P O T E N T I A L   S T R U C T U R A L   M A T E R I A L S

A N D   D E S I G N   C O N C E P T S   F O R

L I G H T   A I R P L A N E S ,   P A R T   I V

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INTRODUCTION

This four-part paper is based on a study conducted by San Diego Aircraft Engineering Company for NASA, Mission Analysis Division, Ames Research Center. The complete report of the study was published as NASA CR-1285, March 1969; a summary report was published as NASA CR-73257.

The series of papers presented here contains material of possible interest to sailplane designers and builders. The NASA report CR-1285 is available for sale @ $6.00 through CFSTI, Springfield, Virginia 22151.

Part IV is contained herein. The three preceding parts were published in successive issues of Technical Soaring beginning with Vol. I, No. 4, April 1972.

PART IV

FASTENING DEVICES AND METHODS

Metals may be joined by either mechanical means (such as bolting) or by welding, brazing, soldering, or adhesive bonding. All of these methods may be used to some degree in aircraft construction. Soldering is never used for structural purposes, but is frequently used in electrical work.

This section includes a discussion of the various joining processes adaptable to aircraft construction. Each method is presented in the following manner:

(1) A brief description.

(2) Illustrations are provided as necessary to clearly define the method of construction.

(3) Typical allowable strengths are given where applicable.

(4) Some comparisons (Fatigue and Static Strengths) are made between two or more of the techniques used.

(5) Advantages and disadvantages of each method are listed.

(6) Typical applications in aircraft manufacturing are given for each joining process.

Riveting

Rivets play an important role in the light aircraft industry. At the present time, it is the primary method of joining aluminum. Riveted construction is readily controlled and inspected, and it does not require the application of heat that might partially anneal or significantly impair the corrosion resistance of the heat-treated alloys used. The limited heating
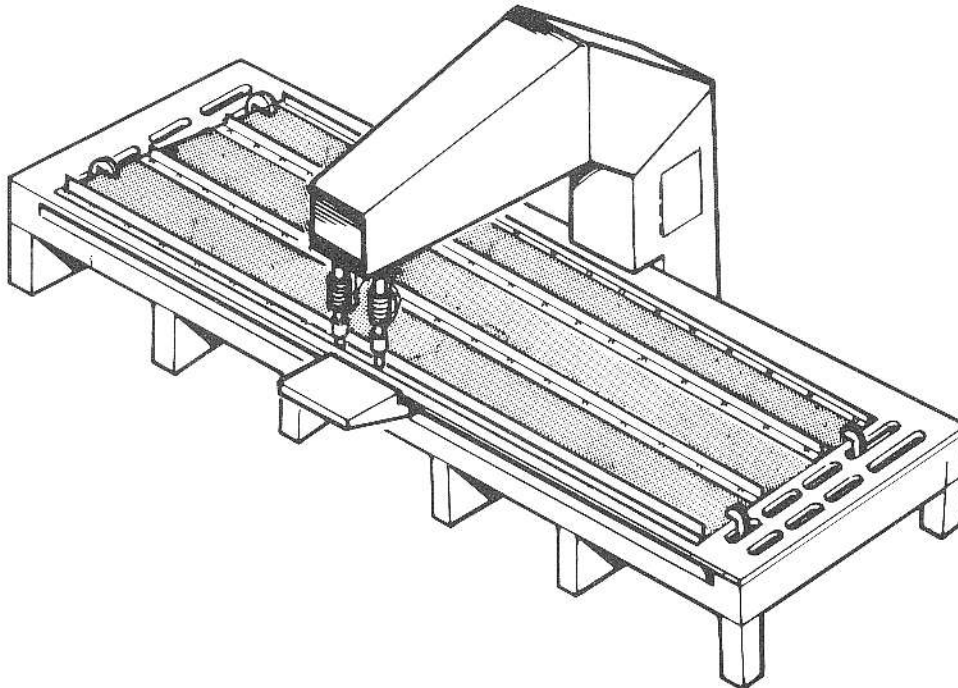
STANDARD AUTOMATIC RIVETING MACHINE

FIGURE 1

STANDARD AUTOMATIC RIVETING MACHINE

required in dimpling sheets of some al-
loys, and tempering before riveting, does
not impair essential properties. Sheets
less than 0.050 inch thick generally are
dimpled for countersunk head fasteners.
Thicker material is machine countersunk.

Countersunk head rivets are used
primarily for attaching outer skins,
whereas universal-head (modified round)
rivets are used extensively in interior
structures where protruding heads are not
objectionable. Surface skin panels often
are riveted by automatic machines (as
illustrated in Fig. 1) made to form one
or both heads of the rivet. The machines
are fed with rivets or slugs; and the
heads are usually shaved flush with the
exterior surface.

Rivet alloy 2117-T4 is the most popu-
lar for general use, especially for auto-
matic riveting, because it retains good
driving characteristics indefinitely after
solution heat treatment. 2024-T4 alloy
rivets are used occasionally where higher

strength is required; however, these must
be used within 30 minutes after heat treat-
ment, or refrigerated until used.

Specifications for the design of
aluminum-alloy structures generally desig-
nated the rivet alloys to be used. Table
I lists some combinations of structural
and rivet alloys that combine satisfac-
torily in many applications. Compati-
bility from the standpoint of electrolytic
corrosion could be one requirement. Alloy
2213 is generally specified where rivets
are to be used at elevated temperatures;
however, this probably would not apply in
the light aircraft field.

It is considered poor practice to use
a large rivet in relatively thin metal or
a small rivet in thick metal. Further-
more, a loss in shear strength can result
when a relatively soft rivet is driven in
a hard thin plate. Tests indicate reduc-
tions in shear strengths of approximately
30 percent when the rivet diameter is
four times greater than the sheet being
joined.

TABLE I

ALUMINUM - SATISFACTORY COMBINATIONS
OF STRUCTURAL AND RIVET ALLOYS

STRUCTURAL ALLOYS	RIVET ALLOYS
1 xxx SERIES	1100
3 xxx SERIES	6053,6061
5 xxx SERIES	5056,6053,6061
6 xxx SERIES	6053,6061,7277
2 xxx and 7 xxx SERIES	2017,2024,2117,2219
	6061,7075,7277
Magnesium Base	5056

The type of rivet to be driven generally governs the selection of the driving method. All standard rivets require backing up, pressure, or impact, and a driving-set or head-forming fixture. Blind rivets require special tools. Common practice is to drive solid aluminum rivets with either squeeze riveters or pneumatic hammers. The cup in a rivet set must conform to the style of the manufactured rivet head. Bucking bars or pneumatic backups used in hammer riveting should have sufficient force to counteract the hammer blows.

Flush-riveted joints require countersunk head rivets. Either the manufactured or the driven head can be countersunk; however, in most instances, the manufactured countersunk head is used. Countersinking the metal for flush rivets is done by machine countersinking in heavy gages, or by pre-dimpling or dimpling in thinner gages, as is common in aircraft construction. In a pre-dimpling operation, dies are used to press countersink the metal, whereas in dimpling the rivet is used with a die. For some alloys, heated dies must be used. Countersinking can also be accomplished by spinning rather than pressing. Either technique used is influenced by the thickness and strength of the alloy, rivet size, hole diameter, and countersink angle.

It is important that all driving sets have smooth polished surfaces, so the metal can flow easily while being formed. As a rule, the diameter of the driven head should not be less than 1.3 times the diameter of the original shank. The rivet length should be sufficient to fill the hole and form a satisfactory head.

Tubular, semitubular, and split rivets are usually driven with high-speed automatic or semi-automatic riveting machines.

Driving equipment required for blind rivets depends on the rivet type. The drive-pin type can be driven with an ordinary hammer; the explosive type requires a heat source such as a soldering iron. Most manufacturers of blind rivets provide the driving equipment needed.

Careful attention to details in rivet design and fabrication pays big dividends in fatigue life. When a fatigue failure occurs in a structure, it is usually at a point of stress concentration which could have been improved with little or no added expense.

To meet the requirements of large volume production demands, automatic riveting machines must be used to insure high quality with reasonable costs. Commercial and military aircraft manufacturers have been using automatic riveting for more than five years. It has been estimated that fatigue life is increased by approximately 200 percent over hand riveting. This increase is attributed to riveting uniformity, something impossible with hand riveting.

