, may still result in core failure.

SPF/DB RECTANGULAR CORE SANDWICH PANEL

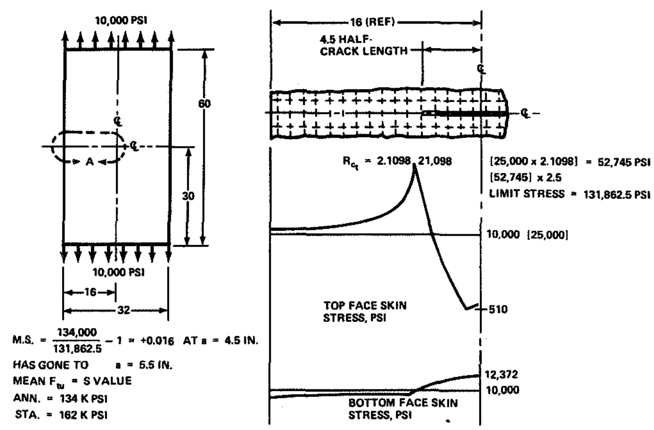
THEORETICAL AND ACTUAL



The unstiffened sheet panels and SPF/DB rectangular core sandwich panels were analyzed starting from an 0.125-inch half-crack length elox slot.* The theoretical SPF/DB sandwich, starting from an elox slot on one side, can sustain one lifetime of 21,100 flights. The unstiffened sheet panel cannot sustain one lifetime starting from an initial elox slot. Verification has been attained by test. It should be noted that a web crack occurred in the SPF/DB titanium sandwich before one lifetime of testing. This was found using a fiber optic probe on a 3-1/2-inch-wide allowables crack propagation specimen. The probe was inserted through the gas holes from the side of the specimens.

*Elox is an electronic discharge that creates a slot.

THEORETICAL MARGIN OF SAFETY USING FINITE-ELEMENT ANALYSIS AND R_{C_t} FOR SPF/DB TITANIUM SANDWICH



A finite-element model of a 32-inch-wide SPF/DB titanium sandwich panel was analyzed to determine the theoretical R_{c_t} value to expect with a half-crack length of 4.5 inches (on one side). The analysis showed a value of 2.1098. Applying this, using the mean value of the ultimate strength in MIL-HDBK-5, a margin of safety of 1.6 percent is available at limit stress (assuming the 6Al-4V annealed properties). The actual panel went to a half-crack length of a = 5.5 inches and sustained limit stress.

R_{c_t} DERIVED FROM TEST

$$R_{c_t} = \frac{\text{CRACK TIP STRESS IN UNSTIFFENED PANEL}}{\text{CRACK TIP STRESS IN STIFFENED PANEL}}$$

MEASURED a_c = 5.5 INCHES AFTER LIMIT LOAD WAS APPLIED

MEASURED DATA, K_c = 130,000 PSI $\sqrt{\text{IN.}}$

σ_R = GROSS LIMIT STRESS APPLIED
= 62,500 PSI (2.5 x 25,000 PSI)

THEREFORE, FROM EQUATIONS ON PREVIOUS SLIDE:

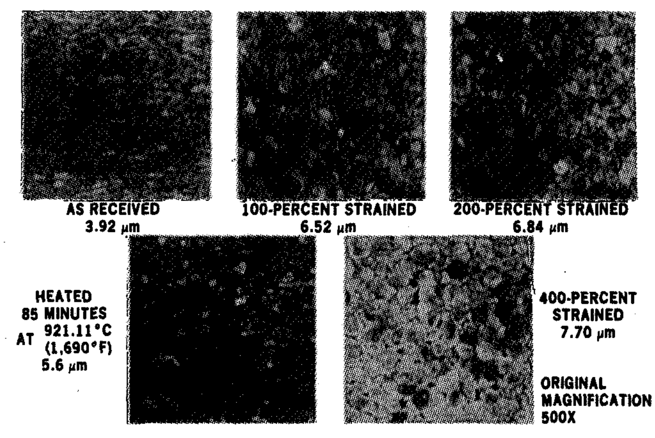
$$R_{c_t} = \frac{\sigma_R}{K_c}\sqrt{\pi a_c}$$

