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# Design of Bonded Joints

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## Introduction

The design environment, weight, and performance goals of the U. S. Air Force B-58 supersonic bomber required an efficient, multipurpose structure. Specifically, the structure had to provide aerodynamically smooth surfaces, serve as fuel tank insulation, contain large quantities of fuel, support high stresses, and withstand high fuel pressure, severe acoustic noise, and induced thermal stresses. The bonded structure of the B-58 performs all the required functions, yet has the lowest structural weight to gross weight ratio of any airplane the U. S. Air Force flies today (0.165).

Essentially the entire surface of the B-58 is aluminum-bonded panel construction. Extensive application of bonded construction coupled with the demanding requirements placed on the primary and secondary structure required that a great amount of engineering consideration be given the design of bonded joints. Since theoretical techniques for the analysis of such joints were not considered reliable, what may be termed "empirical procedures" were followed. These procedures required extensive testing to establish and confirm joint design adequacy and bonded assembly allowable stresses.

Primary structures are those which must maintain their structural integrity to prevent the aircraft from malfunctioning. Failure of a secondary structure would not be considered critical to the operation of an aircraft.

The design of the B-58-type bonded structure has proved to be sound and, in fact, has exceeded early expectations. In an effort to improve design procedures, better theoretical methods of joint analysis have been pursued.

The information and data to be presented include a description of the procedures used in B-58 design and a description of theoretical approaches now being considered.

## Discussion

The B-58 design includes extensive primary and secondary structure of adhesive bonded sandwich and bonded metal construction (Fig. 1). Essentially the entire wetted surface is either bonded or brazed construction. It consists of bonded aluminum, brazed stainless steel, and laminated plastic panels. The majority of these are sandwich construction which is used throughout the wing, control surfaces, nacelles, exterior doors, fairings, and floor panels.

These are approximately 4500 sq. ft. of bonded paneling per airplane, using over 900 lb. of adhesives. Brazed sandwich represents about 800 sq. ft. of surface while the bonded-aluminum sandwich on the wing represents approximately 2000 sq. ft. of surface. Nearly all of these panels have compound curvature. Some are slight, but many are severe such as the leading edge and nacelle panels.

The entire outer wing skin is attached solely by structural adhesives. All skin loads must be transmitted across this bond line under environments such as extreme cold (−67°F.), aerodynamic heating (+260°F.), and high intensity sound (up to 170 db.).

The wing sandwich consists of aluminum alloy facings bonded to Fiberglas honeycomb core. Areas outside of the fuel tank use aluminum honeycomb core. All metal-to-metal bonds occurring at attachment lines are made with a nitrile rubber phenolic adhesive. All skin-to-core bonds are made

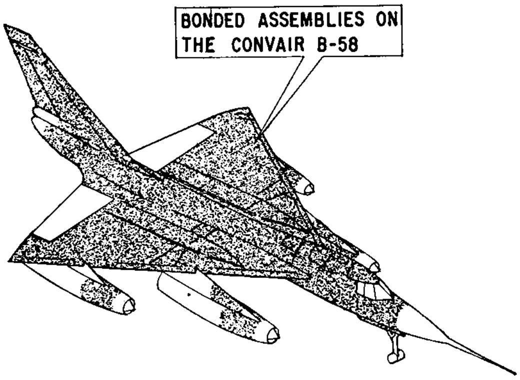

Fig. 1. The B-58 design.