Rivet Gun

Portable Squeezer
"Alligator" Type Yoke
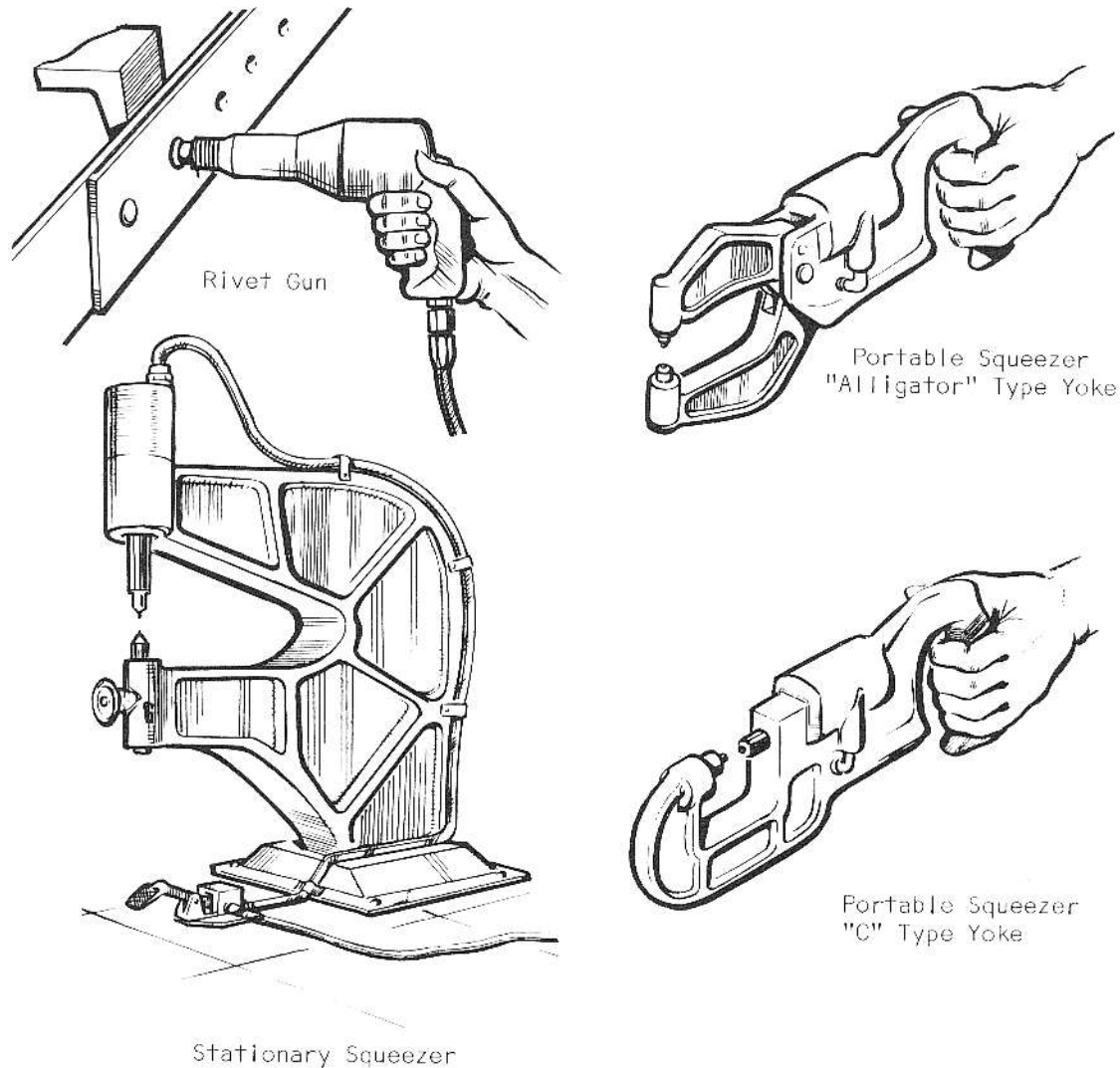
Stationary Squeezer

Portable Squeezer
"C" Type Yoke

FIGURE 2

RIVETING EQUIPMENT

A large commercial aircraft manufacturer is installing one of the world's largest automatic riveting machines at its plant. Riveting will be performed at the rate of six seconds per rivet.

This machine is equipped with an automatic-sensing device, whereby riveting is performed to tolerances of 0.005 inch while maintaining consistent repeatability. Normality sensors automatically determine the contour of the wing surface and guide the angle of the drill accordingly so all holes are exactly alike. All operations of this system are preplanned on perforated tape to automatically cycle from hole to hole while drilling, countersinking, pressure squeezing, impacting, and shaving the rivet to a smooth surface corresponding to the panel contour.

Automatic riveting machines can be set up to travel over the panel or remain stationary while the work, held in a fixture, moves past the machine.

The size and shape of the assemblies determine which method is more suitable.

Tack rivets are used to temporarily fasten the sheets together, and later are replaced by permanent hand-driven types.

Design-allowable strengths. - The strength of a riveted joint is governed by the shear strength of the individual rivets, the bearing strength of the sheet, and the efficiency of the sheet in tension. Some typical ultimate shear strengths of single rivets are given in Table II, based on values shown in MIL-HDBK-5 (Strength of Metal Aircraft Elements). Due to the light loadings anticipated, joint strengths will probably be based on the bearing strength of the sheet, or the shear strength of the rivets.

A fatigue life comparison of a well designed riveted joint to several adhesive bonded joints is shown in the section on bonding in Fig. 9. It appears, at least from this standpoint, better performance would be expected from a bonded joint; however, considering all the parameters (cost, reliability or quality control, production schedules, etc.), the automatic riveting concept could prove most worthy.

Electric Welding

Electric welding is often used in aircraft construction. It is the only welding method used for joining structural corrosion-resistant steel; and has been generally adopted for most aluminum alloys. Six basic resistance welding processes are commonly used with aluminum: spot, seam welding to make lap joints, upset and flash-welding for butt joining, percussion welding to attach studs to surfaces.

These processes are rapid and economically justified for high volume production. With proper material preparation, consistent weld quality may be achieved automatically by the welding equipment. This technique is independent of operator skill; and one machine may be used to weld a range of thicknesses and sizes.

Spotwelding. - Used primarily in shear applications; however, it is not recommended in the following areas:

(1) Attachment of flanges to shear webs.

(2) Attachment of spar caps or shear web flanges to wing skin.

(3) Attachment of ribs to spars or shear webs.

(4) At truss panel points in spars or ribs.

TABLE II

ALUMINUM RIVET ULTIMATE SHEAR STRENGTH
(Single Shear in lbs)

Rivet Size / Sheet Gage	Protruding Head		Dimpled Sheet 2024-T3,T42,T81		Countersunk Sheet 2024-T42 and higher Structural Aluminum	
	(3/32") AD3	(1/8") AD4	(3/32") AD3	(1/8") AD4	(3/32") AD3	(1/8") AD4
0.020	202		209	299	132	163
0.025	210		235	360	156	221
0.032	217	374	257	413	178	272
0.040		386	273	451	193	309
0.050		388		484	206	340

Sheet gage is thickness of thinnest sheet in a single shear application. Bearing strength of particular sheet used must also be checked.

(5) At junction points of stringers or stiffeners with ribs, unless a stop rivet is used.

(6) At ends of stringers or stiffeners, unless a stop rivet is used.

(7) On each side of a joggle, or wherever there is a possibility of a tension load component, unless a stop rivet is used.

(8) Splices exposed to the airstream should be so designed that flow of the airstream would not tend to pry it apart.

Anodically treated surfaces cannot be spotwelded; consequently, the faying surfaces of a spotwelded seam must be left unprotected prior to welding. The assembled parts are anodically treated or painted after welding. For this reason, there is some doubt about the advisability of spotwelding aluminum alloys, other than 5052 or clad materials, if the assemblies are subject to severe corrosion. It is possible to spotweld through wet zinc-chromate primer applied to the faying surfaces.

A French aircraft company has recently developed a series of light aircraft, using spotwelding quite extensively. This company set out to incorporate mass-production techniques and, in so doing, reduced costs accordingly. The number of parts is reduced by using certain components in several applications. Standard joining techniques are employed in fabricating major subassemblies (wing section, forward fuselage section, aft fuselage section, etc.). These are mated on the final assembly jig as in an automobile assembly line.

Normal riveting is limited only to primary joints; whereas all the remaining connections are spotwelded with automatic welding machines. These machines are programmed with perforated tape to perform the complete welding operation; consequently, the operator stands by and only takes over in the event of any malfunctioning.

Fuselage welding is performed in two stages. By using this fabrication technique, the main structural elements of the fuselage are welded by machine in about ten hours.

The fuselage consists of a forward section and tail cone, joined by a riveted skin splice. The longerons also extend out from the rear section and are spliced with rivets to the longerons of the forward section. This constitutes an all riveted primary joint (see Fig. 3).

Fabrication of the wing is performed in a very similar manner, whereby riveting is used only on the wing spars, ribs to stiffeners, stiffener to spar cap attachments; all these considered as primary joints.

The ailerons and flaps have identical profile. The skin is formed over the contour and spotwelded to the ribs and bent-up sheet metal longeron (reference Fig. 4). The trailing edge is constructed with beaded sheet metal skins spotwelded to the ribs, the longeron and at the trailing edge. This process applies to all movable surfaces on the aircraft.

Design-Allowable Strengths of Resistance Spotwelds: The strength of a spotwelded joint is governed by the shear strength of the individual spots and the effect of the spotwelds on the tensile strength of the basic sheet. Therefore, both the shear strength of the spotweld, and the tension efficiency of the spotwelded sheet, must be considered in determining the strength of a spotwelded joint.

The allowable ultimate shear strengths of single spotwelds are given in Table III. Values are reproduced from MIL-HDBK-5. The allowable strength of a spotweld between two sheets of different material or thickness is the lower of the allowables for the individual sheets, as determined from the tables. Due to the anticipated light loadings involved with this type of aircraft, the joint strengths would be based primarily on the shear strengths of the spotwelds.