$$R_{c_t} = \frac{62{,}500}{130{,}000}\sqrt{\pi \times 5.5}$$

$$R_{c_t} = 1.998 \approx 2.0$$

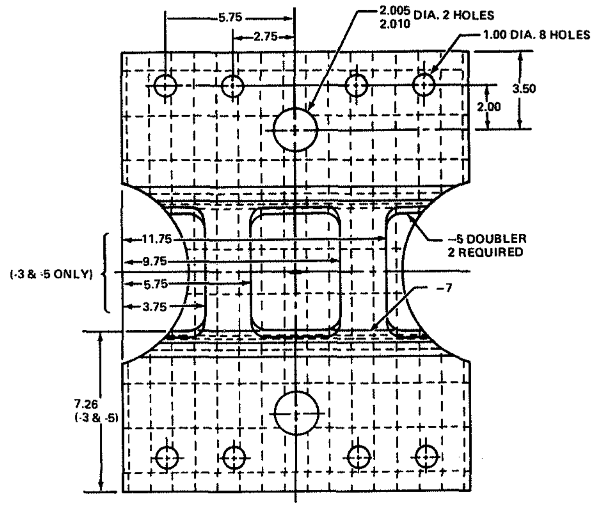
The R_{c_t} derived from the test of the SPF/DB titanium wing panel with a half-crack length of 5.5 inches at limit gross stress of 62,500 psi (using a 1g stress of 25,000 psi), indicated that the R_{c_t} value is 1.998 ≈ 2.0. Therefore, from theory (previous figure) or from test, the SPF/DB sandwich reduces the crack tip stress of an unstiffened panel by a factor of approximately 2.0.

EFFECT OF THERMAL PROCESSING ON GRAIN SIZE OF Ti-6Al-4V 0.127 cm (0.050 IN.)



The grain sizes increase with higher percent elongation during the SPF pressure-temperature-time cycle. At 400 percent strained, the grain size has almost doubled. The effect of the heating and time (no elongation) accounts for approximately 48 percent of the increase in grain size (compared to the 400-percent strained specimen). The increase in grain size, which occurs in superplastic forming, does deteriorate the strength. However, if the designer minimizes the elongations, and diffusion bonds to create a sandwich, the damage tolerance and rate of crack growth are superior for the sandwich SPF/DB panel (compared to an unstiffened sheet or a sheet-stringer).

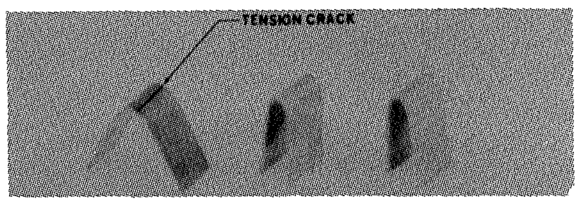
SPF/DB TITANIUM SANDWICH WITH MMC CRACK STOPPERS AND EXTERNAL DOUBLERS AI BRAZED



The above sketch is a crack propagation panel that has a metal matrix composite crack stopper doubler brazed to an SPF/DB titanium sandwich. An elox slot starts a crack that propagates across the 9.5-inch throat. A supersonic transport fatigue spectrum is imposed through the bolts and doublers. The number of lifetimes with and without the metal matrix composite doublers is compared.

BEND TESTS: SURFACE CONDITION AFTER SUPERPLASTIC FORMING

MAGNIFICATION: 0.5X

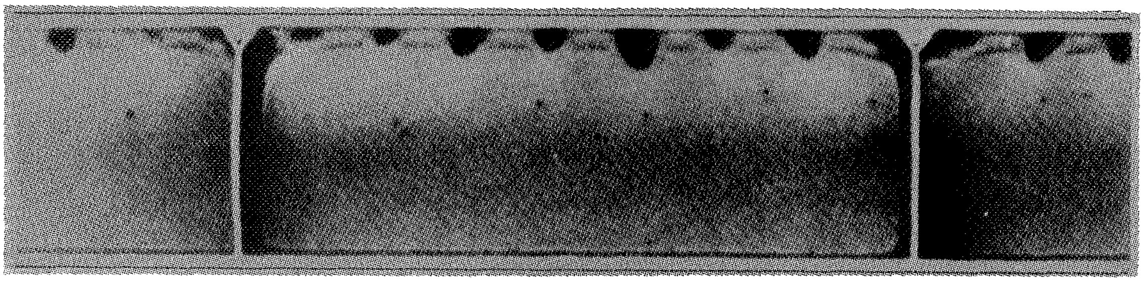


EXTERIOR SURFACE BORON NITRIDE EMBRITTLED | **SURFACE CHEM-MILLED 0.00889 cm (0.0035 IN.) REMOVED** | **AS-RECEIVED SHEET**