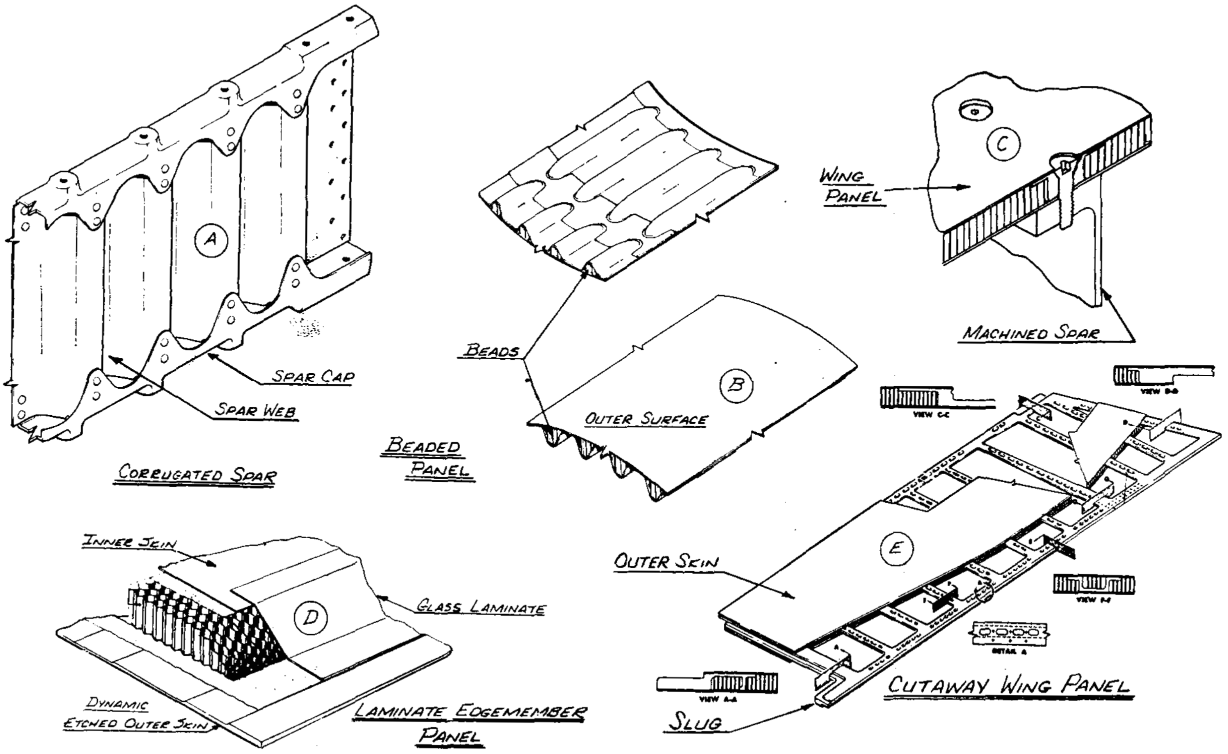

Fig. 2. Structural composites.

with an epoxy-phenolic adhesive. A typical section is shown in Figures 2 and 3.

The intermediate slug and edge members are an integral piece machined out of a single plate of aluminum (Fig. 2*E*). The integral slug concept greatly aided in achieving the structural weight goals established for the B-58. The advantages of the integral slug concept include: (*1*) elimination of splice plates (dagger plates), (*2*) reduction of tolerance problems connected with the fit of many detail parts, (*3*) reduced panel sealant problem in fuel tank areas, (*4*) provision for a much simpler substructure, (*5*) load introduction moved closer to the centroid of the panel, and (*6*) a more convenient assembly fixture.

In general the slug lips were added to provide a means of transferring core shear loads into the boundary or splice slugs (Fig. 2*E* and Fig. 3 slug lip *A*). Since the bond between the edge of the core and the boundary slug cannot be adequately inspected, it cannot be depended upon to transfer the shear stresses from the core to the boundary slug. In some cases the length of the slug lip is established by the bond overlap length required to develop the outer skin (Fig. 3 slug lip *B*).

Since the stress distribution across a bonded joint is not uniform and cannot be predicted from a simple lap shear test, the failing load of one overlap cannot be used to predict the strength of another overlap. The results of a given lap shear test

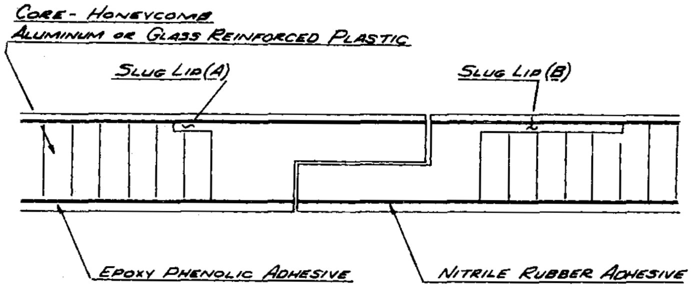

Fig. 3. Details of slug lip design.