Seam welding. - Identical to spotwelding, except for the use of power-driven rollers as electrodes. A continuous airtight weld can be obtained at the rate of two to seven feet per minute by this method.
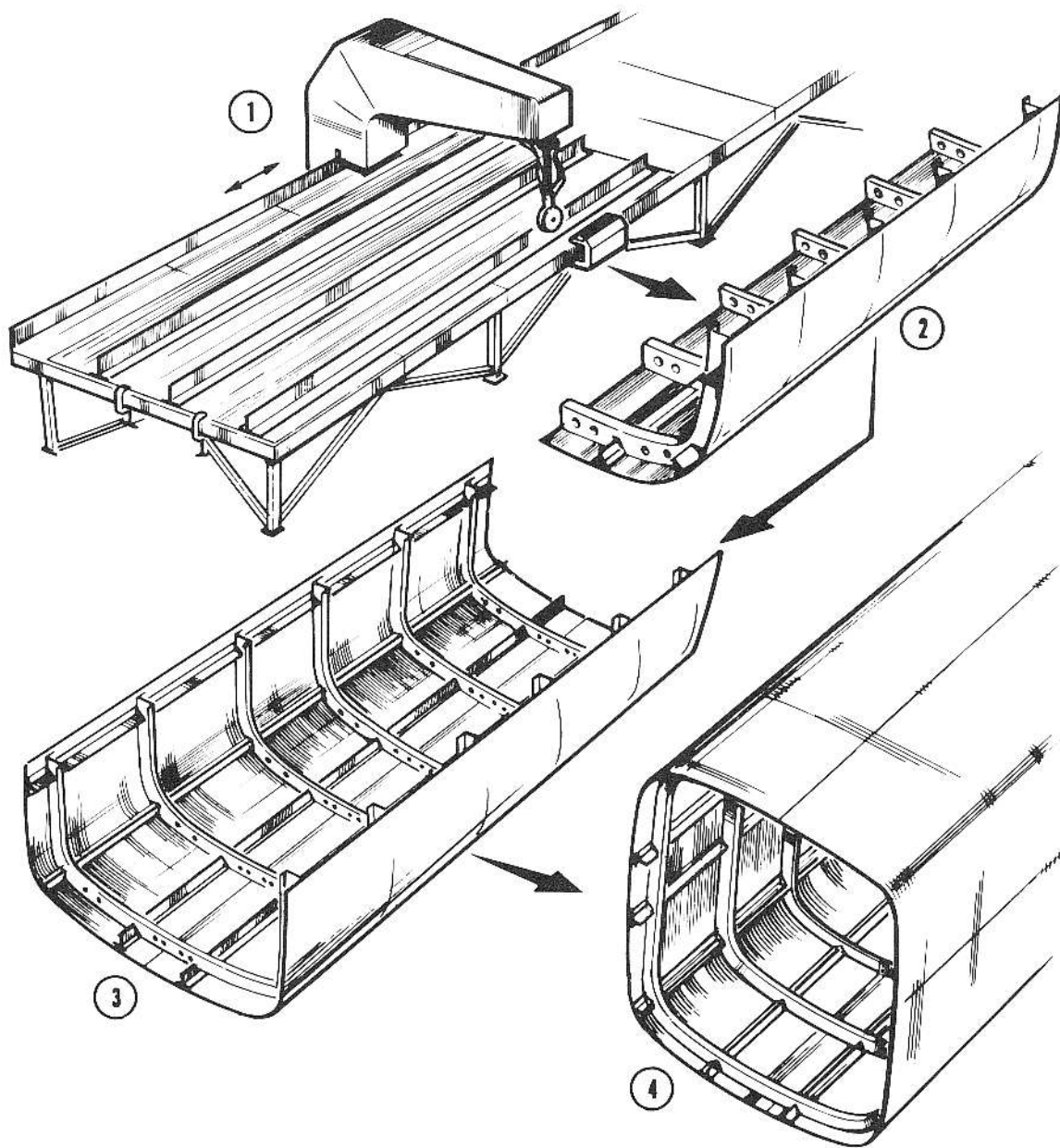
FIGURE 3

CURRENT LIGHT AIRCRAFT SPOT WELDED FUSELAGE CONSTRUCTION

NOTE: The longitudinal stiffeners are first welded to the skins. The
       transverse members are then welded to the panel which is suffi-
       ciently flexible to be fitted into the second stage jig without
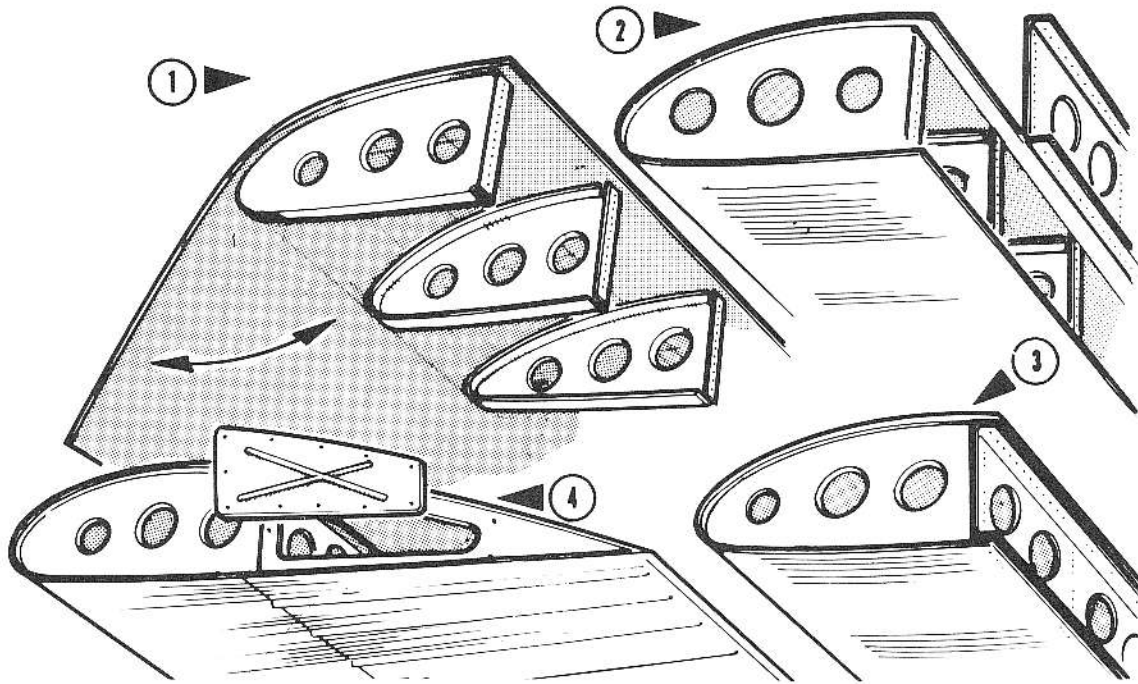   any shaping.

FIGURE 4

CURRENT LIGHT AIRCRAFT SPOT WELDED FLAP CONSTRUCTION

TABLE III

ALLOWABLE ULTIMATE SHEAR STRENGTHS OF SINGLE SPOTWELDS (ALUMINUM ALLOYS)
(Pounds per Spotweld)

Sheet Thickness (inches)	Aluminum Alloys, Clad or Bare Ultimate Tensile Strength of Material - psi			
	Below 19,500	19,500-27,999	28,000-55,999	56,000 & Above
	3003-0	3003-H14 5052-0	6061-T4 6061-T6	2024-All Tempers 7075-T6 7178-T6
0.012	16	24	52	60
0.016	40	56	80	88
0.020	64	80	108	112
0.025	88	116	140	148
0.032	132	168	188	208
0.040	180	240	248	276
0.050	236	320	344	372

Some advantages of electric resistance spot and seam welding:

(1) Spotwelding is faster than riveting because no layout and drilling of holes are necessary. Numerous spotwelds can also be made in the time required to insert and head one rivet.

(2) Spot and seam welding do not add weight to the structure.

(3) Seam-welded watertight joints do not require the insertion of tape and a sealing compound. Weight and expense are saved.

(4) The drag of rivet heads is eliminated on exterior surfaces.

Butt welding. - Butt welding is applicable to almost all metals. The work to be welded is clamped in large copper jaws also serving as electrodes. One of the jaws is movable. At the proper time, pressure is applied to the movable jaw to bring the work in contact. When the electric current is applied after the parts are pressed together, it is called upset butt welding. In flash welding, the edges are brought close enough together to start arcing and, when they reach fusion temperature, the current is turned off and pressure is applied. All wrought alloys of solid cross-section up to about 0.5 square inch in cross-sectional area can be upset butt welded. Square-cut abutting surfaces, free of lubricant, are required for optimum welding results. Shearing or sawing the ends just before welding is adequate preparation.

Arc welding. - Arc welding is based on the heat generated in an electric arc. Variations in this process are metallic arc welding, carbon arc welding, atomic-hydrogen welding, inert-arc welding (heliarc), and multiarc welding.

Arc welding to a limited extent has been used for many years in aircraft fabrication. Probably the flexibility and general all-around good results obtained with gas welding retarded its extensive use; however, in recent years, its use is increasing rapidly as its economics and advantages become more apparent. In arc welding, the applied heat is more concentrated, resulting in a quicker welding with less expansion and warping as compared to gas welding. This makes it possible to hold closer tolerances on parts requiring machining after welding. An allowance of 1/16 inch is usually sufficient for most assemblies.

By using the heliarc (inert-arc) welding process, satisfactory welds may be made with aluminum and, if argon is used for a shielding gas, no flux is required. Dispensing with flux is a definite advantage because flux removal from aluminum welded joints is extremely important to avoid corrosion. Many types of welded joints cannot be made when using welding methods requiring fluxing. Corrosion-resisting steel as thin as 0.010 inch can be welded by this process. Steel, copper, and many alloys can be readily welded by this process.