The bend test puts tension on the outer fibers. After using boron nitride as a stop-off* and then subjecting the sheet to a typical SPF/DB cycle, the part is then bent as shown. It should be noted that a crack forms from the tension stress. If the surface is chem-milled and the "white layer" removed, the part can be bent 180 degrees without cracking (middle picture). Also, as-received sheet can be bent without cracking. Therefore, only the combination of pressure, temperature, and time of the superplastic process causes the embrittlement. Accordingly, Douglas would not consider using stop-off on the inner core to face sheet. At Douglas, it is used only on an exterior surface where the "white layer" can be removed.

*A stop-off is a chemical compound that inhibits diffusion bonding of the parts.

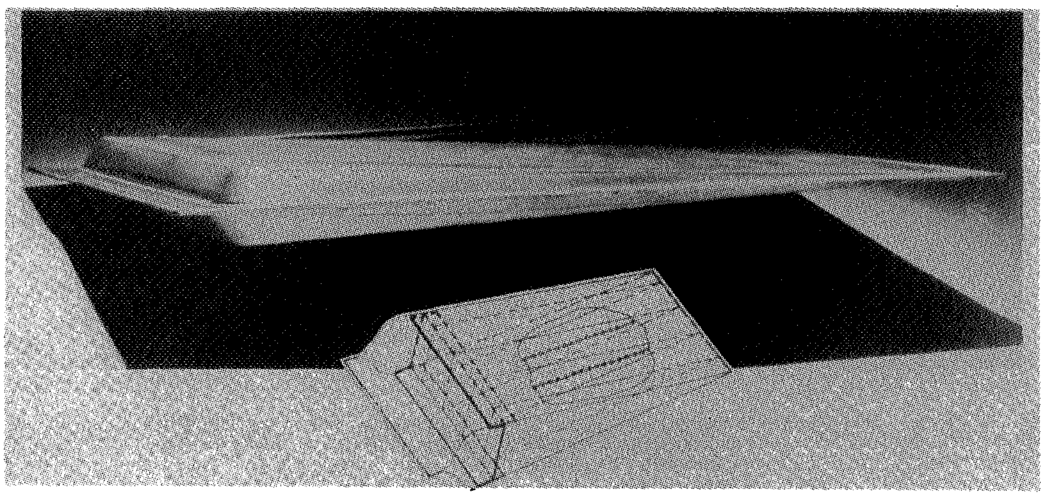
SECTION THROUGH A THREE-ELEMENT PANEL



The three-sheet sandwich structure is a unique Douglas design. The top face sheet and core sheet are spot welded into rectangular cells and the core sheet is then blown to the bottom face sheet where it is diffusion bonded. Ultra-lightweight strong sandwich structures can easily be formed by this process.

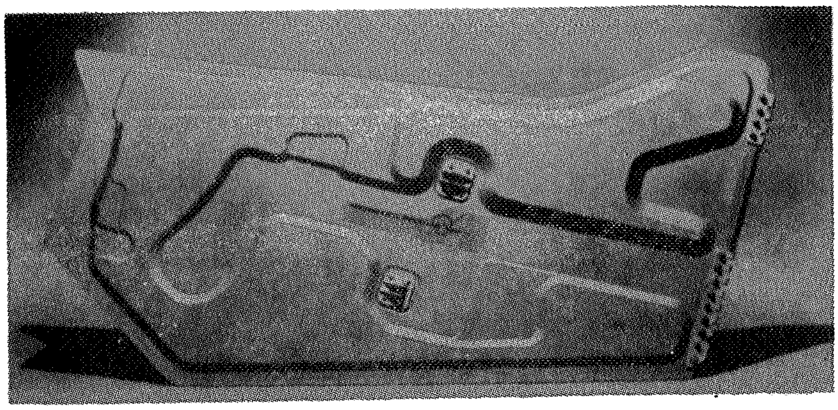
WING TRAILING-EDGE SECTION

SPF/DB SANDWICH (RECTANGULAR PATTERN)



A typical trailing-edge four-sheet process has been successfully developed at MDC for application to a trailing-edge structure of a fighter aircraft.

