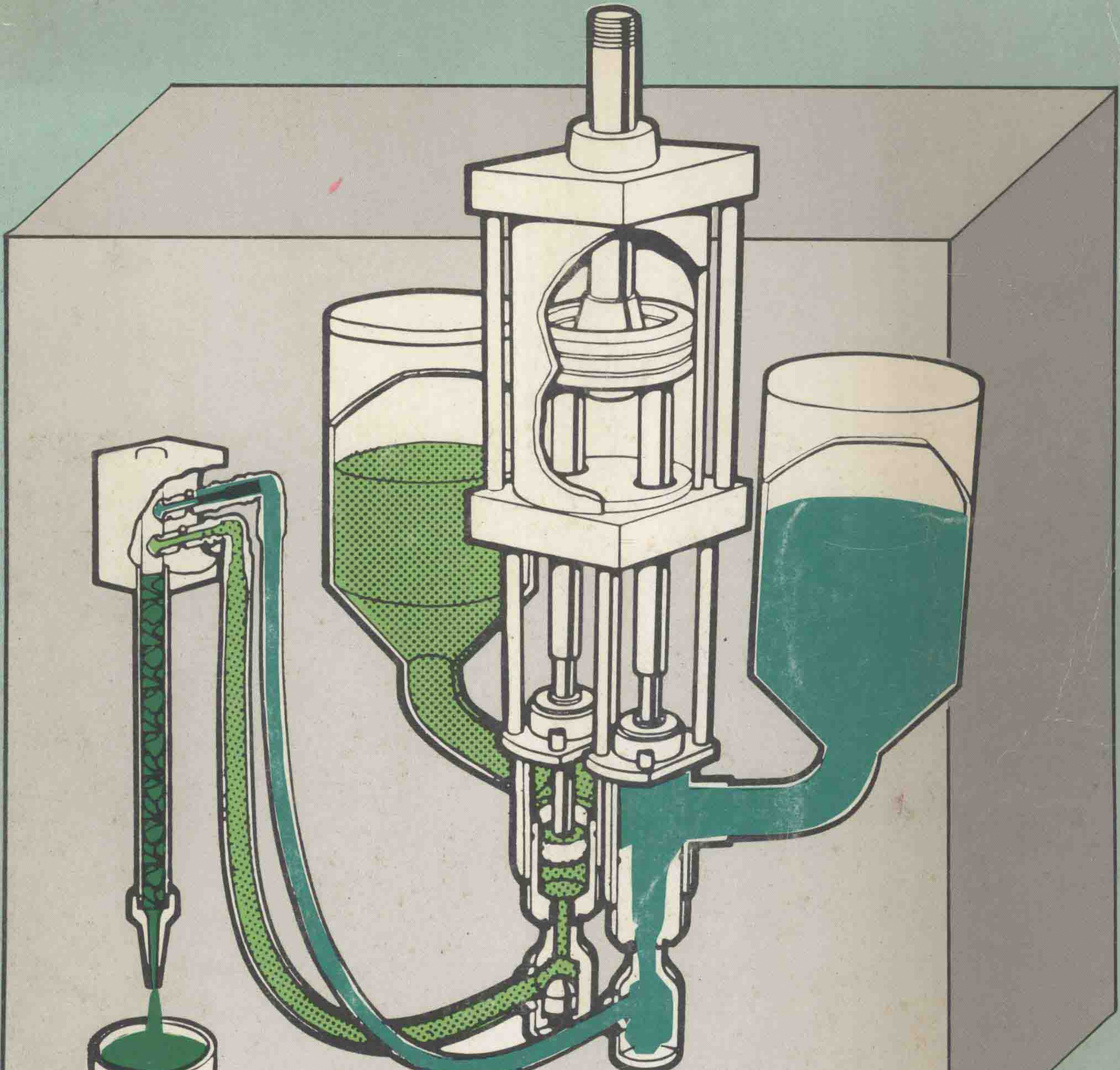
Structural Adhesives in Engineering



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STRUCTURAL ADHESIVES IN ENGINEERING

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CONTENTS

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Stress analysis concepts for adhesive bonding of aircraft primary structure

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1. INTRODUCTION

Structural bonding with organic adhesives is a mature industry. Perhaps the most significant work has been done in the field of aircraft structure, where weight saving and fatigue life are the primary driving forces. In recent years, bonding has progressed from secondary structures, (not critical to safety of flight), to primary structure, where failure leads to the loss of the aircraft. This step could not have been taken without the capability of proper stress analysis. This is discussed, with emphasis on current instrumentation to provide vital data on adhesive shear stiffness. A current example of primary structure bonding is presented and discussed in light of decisive adhesive stiffness properties and their quality control.