Parent material weld allowables: Allowable ultimate tensile stress in alloy steels for material adjacent to the weld, when structure is welded after heat treatment, is shown in Table IV.

TABLE IV

ALLOWABLE ULTIMATE TENSILE STRESSES NEAR FUSION WELDS
IN 4130, 4140, 4340, or 8630 STEELS

Section Thickness 1/4 Inch or Less	
Type of Joint	F_{tu} (ksi)
tapered joints of 30° or less	90
all others	80

For alloy steel members subjected to bending, the allowable modulus of rupture when welded after heat treatment should not exceed the F_b equivalent to that for steel having a $F_{tu} = 90,000$ psi.

Strength of Weld Metal (Welding Rods)

Table V indicates allowable weld metal strengths for various steels. These are based on 85 percent of respective minimum tensile ultimate test values.

Welding Considerations

There are many general considerations all designers should be familiar with in designing welded joints. The following apply particularly to arc welding:

(1) Straight tension welds should be avoided because of their weakening effect. When a weld must be in tension, a fishmouth joint or finger-patch should be used to increase the length of the weld and to put part of it in shear.

(2) A weld should never be made all around a tube in the same plane.

A fishmouth weld should be made. This situation arises frequently when attaching an end fitting to a strut.

(3) Two welds should not be placed close together in thin material. Cracks will result because of the lack of metal to absorb shrinkage stresses.

(4) Welds should not be made on both sides of a thin sheet.

(5) Welds should not be made along bends, or cracks will develop in service.

(6) Welded reinforcements should never end abruptly. The sudden change of section will result in failures by cracking when in service.

(7) Aircraft bolts should never be welded in place unless they are made of weldable material and are going to be welded to a similar metal. Furthermore, welding will destroy the heat-treated condition of the bolt. This has to be considered in

TABLE V

WELD METAL STRENGTHS FOR WELDED JOINTS (Welding Rods)

Material	Heat Treatment After Welding	F_{su} ksi	F_{tu} ksi
Carbon and alloy steels	none	32 32	51 51
Alloy steels	none	43	72
Alloy steels	stress relieved	50	85
Alloy steels	stress relieved	60	100
Steels	quench & temper		
4130 4140 4340	125 ksi 150 ksi 180 ksi	63 75 90	105 125 150

the design/analysis. The same comments are valid for aircraft nuts. However, when required, tack welding in three places is usually all that is necessary to position them.

(8) When possible, welded parts should be normalized or heat-treated after completion, to refine the grain and relieve internal stresses caused by shrinkage.

If welded parts are not normalized, they could develop cracks in service, particularly if subjected to vibrational stresses. This is because weld material is cast metal lacking the strength, ductility, or shock resistance of wrought metal. The internal stresses are also seeking to adjust themselves. Sharp bends or corners, or rapid changes of section in the vicinity of welds, are especially liable to cracking.

In the design of tubular joints, care should be taken to make all welds accessible. Fig. 5 illustrates industry accepted design practices. These configurations provide proper stress distributions through the joints and should be followed as much as possible.

Brazing

Brazing is a method of metal joining, using a filler metal having a melting temperature less than the parent material being joined. Brazing is primarily used for joining assemblies for use at normal atmospheric or slightly elevated temperatures because the usual brazing alloys are compositions which soften readily at relatively moderate temperatures. Brazing is distinguished from soldering by the melting point of the filler metal (filler metal for soldering has a much lower melting point) and differs from welding in that no substantial amount of the base metal is melted. Thus, the temperatures for brazing are intermediate between those for welding and soldering. The strength and corrosion resistance characteristics of a brazed assembly also generally fall between those of welded and soldered assemblies.

Brazing aluminum. - Nonheat-treatable wrought alloys brazed most successfully are the 1xxx and 3xxx series and the low-magnesium 5xxx series. Alloys containing a higher magnesium content are more difficult to braze by the usual flux methods, because of poor wetting by filler metal and excessive penetration. Filler metals are available that melt below the melting temperature of all commercial-wrought nonheat-treatable alloys.

Of the heat-treatable alloys, those most commonly brazed are the 6xxx series. The 2xxx series may be brazed quite satisfactorily; however, the 7xxx series is low melting and, therefore, not normally brazeable, with the exception of 7075 and x7005.

Material Combinations - Aluminum

(1) It is desirable from a production standpoint to design assemblies in their entirety from 2xxx or 3xxx alloys, or combinations of these two materials.

(2) Combinations of alloys (2xxx to 61xx, 2xxx to 53xx, etc.) are difficult to braze and should be avoided.

(3) Combinations of 61xx or 53xx to 61xx are satisfactory.

(4) Brazing sheets must be used in combination with 2xxx or 3xxx alloys only.

Brazing sheets should be used where a large number of joints are necessary in flat or formed sections of sheet; or possibly for ducts, tanks, or other assemblies where it would be difficult to secure wire or other forms of filler material adjacent to the joints. This material would also be used in an area requiring brazing in a position other than one allowing gravity flow of the filler material. Typical examples of brazed joints are shown in Fig. 6.

Brazing steel. - Joining steel parts into single units may be done by brazing with copper or silver alloys.

When copper alloys are used, brazing is performed within a furnace (copper furnace brazing), having a controlled heat of 2050°F. This is above the melting point of copper (1985°F); therefore, this may be accomplished by induction, torch, resistance, furnace, or dip methods.

BAD

a) Grinding or machining of weld could result in failure

BAD

b) Pinched end, even with reinforcing sleeve is prone to crack at the bend as a result of cold-working in manufacture or fatigue in service.

ACCEPTABLE

c) Lightly loaded attachment, angle α not more than 30°.

BAD

d) (Require excessive cold working of tube.)

ACCEPTABLE

e) (For light loads)

GOOD

f) For light loads.
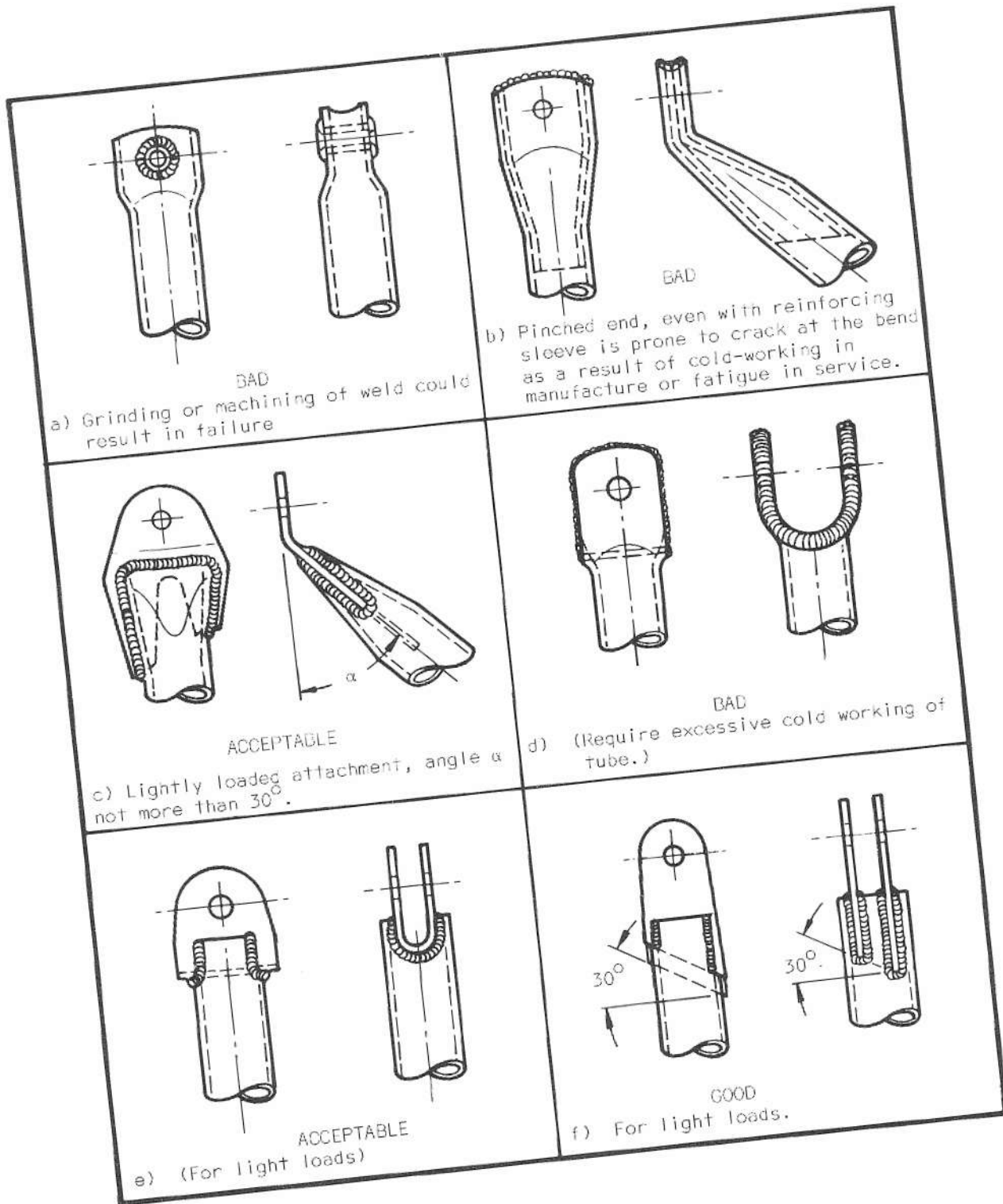
FIGURE 5

DESIGN PRACTICES FOR WELDED TUBULAR JOINTS

LIGHT LOADS
g) (Not very strong in compression due to crushing under spacer tube).