T-38 MAIN LANDING GEAR DOOR

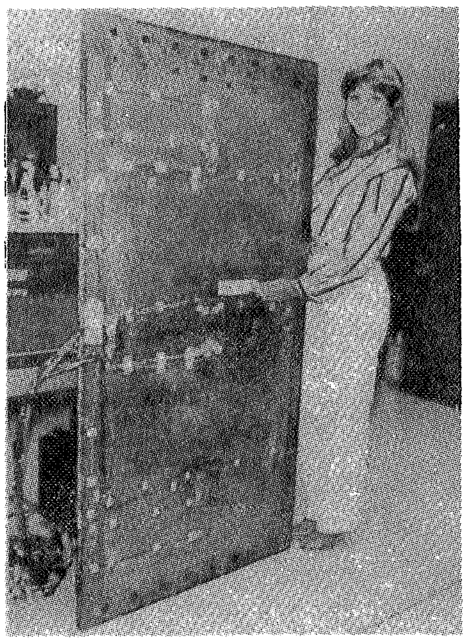


SPF/DB SANDWICH (RECTANGULAR PATTERN)
RELATIVE STIFFNESS + 10 PERCENT
RELATIVE WEIGHT — 8 PERCENT

The four-sheet SPF/DB titanium sandwich has been successfully developed as a substitute for the main landing gear door panels in the T-38 which are currently made from aluminum honeycomb sandwich. The SPF/DB titanium sandwich is 10-percent stiffer for 8-percent less weight.

3- BY 5-FOOT TITANIUM SPF/DB SANDWICH

WING FATIGUE PANEL — INSTRUMENTED FOR TEST



The above wing fatigue test panel has undergone one complete fatigue lifetime, and then was checked for limit load, elox slotted, and instrumented for crack propagation tests. Since then, it has achieved another one full lifetime after the initial crack. It has been checked again for limit load and is still stable (crack size will still hold).

CONCLUDING REMARKS

In conclusion, three methods of joining have been described that are applicable to SPF/DB titanium sandwich and its reinforcement with metal matrix composites. The core materials are joined by spot welding and/or roll seam welding and then, by applying enough heat and pressure to make the titanium superplastic, the core sheet cells are "blown" and diffused to the face sheets and doublers. Diffusion bonding is very effective — repeated tests and nondestructive evaluation confirm that a very efficient sandwich structural assembly is obtained. Many examples have been illustrated, with the largest a 3- by 5-foot wing panel. In addition, by aluminum brazing metal matrix composites to lightweight SPF/DB titanium sandwich, the structural efficiency has been enhanced significantly.

Scale-up of the SPF/DB titanium sandwich concepts to larger wing and fuselage sections should be attempted as soon as possible and should result in additional weight and cost savings. The larger the panel, the smaller the effects of the edge doublers and splice attachment parts, therefore reducing the number of parts and resulting in lower cost per square foot. Scale-up of large SPF/DB titanium sandwich panels that are double contoured can easily be achieved at superplastic temperatures. The dies for this are initially expensive, but worth investigating if a quantity production run is expected.

Brazing of reinforcement sheets to ultra-lightweight titanium sandwich can be done in a braze oven or a heated autoclave. In the past, Douglas has successfully fabricated large titanium panels by spot welding and then aluminum brazing. Similarly, brazing metal matrix composite reinforcement strips or sheet to titanium ultra-lightweight panels should be considered for scale-up for future aircraft.

SPF/DB titanium sandwich is very good for resisting stress corrosion. Also, the three-sheet sandwich, which has been developed successfully by Douglas and has been described previously, can be made into ultra-lightweight panels. These panels can compete in structural efficiency with aluminum honeycomb panels and aluminum conventional panels for new aircraft, and are especially efficient in their damage tolerance and life-cycle costs.