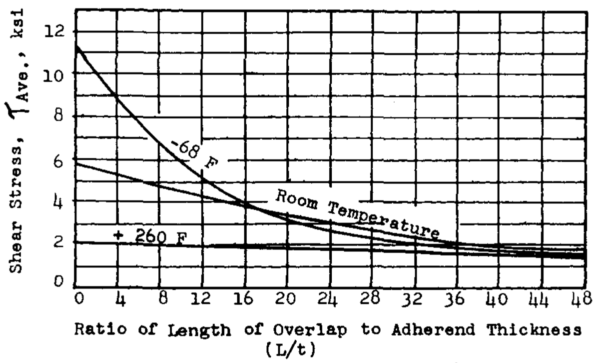

Fig. 4. The Pl 620 adhesive-double overlap specimens.

pertains only to joints of similar gage and overlap length. This relationship is referred to as the *L/t* ratio (ratio of length of overlap to adherend gage).

This empirical parameter varies from one adhesive to another and often appears in the form of $L/\sqrt{t}$. The results of a large number of lap shear tests of specimens with varying gage and overlap length are used to establish an *L/t* curve (see Fig. 4).

The required overlap length can be established without determining the actual stress distribution since average shear stresses were used in plotting the *L/t* curve. Any given *L/t* curve pertains to only one adhesive, bonded by a specific process, to adherends of a specific metal, and subjected to a specific operating temperature or environment. In other words, a different *L/t* curve is required for each adhesive, each operating temperature, each type of adherend, and each type of specimen, e.g., single overlap and double overlap. For this reason, sufficient quality control measures must be implemented to insure that the quality of the adhesive and process are maintained. The designer must assume that the quality of the bonded joint will not change.

In general, two principal types of shear specimens are being used at present.

The single lap shear is the most commonly used specimen. It is simple and easy to fabricate; however, the results may be misleading. The stresses on each adherend vary across the overlap; consequently, the resulting shear stress in the adhesive is not a uniformly distributed stress *P/A* but rather follows a distribution with stress concentrations at the lap ends where both adherend and adhesive are deflected sharply (see Fig. 5). These stress concentrations are a result of a combination of axial stress *P/A* and bending stress *MC/I* due to the eccentricity inherent in the single lap shear specimen as well as the modulus relationships between the adhesive and adherend. As the loads shift from eccentric to collinear, a peeling action is induced. If the adhesive is flexible, the load will be spread over a greater area, but if the adhesive is a rigid or brittle, the load will only act over a small portion of the adhesive area (approaching line contact) resulting in high stress concentrations and failure of the joint.

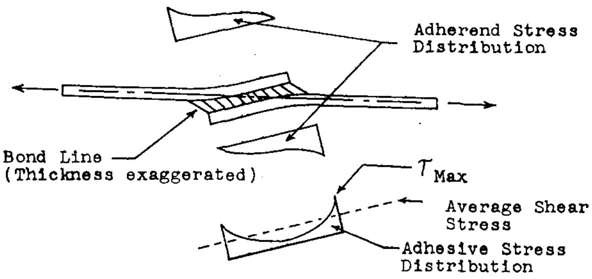

Fig. 5. Single lap shear specimen.

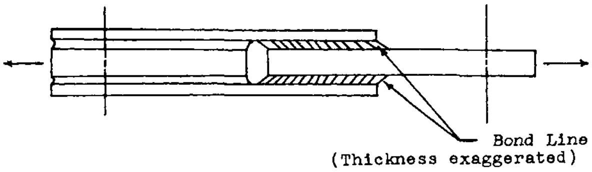

Fig. 6. Double lap shear specimen.