2. THE SKIN-DOUBLER CONCEPT AS A MODEL JOINT

It is desirable to establish simple configuration of bonded joint for study and stress analysis. Such a joint should represent "real life" structure in a typical and fundamental way. The so called lap shear specimen does not serve well; it is too short to develop the full, efficient, shear stress distribution in the adhesive. The configuration selected is the skin-doubler specimen described in Ref. 1. The bonded joint is that between an infinitely long skin and a doubler which is also infinitely long. The skin is loaded in tension and the adhesive transfers tension load into the doubler. Fig. 1 shows the configuration.

2.1 STRESS ANALYSIS OF THE SKIN-DOUBLER SPECIMEN

The shear stress distribution in the adhesive is described in Fig. 1. There is a peak at the doubler tip which fades away to zero stress at some point along the joint. At this point, the tension stress, or strain in the doubler equals that in the skin, hence no further load transfer is needed. The equations shown in Fig. 1 are for the case when stiffness parameters are linear, the skin gauge equals the doubler gage, and the glue line thickness is constant. The equations shown are developed in refs. 1 and 3.

2.2 INSIGHT ON THE ADHESIVE AS A FASTENER

The formulae shown in Figure 1 give the maximum adhesive shear stress (at the doubler tip) and the distance required for the adhesive stress to fade to zero. These two values are seen to be driven by stiffness of the glue line.

If the shear modulus, G, is reduced, the peak adhesive shear stress is reduced, with no change in load on the structure. Thus the adhesive, as a fastener, exhibits very unique behavior. It will vary its peak stress in a joint with changes in its stiffness (from temperature, fluid absorption, and glue line thickness), with no change in the load on the structure. The distance to zero adhesive shear is also dependent on adhesive stiffness change.

2.3 INSIGHT ON JOINT DESIGN

Inspection of the formulae in Fig. 1 shows that as the metal gauges go up the adhesive shear stress goes up. This is because thicker skin can carry more load. Also, when the doubler becomes thicker, the peak shear stress increases, see Ref. 1.
These phenomena mean that proper joint design involves limiting the ratio of skin gage to doubler gauge. If a thick skin must be unloaded, a single thick doubler will not serve. The doubler must be "stepped" or varied in thickness from the doubler tip.

3. EXTENSOMETER FOR ADHESIVE SHEAR STRAIN

The need for adhesive shear stiffness data is apparent. It is necessary for all stress analysis. It must also be known for all aircraft environments, since it will change with temperature. The early test methods, such as torsion tubes, proved too costly. The expense of sufficient data for statistical confidence was prohibitive. To solve the problem economically, the thick adherend specimen (Fig. 2) was developed. It is essentially a lap shear specimen, but with metal so thick that the adhesive shear stress is nearly uniform over the test area. Next, the KGR-1 extensometer was developed (Ref. 2) to measure the shear movement of the glue line. This instrument is described in Fig. 3. The movement of the glue line is made to move the core in an LVDT. The voltage change is fed to a recorder which produces a curve of load vs. glue line movement. Two instruments are used to eliminate errors from unsymmetrical specimens. They are held on the specimen by being attached to each other by springs as in Fig. 4. These springs cause the steel points of the extensometers to grip the specimen and thus support each other.

3.1 KGR-1 EXTENSOMETER DATA REDUCTION

Figure 5 presents a typical shear stress-strain curve obtained with KGR-1 extensometer. The recorder produces a curve of specimen load vs. total specimen deformation in shear. For any point on the curve, the shear stress is found by dividing the load by the bond area . The adhesive shear deformation is found by simply subtracting the metal deformation from the total deformation signal. (Reference 2 presents the method and validity of obtaining the specimen metal deformation). Shear strain is deformation divided by glue line thickness. The shear modulus (G) is found (for the initial linear portion of the curve) by dividing the shear stress by the shear strain.

Three basic points are presented to adequately define the curve. they are, 1) LL (Linear Limit), 2) KN (Knee) and 3) UL (Ultimate Strength). The rationale for simplifing the full curve to these three points is as follows:

LL - Linear Limit - this is arbitrarily chosen as that point at which the curve departs from a straight line through the origin. The coordinates of this point establish the shear modulus (G) for use in stress analysis in the linear range. Since modulus is the prime usefulness of the LL point, it does not matter if personal judgement produces a scatter in the stress values, so long as the point is taken on the curve. Should the curve have no straight line portion, the coordinates of LL are presented as zero stress and zero strain.

KN - Knee - This point is found by bisecting the angle between the initial tangent and another tangent drawn to the curve beyond the "knee" region, (Figure 5). The worth of this technique can be judged from the following considerations:

1) The purpose, no more and no less, is to establish a region, not a point, where a rapid drop in stiffness occurs.

2) This region has been found, so far, to be possibly decisive for repeated loads. For load above the knee region, there appears to be a loss of useful fatigue life. This suggests that irreversible mechanical damage has occurred, and that it may reduce environmental durability. Repeated loads, quite near to KN, have shown a reduction, for each single cycle, of LL stress and shear modulus. This seems to say that useful fatigue life exists below KN, but above LL. (See Ref. 5).

3) It is rational to assume a range, not a point, for fatigue life, i.e., higher stress with lower number of cycles and vice versa.