LIGHT LOADS
h) (This is an improvement on "g" Provide enough material on bushing to avoid machining of weld).

30°

HEAVY LOADS
i) Stagger termination of welds at opposite sides of tube.

ACCEPTABLE
j) Welding of standard clevis

k) Satisfactory for a fixed end attachment

l) Satisfactory for a fixed end attachment

FIGURE 5 - Continued

DESIGN PRACTICES FOR WELDED TUBULAR JOINTS

m) Minimize eccentricity between tube center lines and loads.

Note: applicable to any weldment: Keep thickness ratio between two welded parts (t_1 and t_2) less than 2 to 1 to prevent burning through thinner sheet.

t_2

t_1

HEAVY LOADS

n) Fitting plate attachment.

LIGHT LOADS

o) Fitting plate attachment.

FIGURE 5 - Continued

DESIGN PRACTICES FOR WELDED TUBULAR JOINTS

p) Fitting plate attachment

CORRECT

INCORRECT

q) Tube Cluster - (Keep eccentricities to minimum)

GOOD

BAD

r) Tube Cluster - (Keep eccentricities to minimum)

GOOD

BAD

FIGURE 5 - Continued

DESIGN PRACTICES FOR WELDED TUBULAR JOINTS

s) Gusseting

t) Gusseting – Use when the joint is subjected to vibration or reversed loads.

BUTT WELD

FISHMOUTH WELD

u) Tube Splices

FIGURE 5 – Concluded

DESIGN PRACTICES FOR WELDED TUBULAR JOINTS

Brazing Sheet
For Aluminum

Shim of Filler Material

0-3 degree

Thin Sheet 0.25 Inch or less

Cylindrical

Undesirable
Makes a Line Contact

Good

Brazing Sheet
Filler Material

For Tacking
Spotweld

1 Inch

Shim of
Filler Material

Tube
Bar Stock

Filler Material

Brazing Sheet
for Aluminum
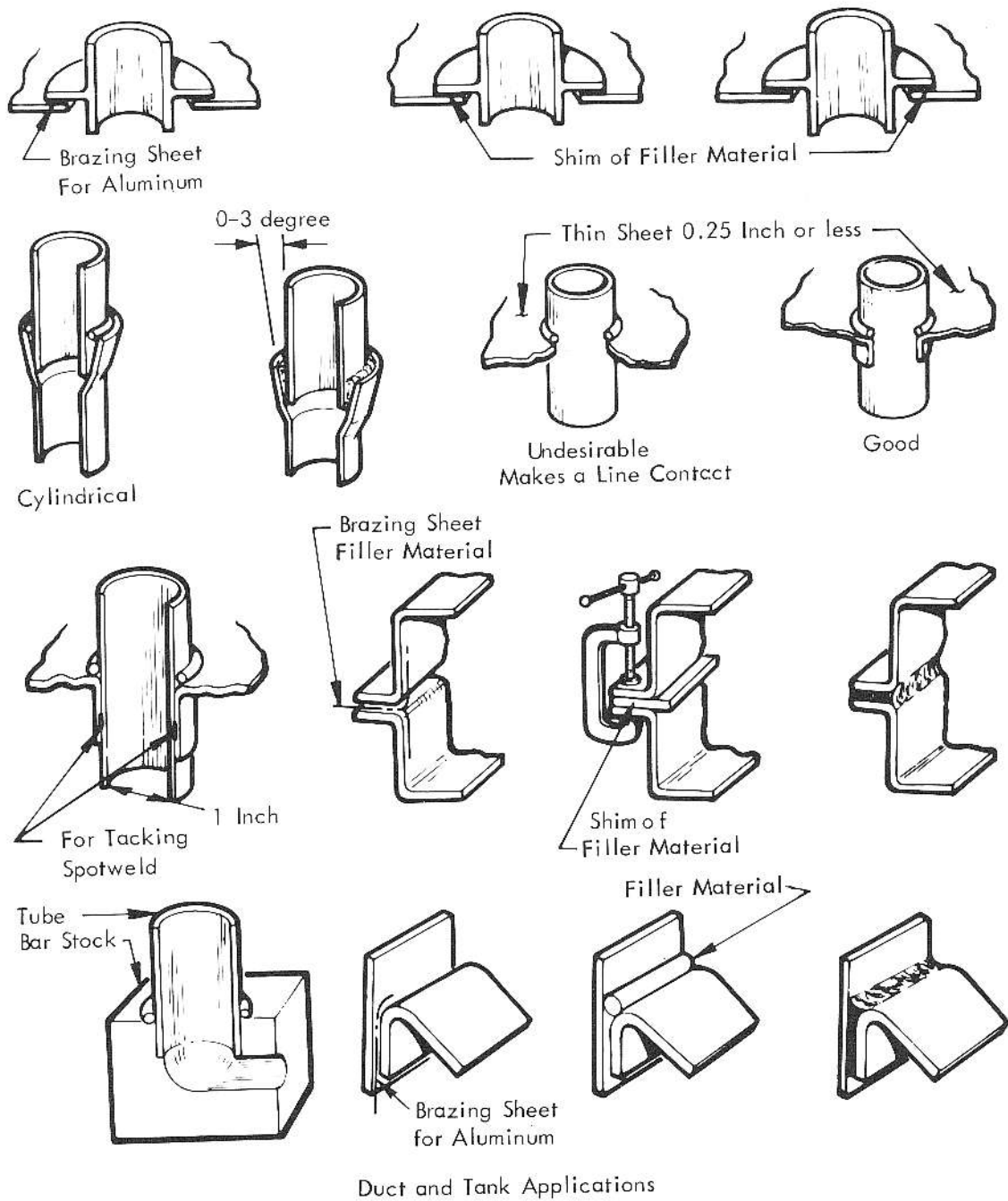
Duct and Tank Applications

FIGURE 6

TYPICAL EXAMPLES OF BRAZING

The selection of the brazing method depends upon the materials involved, the shape and size of the parts, whether heat treatment after brazing is required, the number of parts, etc.

Materials for brazing steel: Most steels may be brazed by either method; however, corrosion-resistant steel may not be copper-furnace brazed. Only the stabilized grades of 18-8 stainless steel (321 and 347) can be silver brazed as the temperatures involved impair the corrosion resistance of the unstabilized grades (302 and 303). The physical properties of heat-treated and cold-worked materials are reduced by the temperatures required for brazing.

Heat treatment may be performed on copper-furnace-brazed assemblies; however, due to the low melting point of the silver alloys, it is not possible to heat treat steel assemblies after silver brazing has been performed.

Fusion welding after brazing is normally prohibited within three inches of a brazed joint.

The same general design guide illustrated for various joints in Fig. 6 should also be used for steel materials.

Allowable stresses. - F_{su} = allowable ultimate shear stress for the brazed area = 15,000 psi (this applies to all conditions of heat treatment for all applicable materials).

Because of decarburation occurring during brazing, the strength of the parent material in most cases is reduced as shown in Table VI.

Advantages of brazing. -

(1) Parts too thin to weld may often be brazed.

(2) Heavy sections may be joined to thin sheets.

(3) Warpage and distortion are reduced.

(4) Brazed joints are vacuum tight.

Disadvantages of brazing. -

(1) Assemblies made of 2xxx and 3xxx aluminum alloys are fully annealed during brazing and cannot be restored to the original hardness; steels must be heat treated again to obtain original strengths.

(2) Series 53xx and 61xx aluminum alloys must be heat treated and artificially aged after brazing to obtain the condition required.

(3) Brazed assemblies cannot be put into the furnace for a second brazing unless there is a filler material with a lower melting point than used in the previous brazing.

TABLE VI

EFFECT OF BRAZING ON ALLOWABLE STRENGTH

Material	Allowable Strength
Heat-treated material including normalized used in as-brazed condition	Mechanical properties of normalized material
Heat-treated material (including normalized) reheat-treated during or after brazing	Mechanical properties corresponding to heat treatment performed

(4) Resistance to corrosion of aluminum alloys generally is not impaired by brazing; however, if flux is not completely removed, the residue will cause corrosion (interdendritic attack on the fillets, and intergranular attack on the base metal); if flux is not removed, it causes rapid pitting in the presence of moisture.

(5) When two aluminum alloys are brazed together, exposure to salt water or some other electrolyte may result in attack on the more anodic part; this condition is aggravated if the anodic part is relatively small compared to the other piece.

(6) Furnace brazing causes a certain amount of diffusion of a clad surface reducing its corrosion resistance; Brazing Sheet No. 100 must be used for such applications (filler metal on one side and a special alclad alloy on the other side).

Applications of brazing. -

(1) Controls and mechanisms for:

   (a) Accessories.

   (b) Electrical system.

   (c) Fuel and oil system.

   (d) Heating, ventilating, and de-icing systems.

   (e) Power plant controls.