Very few, if any, production designs have joints which experience the degree of peeling action defined above. For this reason, more usable results can be obtained with double overlap specimens (Fig. 6) which reduce or eliminate the effect of the peeling or tearing forces.

The B-58 *L/t* curves were established by room-temperature −67 and 260°F. tests using the double overlap specimen (see Fig. 4). Each joint was then analyzed considering the maximum loading and adhesive strength at each temperature.

The required length of overlap is determined by:

*1.* Obtaining a trial overlap length by dividing the allowable shear strength corresponding to an *L/t* of 16 (Fig. 4) into the load to be transferred across the joint.

*2.* Using this trial overlap length and the actual adherend thickness, calculate the corresponding *L/t*.

*3.* Obtain the allowable shear stress (Fig. 4) corresponding to the *L/t* value calculated in step 2.

*4.* Using the allowable shear stress from step 3, calculate the second trial overlap length.

*5.* Repeat steps 2, 3, and 4 until the corrections to the required overlap length are negligible.

In addition to providing for adequate strength, the designer must consider many other factors such as minimization of tolerance requirements. If possible, the joint should be self-adjusting to compensate for possible mismatch conditions between the various components of the joint.

A novel example of a design to minimize tolerance requirements is the use of glass-reinforced plastic (GRP) edge members (Fig. 2*D*) in the design of aluminum sandwich panels. The "wet lay-up" glass-reinforced edge members adjust to slight variations in core thickness and mismatch of detail parts.

The design of these edge members was complicated by the fact that the modulus of elasticity of the GRP edge members was much lower than the aluminum panel facings. The optimum design utilized the full shear transfer ability of the core to assist the GRP edge members in transfering the load to the inner sandwich face. The thickness of the GRP edge member was then determined from considerations of consistent deformations of the various components. Using this thickness, the required overlap length was determined employing the *L/t* procedure described earlier. The designer should constantly strive to eliminate bonding problems which will make his design very costly or even unproducible. In all cases, the total tolerance buildup that is possible should be considered.

The various bonded panel designs on the B-58 were confirmed by tests of full size test panels designed to be representative of the various production configurations. These panels were tested under loadings considered critical for each type of structure. Tests were conducted at −67°F., room temperature, and 260°F. Subsequent tests showed the B-58 bonded structure, with relatively minor and inexpensive modifications, to be capable of sustained exposure to temperatures up to 325°F. Test panels were loaded in axial compression and tension with and without internal pressure, in-plane shear, combined axial compression and in-plane shear, and combined axial compression, bending and shear. In addition, the joints were tested to establish sonic and cyclic fatigue resistance as well as creep strength. This test program involved 2000 bonded test panels. The results of these tests were used to establish design allowables for the various bonded panel configurations. If a significant change in adhesive, metals, or process is made certain portions of this program must be repeated.

The *L/t* approach does not account for the fact that the amount of load picked up by a doubler or slug depends upon the shear ratio of the adhesive (shear modulus to shear strength) and tensile ratio of the adherends (tensile modulus to strength). This relationship, in turn, greatly influences the amount of load that must be transferred through the bond line to the skin and thus the length of overlap required. In order to insure compatibility of the constituents of a joint, the shear ratio should be less than the tensile ratio. The exact relationship required has not been determined. The shear ratio for the successful B-58 bonded aluminum system is approximately 1/10 of the tensile ratio. The shear ratio of an unsuccessful experimental bonded titanium system was about equal to the tensile ratio.

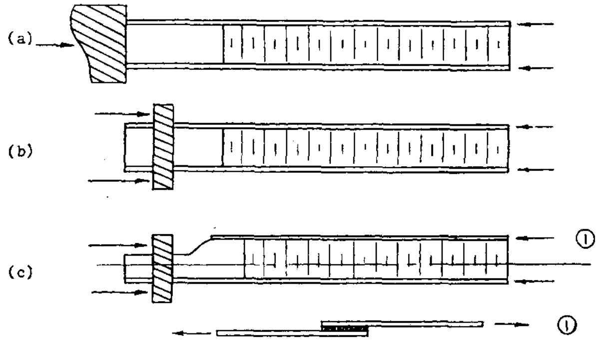

Fig. 7. Basic types of bonded joints.