   (f) Hydraulic equipment.

(2) Supports and attachments for:

   (a) Accessories, instruments, radio, etc.

   (b) Antenna masts and housings.

   (c) Pitot masts.

   (d) Landing gear doors or entrance doors.

(3) Miscellaneous:

   (a) Landing gear up-lock systems.

   (b) Handles (assist, door, pump, seat adjustment, etc.)

Bonding

Many times, adhesives are called the modern tool for joining assemblies; however, the only modern aspect is that bonding agents have been greatly improved. There is much historical precedent associated with this technique back to the era when wood aircraft structure was first glued together. The old Mosquito bomber of the early 1940's used plywood wings bonded with wood glue.

Although much research was conducted prior to 1940, the initial successful adhesives were not developed until the early 1940's. A group of phenolic resin-synthetic rubber hybrids were developed by one United States automobile manufacturer which maintained high strength over a wide range of temperatures. About this same time, an adhesive manufacturing company in England was experiencing success with an adhesive formulation based on a phenolic resin-polyvinyl combination.

The American-developed adhesives were single component systems which could be easily applied with simple tools (brush, roller, etc.), whereas the British system was a more sophisticated two-part system. With this process, it was necessary first to apply a liquied phenolic resin to the adherends, followed by a layer of powder over the liquid film. The powder, a polyvinyl formal, developed the necessary toughness or elasticity in the bonded joint, while the phenolic resin provided the proper adhesion characteristics.

Due to the apparent simplicity in applying the single-component system, further development of these adhesives were more closely followed in the United States and abroad.

Coincidental with the development of these newer adhesives, the airplane was playing a major role in the fighting of World War II. The aircraft industry was,

therefore, desperately in search of unique manufacturing techniques to save weight or provide smoother airfoil surfaces. This urgency led to the immediate acceptance of adhesive bonding for use in aircraft structure. In the United States, the government approved the single component adhesive system as an aircraft structural bonding agent, while England began utilizing the double component system for joining metal to wood in the De Haviland Hornet.

Within a few years, vinyl-phenolic bonded-sandwich structures became more predominant for use in wing panels and fuselage sections of the B-57 and Matador missile. By the mid 1950's, structural adhesive bonding was used extensively in the manufacturing of the B-58. Since then, new epoxy adhesive systems have been used more consistently and more daringly. Bonding of aluminum to itself, and to other metals and non-metals, has become common practice. Because of the great potential in weight reduction, the major technical effort to develop reliable adhesive bonding data has been restricted to aluminum alloys used in aircraft such as bare and alclad 2020-T6, 2024-T3, T6, T86, and 7075-T6.

A dramatic example in present-day application of adhesive bonding is the supersonic F-111 fighter-bomber. Most of the entire exterior skin is an adhesive-bonded honeycomb-sandwich structure. Another prime example of complex bonded structures being made today is associated with helicopter rotor blades. The Bell Helicopter (model UH-1D) uses an adhesive to bond an aluminum honeycomb core and doublers to the main spar, a brass nose bar, and a stainless-steel leading edge. This 22-foot long all-bonded assembly is cured at 120 psi and 350 degrees F.

It is apparent that adhesive bonding has a definite place in the aircraft industry. The crippling strength of compression panels is significantly improved due to the integral stiffening effect of the bonded laminates (ref. Fig. 7).

The fatigue strength of compression panels is increased thru the use of good bonded design. Fig. 8 compares three configurations and reveals that the one with insufficient skin width to stringer bond is inferior to the riveted configuration beyond 10^4 load cycles, thus

demonstrating the importance of proper bonded design.

Fatigue strength comparisons of Redux bonded single and double lap joints with a riveted joint are made in Fig. 9. Here again, the superiority of well designed bonded joints is evident. Results of box beam fatigue tests involving riveted, bonded, and integrally stiffened construction are presented in Fig. 10. The advantage gained by using scarf joints in lieu of lap joints is shown in Fig. 11 where the S-N curves for both configurations are plotted.

Higher strength-to-weight ratios are possible with sandwich materials. Often it is the only way to join thin-gage sheets; the adhesive bond can double as a seal; dissimilar metals can be fastened without corrosion effects and irregular shapes or complex sections can be fastened comparatively easily. Helicopters, for example, because of vibration, require the damping provisions provided by the nitrile rubber-epoxy adhesive system. Table VII lists the many advantages as well as the limitations occurring through the use of bonded structures.

General design and production philosophy associated with bonded structures. -

(1) Know the materials (test data).

(2) Structures should be properly designed for the use of adhesives.

(3) Use appropriate prebond treatments, tightly written instructions, and permit no deviations.

(4) Insist that the recommended process or specifications be rigidly adhered to when:

(a) Applying and curing the adhesive.

(b) Handling, fitting, and jigging of the parts.

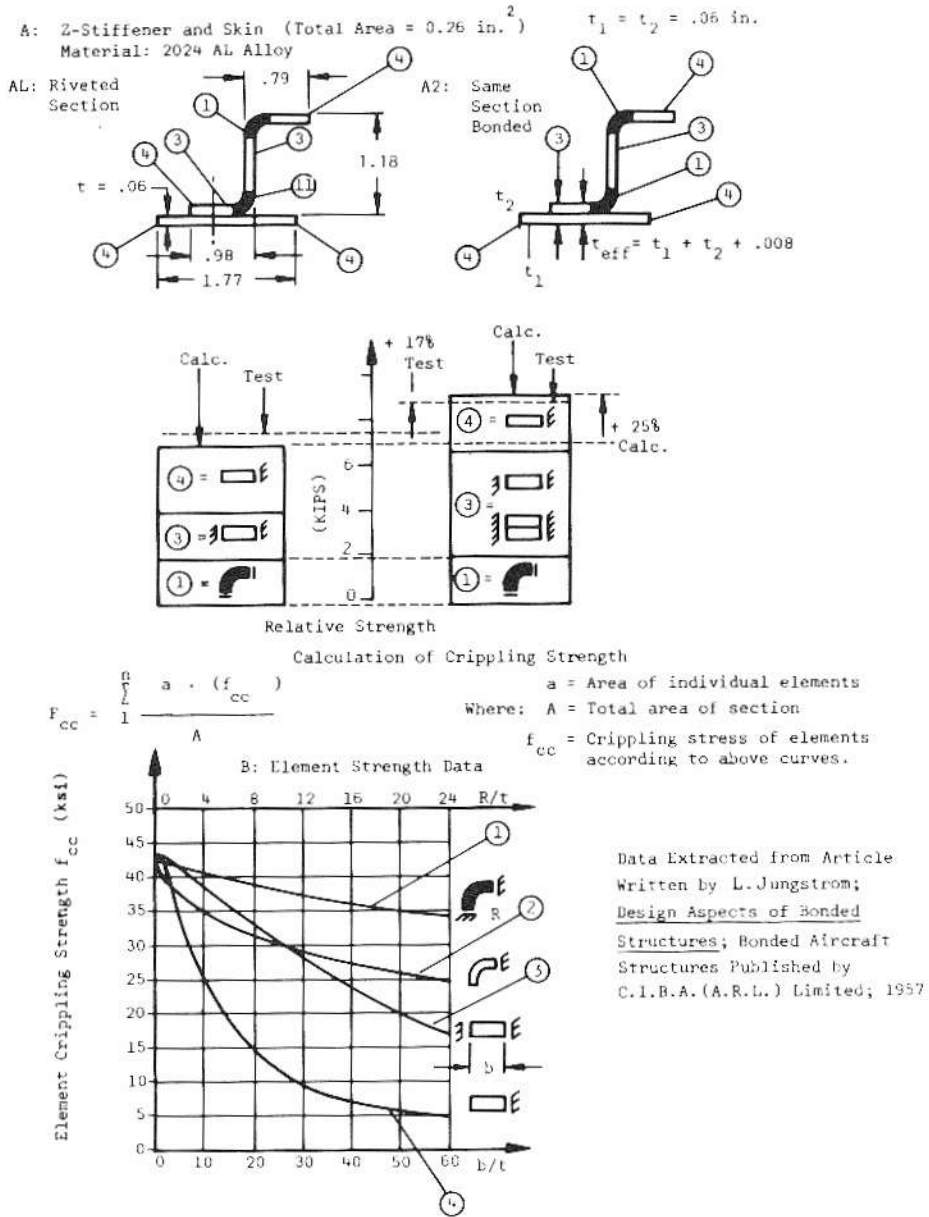(5) Train personnel to understand the importance of good workmanship and its influence on joint strength and life.

A: Z-Stiffener and Skin (Total Area = 0.26 in.^{2})
   Material: 2024 AL Alloy

$t_1 = t_2 = .06$ in.

AL: Riveted
    Section

A2: Same
    Section
    Bonded

.79

1.18

$t = .06$

.98

1.77

t_2

t_1

$t_{eff} = t_1 + t_2 + .008$

Calc.

Test

+ 17%
Test

Calc.

Test

(KIPS)

+ 25%
Calc.

④ = $\square\mathcal{E}$

③ = $\mathbf{3}\square\mathcal{E}$

① = ⌐

④ = $\square\mathcal{E}$

③ = $\mathbf{3}\square\mathcal{E}$

① = ⌐

Relative Strength

Calculation of Crippling Strength

$$F_{cc} = \frac{\sum\limits_{1}^{n} a \cdot (f_{cc})}{A}$$

Where:

a = Area of individual elements
A = Total area of section
f_{cc} = Crippling stress of elements according to above curves.

B: Element Strength Data

Element Crippling Strength f_{cc} (ksi)

						R/t
0	4	8	12	16	20	24

50
45
40
35
30
25
20
15
10
5
0

0   10   20   30   40   50   60   b/t

① $\mathcal{E}$

② R

③ $\mathcal{E}$

④ b

FIGURE 7

COMPARISON OF CRIPPLING STRENGTH OF BONDED AND RIVETED
BUILT-UP COMPRESSION ELEMENTS

Load Cycle: Pulsating Compression With P_{min} = 1100 lb

Test Specimen
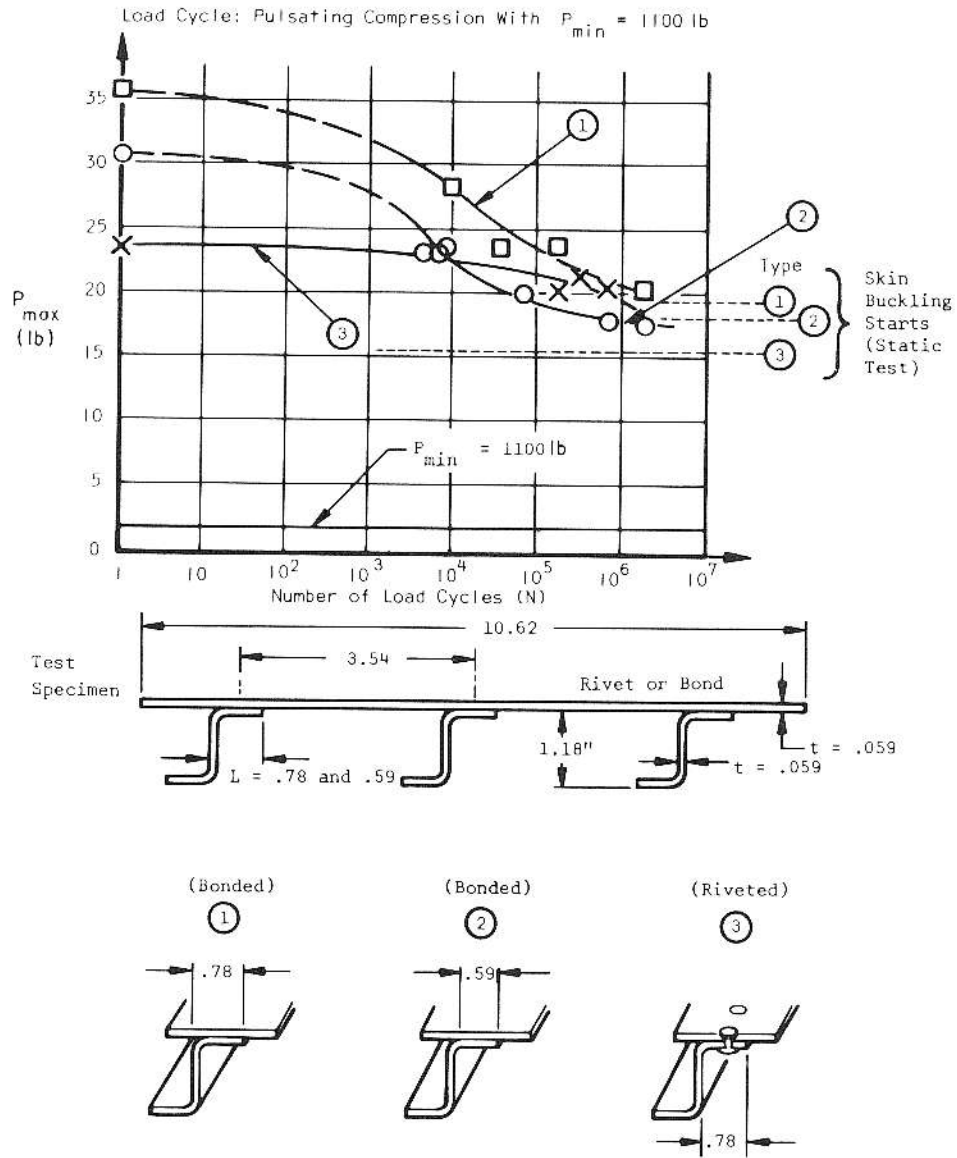
Data Extracted from Article Written by O.L. Jungstrom;
Design Aspects of Bonded Structures; Bonded Aircraft
Structures Published by C.I.B.A. (A.R.L.) Limited 1957

FIGURE 8

EFFECT OF WIDTH OF SKIN TO STRINGER BOND ON
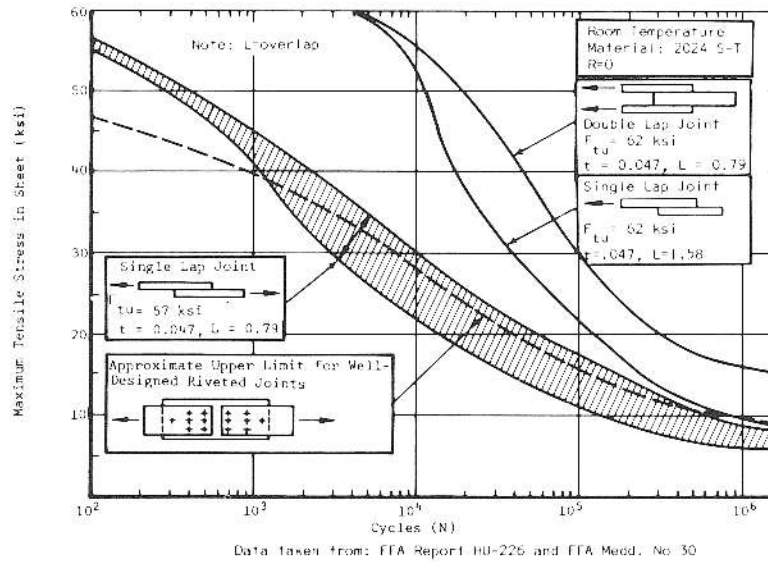FATIGUE STRENGTH OF COMPRESSION PANELS

FIGURE 9

COMPARISON OF FATIGUE STRENGTH OF BONDED
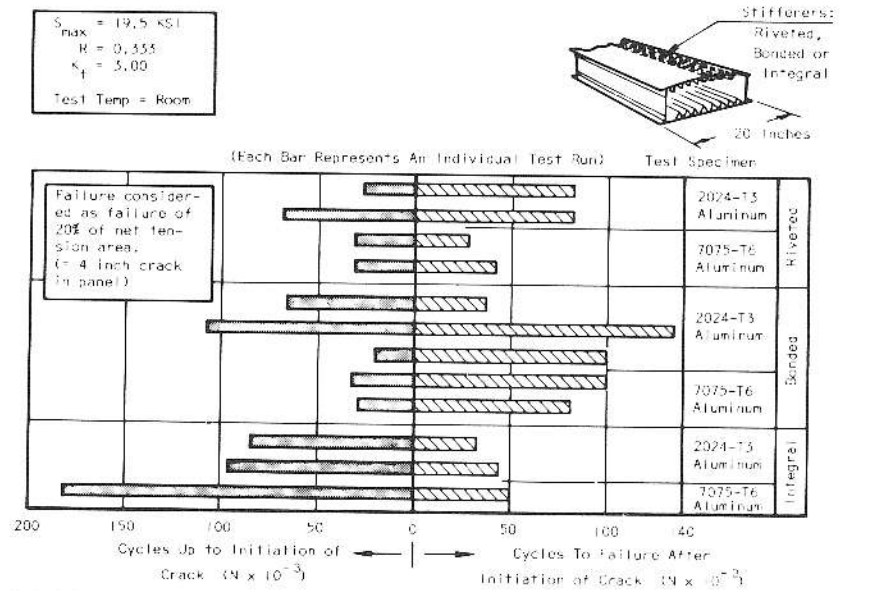SINGLE- AND DOUBLE-LAP JOINTS WITH A RIVETED JOINT