Since the methods of bonded joint analysis presently used are empirical, costly, and involve the possibility of serious errors in the extrapolation of existing data to other materials and environments, an accurate theoretical method of predicting joint strength has been approached.

In developing such techniques, three basic types of bonded joints have been considered as shown in Figure 7. In Figure 7*a*, the slug and facings are loaded together in bearing. In Figure 7*b*, the slug and facings are loaded together in bearing by a bolt. The slug transfers its load to the skin through the bond line. In Figure 7*c*, one half of the joint is the same as Figure 7*b*, but the other half transfers the load from the slug to the skin solely through the bond line.

Theoretical expressions are being developed for the three basic joint types. The expression for predicting the joint strength of type Figure 7*a* (derivations given in 1960 ASTM preprint No. 86b) is:

$$P = \tau_{\max} \frac{E t_f t_b K}{G \tanh K} = \text{load introduced into one face}$$

where:

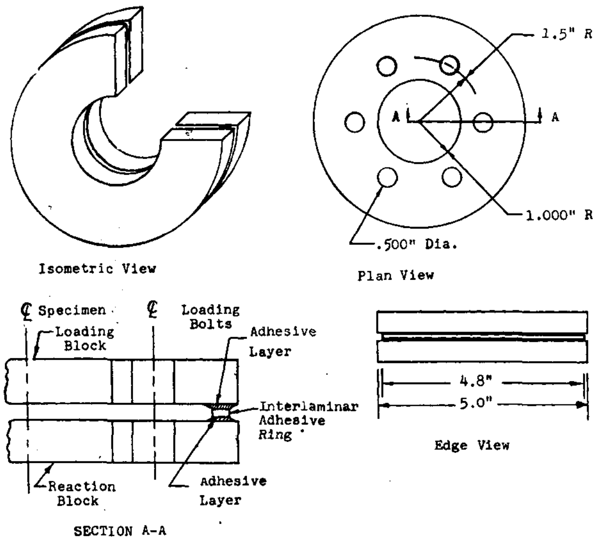

Fig. 8. Double shear torsion specimen.

$$K = \sqrt{\frac{G}{Et_b}\left(\frac{1}{t_s} - \frac{1}{t_f}\right)},$$

$\tau_{\max}$ is the maximum, or true, shear strength of the adhesive (rather than average); $G$ is the adhesive shear modulus, psi; $E$ is Young's modulus of elasticity for the panel facings, psi; $t_b$ is the thickness of the bond line, inches; $t_f$ is the thickness of the face, inches; and $t_s$ is the one-half thickness of slug, inches.

In order to use this expression the shear modulus and maximum shear strength of the adhesive must be determined.

A specimen simulating the torque loading of a large diameter thin-walled tube has been selected to obtain these values. This specimen consists of two large discs or loading blocks with a thin narrow ring bonded between them (Fig. 8). The specimen size is not critical as long as the diameter of the adherend ring is large compared to the width of the ring. If this ratio is 20 or more, the shear stresses in the bond line will be very nearly uniform. The maximum shear stress, $\tau_{\max}$, can then be determined from the following expression:

$$\tau_{\max} = \frac{Tr}{I_p}$$

where

$$I_p = \pi \frac{(r_0^4 - r_i^4)}{2}$$

$T$ is the applied torque at failure, $r$ is the radius to mid-point of interlaminar adherend ring, $r_0$ is the radius to outside of interlaminar adherend ring, and $r_i$ is the radius to inside of interlaminar adherend ring.

By carefully measuring the rotational deflections within the elastic range of the adhesive, the shear modulus of the adhesive can be determined:

$$G = \tau/\gamma_b$$

where $\gamma_b$ is the strain per unit thickness of adhesive (care should be taken to correct strain measurements for the deflection of interlaminar adherend ring).

In order to obtain accurate values for the shear modulus, an optical lever system (Amsler Muroe apparatus, type SA37) has been found necessary for obtaining the adhesive strain measurements.

Theoretical methods for predicting the joint strength of the other two basic types of joints will be developed as soon as the expression presented here has been checked out using the double shear torsion specimen to obtain the required values of $G$ and $\tau_{\max}$. This work has been closely coordinated with the ASTM Committee on shear and torsion and has been recommended for adoption as a standard upon the successful completion of the test program.

The degree of refinement required in design procedures is dependent upon the degree of optimization desired or considered economically feasible. Primary aircraft structure with low factors of safety may demand more refinement than would be considered necessary for other types of structure where minimum factors of safety are not so mandatory.

## References

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## Synopsis

Essentially the entire surface of the U. S. Air Force B-58 supersonic bomber is aluminum-bonded panel construction. Primary as well as secondary structural bonded panels were designed and manufactured to operate under demanding service conditions which include high stress, subzero temperature, high temperature, and severe acoustical vibration. Smooth surfaces are an additional requirement at subsonic and supersonic speeds. These requirements demanded that bonded joints in the B-58 be carefully designed and thoroughly evaluated. Joints in the B-58 were designed by "empirical procedures," established for a specific adhesive system. Large numbers of test panels were required to confirm panel integrity and establish allowables for design. The development and adoption of accurate theoretical technique for predicting joint strengths has been pursued and can be expected to reduce both the cost and the amount of testing required to achieve reliable design with adhesives.

## Résumé

Fondamentalement, toute la surface des bombardiers supersoniques B-58 de l'U.S. Air Force est construite en panneaux soudés à l'aluminium. Les panneaux de construction soudés étaient étudiés et fabriqués pour opérer dans des conditions de service déterminées qui incluent la haute pression, basse et haute température et de nombreuses vibrations acoustiques. Des surfaces lisses sont une exigence supplémentaire pour des vitesses subsoniques et supersoniques. Ces exigences requièrent que les joints de soudure, dans le B-58, soient étudiés avec précaution et évalués parfaitement. Dans les B-58, les joints ont été étudiés par ce qui peut être appelé des "procédés empiriques" établis pour un système adhérent particulier. Un grand nombre de tests ont été requis pour conformer l'intégrité des panneaux et établir leurs possibilités dans les projets. Le développement et l'adaption d'une technique théoriquement juste pour prévoir la résistance du joint ont été poursuivis et il peut en être attendu une réduction à la fois du prix et du nombre de tests nécessaires a l'élaboration d'un projet sérieux en ce qui concerne les adhésifs.

## Zusammenfassung

Im wesentlichen bildet die gesamte Oberfläche des U.S. Air Force B-58-Überschallbombers eine Aluminium-gefasste, getäfelte Konstruktion. Panelplatten für primäre und sekundäre Strukturen wurden für eine Verwendbarkeit unter den Dienstandforderungen, nämlich hohe Spannung, Temperatur unter Null, hohe Temperatur und schwere akustische Schwingungsbelastung entworfen und angefertigt. Glatte Oberflächen bei Unterschall- und Überschallgeschwindigkeit sind ein zusätzliches Erfordernis. Diese Ansprüche machen eine sorgfältige Konstruktion und Testung der Verbindungsstellen im B-58 notwendig. Die Verleimungen im B-58 wurden nach, so zu sagen, "empirischen Verfahren" hergestellt, die für ein spezifisches Klebemittelsystem ausgearbeitet wurden. Eine grosse Zahl von Testplatten war zur Feststellung der Unversehrtheit der Platten und der Aufstellung von Entwurfskriterien notwendig. Die Entwicklung und Übernahme eines genauen theoretischen Verfahrens zur Voraussage der Festigkeit von Verleimungen wurde angestrebt; von einem solchen Verfahren kann erwartet werden, dass es die Kosten und den Umfang der zur Erreichung einer verlässlichen Konstruktion mit Klebestoffen notwendigen Testversuche herabsetzt.