FIGURE 10

COMPARISON OF RIVETED, BONDED, AND
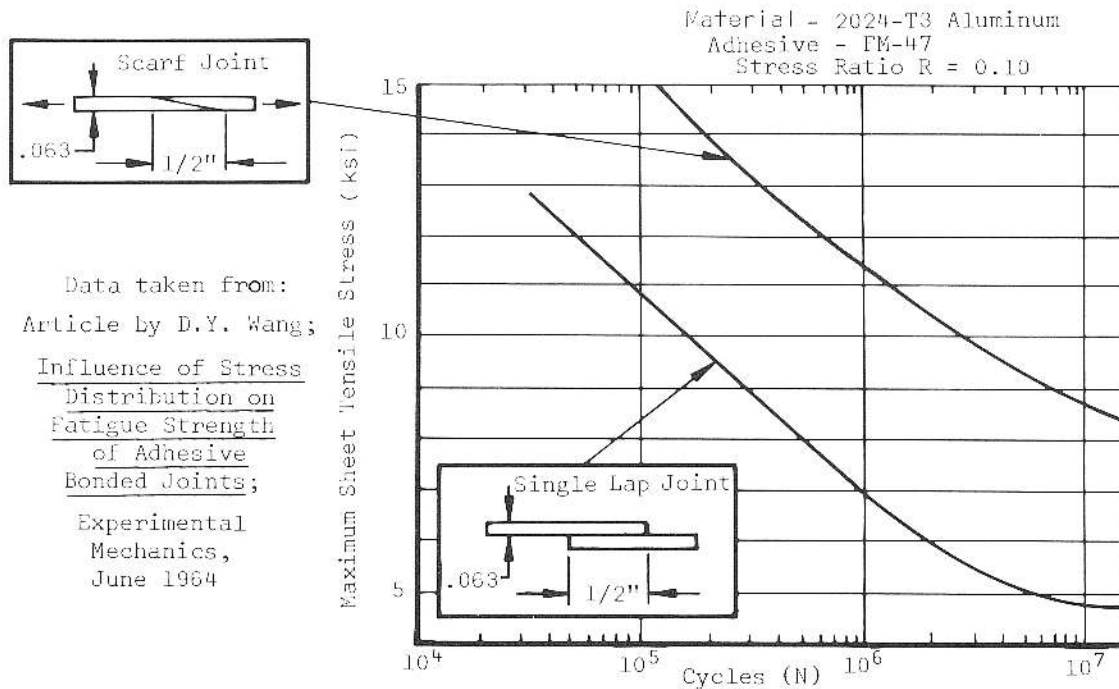INTEGRALLY-STIFFENED ALUMINUM ALLOY BOX BEAMS

Material - 2024-T3 Aluminum
Adhesive - FM-47
Stress Ratio R = 0.10

Scarf Joint

.063   1/2"

Data taken from:

Article by D.Y. Wang;

Influence of Stress
Distribution on
Fatigue Strength
of Adhesive
Bonded Joints;

Experimental
Mechanics,
June 1964

Single Lap Joint

.063   1/2"

Maximum Sheet Tensile Stress (ksi)

Cycles (N)

FIGURE 11

COMPARISON OF FATIGUE STRENGTH OF A SIMPLE LAP JOINT AND A SCARF JOINT

(6) Set up a quality-control system to maintain a high standard of reliability. Destructive test specimens should be frequently processed concurrently with production bonds.

Initial strength of a joint does not constitute a good reliable bond which will satisfy its intended service life. The adherend surface preparation is an important prerequisite in the permanence of joints subjected to simultaneous stress and adverse environment. Joints made with poorly prepared adherends may exhibit the same initial breaking strength as those made with adherends having undergone an elaborate chemical cleaning process. The bonds made with the minimum surface treatment, however, will prove inferior with respect to permanence. Elaborate metal-cleaning procedures might be alleviated by using a pre-priming operation incorporated in the material production line at the mill. This method is already used by a honeycomb panel

manufacturer in the United States. A primer is applied to both surfaces of sandwich facing material, accomplishing the following:

(1) Provides proper substrate for primary honeycomb bonding.

(2) Maintains clean surface for a later secondary bond if necessary.

(3) Primer acts as an additional corrosion-resistant barrier to all exposed surfaces of the adherend, whether or not a secondary bond is made.

This process could easily be incorporated as an additional step at the mill; however, the basic material cost could increase as much as 20 percent.

Repairs for bonded construction. - Repairs to damaged panels and surfaces might be necessary, either during production

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DESIGN FACTOR	ADHESIVE BONDING ADVANTAGES	LIMITATIONS
Aerodynamic Smoothness	Smooth exterior contours greatly improved.	
Cost	Savings achieved through bonding of large assemblies which have been properly designed for bonding or by weight savings.	Special tools and facilities are required for contoured parts.
Corrosion of Dissimilar Material Joints	Versatility of joining dissimilar materials is greatly improved. Corrosion in faying surfaces is reduced. Metals may be readily joined to non-metallics.	Differential coefficient of expansion must be considered due to the build-up of residual stresses.
Stress Concentration	More uniform distribution of stress through a bonded joint along entire length. Greatly reduces stress concentration.	Residual stresses may be induced during heat cure.
Fatigue Resistance	Great improvement--10 to 1 over rivets. Reduces crack propagation.	
Static Strength	Adhesives exhibit high strengths when stressed in shear. The more efficient adhesives either approach or surpass the sheet metal strength at an L/t ratio between 20 and 30. L = Lap length; t = adherend thickness.	Production adhesives are generally limited to 350°F.
Design Factor Weight and Size	Reduction of weight and size may be obtained. Greater capability for joining thin or brittle materials. In properly designed bonded structures, the following weight savings could be achieved over riveted structures: (1) Compression members: up to 25 percent (2) Tension members: 10 to 15 percent (3) Tension members designed by fatigue criteria: up to 20 percent (4) Some miscellaneous weight may be saved by eliminating the necessary local reinforcements usually required with conventional fasteners. NOTE: A typical overall weight savings for civil aircraft is 3 to 6 percent of the total structure weight	
Production	Many details may be eliminated which simplifies the overall design. Large areas may be bonded in a single operation.	A close tolerance between mating parts is essential. Special skills and personnel training are usually required.
Inspection	Non-destructive test techniques are available to insure good reliability.	Extensive quality control must be exercised, since the strength level of bonded joints may not be fully determined through non-destructive testing.
Sealing	Internal fuel cells and pressurized cabins are automatically sealed when bonded.	Bacteria growth in fuel may attack the adhesive. Components may require additional protective coating in these areas.
Electrical Insulation	Excellent.	Jumpers are mandatory for electrical continuity.
Miscellaneous	Compared to welding, thermal damage to parent metals is greatly reduced. Field repair is easily performed.	Proper surface preparation is mandatory for good quality bonds. Work areas for bonding must maintain a high standard of cleanliness.
Experience	Adhesives have been successfully used on military and commercial aircraft for over 10 years.	

TABLE VI.   ADVANTAGES AND LIMITATIONS OF BONDING

or after they are in service for some time. Consequently, effective repair methods must be developed to maintain the original contour, insure structural integrity, and prevent damage propagation.

Repairability requires: (1) the damaged part, dependent upon the extent of the damages, must be removable, if necessary, by some means that will leave the remaining parts undamaged; (2) the damaged part must be capable of being repaired, using mechanical fasteners, adhesive bonding, or a combination of both, without loss of properties to the remaining bonds.

Quite often, repairs are made with materials differing from the material of the damaged structure. Therefore, a repair adhesive must be capable of satisfactorily bonding a variety of materials, preferably under the same conditions of temperature and pressure. Another requirement for any repair adhesive must be that it displays an apparent forgiveness for less efficient cleaning methods in the field as compared to those used in the initial manufacture of the part. Regardless of whether the damaged assembly was made with a combined riveting and bonding technique, or by bonding alone, a repair can usually be made by using follow-up pressure-type mechanical fasteners. Another means of pressure application would be fabricated-in-place vacuum-bag blankets with portable vacuum pumps.

The following summarizes the main requirements of a repair adhesive:

(1) Since ovens, autoclaves, and special equipment will not be available at most field facilities, the repair adhesive must satisfactorily cure at near room temperature.

(2) It must also be capable of easy application within the temperature range of 40 to 100 degrees F.

(3) It must give good bond strength initially and after environmental exposure, for materials cleaned by methods not yielding the best possible surfaces for bonding.

(4) The effects of repeated cure on the original bond must not affect its integrity.

(5) It must withstand exposure to cleaning fluids used in service operations.

(6) It should have a good shelf life (at least 3 months), remain acceptable through a wide range of storage conditions, have at least 2 hours, and preferably 10 hours, of open assembly time.

END OF SERIES
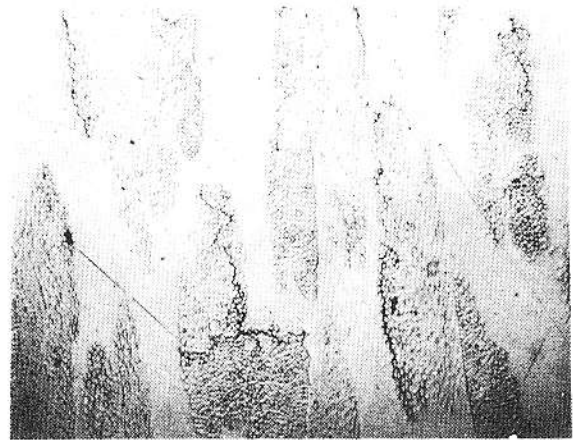
828/181 GLASS CLOTH COMPOSITE SUBJECTED TO 75% UTS FOR 100 CYCLES (100X)
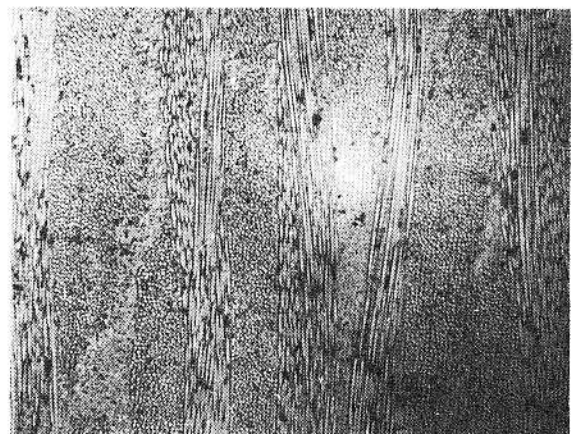
828-10% CTBN/181 GLASS CLOTH COMPOSITE SUBJECTED TO 80% UTS FOR 100 CYCLES (100X)