4) We consider this to mean that the "yield" point concept for metals is not applicable. Metals can be taken beyond yield (forming parts by permanent set) yet still retain stiffness, fatigue life and environmental durability. This cannot be safely assumed for structural adhesives.

In view of these considerations,it is considered fruitless to attempt to define a precise point of any value between LL and KN.

UL - Ultimate Strength - This is simply the point at which ultimate failure occurs. It corresponds to that load which the structure must endure just once in its service life.

4. VERIFICATION OF STRESS ANALYSIS FOR SKIN-DOUBLER SPECIMEN

Withthe advent of accurate adhesive strain data via KGR-1 extensometer, it became possible to verify the skin-doubler formulae in Fig. 1. To do this, another extensometer was needed to measure the adhesive shear strain at the doubler tip. This measured value could then be compared to the calculated value. The second extensometer is identified as KGR-2 and is shown in Fig. 6. As before, the adhesive shear movement, Δa, at the doubler tip is made to move the core of an LVDT. The voltage change is fed to a recorder which plots a curve of load versus adhesive strain at the doubler tip. Tests were run on a skin-doubler specimen and the results are shown on Fig. 7. In addition to measuring the adhesive strain at the doubler tip, scribe lines were made at intervals across the glue line. These lines are offset by the adhesive shear movement. Fig. 7 shows these offset values as they describe the shear stress distribution. Ref. 3 describes this work in detail. As can be seen in Fig. 7, the agreement between calculated and measured adhesive shear strain is very convincing.

4.1 SKIN-DOUBLER ADHESIVE STRAIN IN THE NON LINEAR RANGE

To this point, the stress analysis has been in the linear range of the adhesive shear-stress curve. This range is important, and possibly decisive in design, because it is here that durability in creep and fatigue comes into play. For analysis above limit load and on to ultimate failure, the non-linear portion of the stress strain curve must be used. The Mathematics for this are necessarily complex, but KGR-2 can supplement the work for simple joints. This is illustrated in the next section.

5. SHEAR STRESS-STRAIN DATA FOR THREE ADHESIVES ON THICK-ADHEREND AND SKIN-DOUBLER SPECIMENS

Figure 8 presents data for three adhesives tested on the thick adherend specimen and on the skin-doubler specimen. In order to conveniently show relationships, the two sets of data are plotted using identical adhesive strain scales. Strain is shown on the horizontal axis. The two sets of data are set one above the other with their strain scales exactly aligned. Given a point on one curve, its mate on the other can quickly be found by travelling on the strain line until it intersects the pertinent curve. For example, in the thick adherend test, adhesive A has its knee at a strain of .08 inch per inch. Moving down to the skin-doubler curve on this strain line, we find that the skin metal is at a stress of 40,000 psi. In this way, real life conditions for skin-doubler bonds can be quickly considered because the adhesive strain (stress) is readily found for any skin metal stress. Three adhesives were chosen because they represent actual data for three major differences in properties. These differences are:

1) A difference in shear modulus (the slope of the initial portion of the curve). Adhesive

FM®400 is approximately three times stiffer than FM®300K or FM®73M.

2) A difference in knee value. Adhesive FM®300K has a higher knee than adhesive FM®73M with the moduli being essentially the same.

3) A difference in elongation, defined as strain at the point of ultimate failure.

In addition to the stress-strain curves, the following tables gives conventional test comparisons on the basis of a value of 100 for adhesive FM®400.

ADHESIVE	METAL-TO-METAL PEEL BELL METHOD	LAP SHEAR MMM-A-132
FM®400	100	100
FM®300K	300	140
FM®73M	900	170

Thick adherend test data suggests FM®400 is superior. The confusion is dispelled by the real life skin-doubler data, which shows (for ultimate strength) that adhesive FM®73M is superior, because it can work the skin metal to the highest stress before adhesive failure. However, the advantage of FM®73M is by no means as great as lap shear and peel would suggest. There is here a strong implication that environment (say hot-wet) causing a drop from FM®400 to FM®300K and FM®73M would not be a loss in ultimate strength. In fact, this has been demonstrated with FM®73M adhesive. It is actually stronger on skin-doubler at 140°F with 100% relative humidity than at room temperature, dry.

Returning to Figure 8, skin-doubler tests, we can enjoy insight into durability. Let us query the ability of the bond to survive repetitive loading near limit load on the aircraft. Limit load corresponds to skin metal yield point, say 40,000 psi. Here the adhesive strains are FM®400 - .08, FM®300K - .12 and FM®73M - .15. Following these strain lines upwards into the thick adherend graph, we see that FM®400 and FM®300K are working near their knee points, and FM®73M is slightly beyond. We may conclude:

1) The drop from curve FM®400 to curve FM®300K is not a disaster. The reduction in knee is counteracted by the reduction in modulus, so the value of adhesive stress remains at the knee.

2) The drop from curve FM®400 to curve FM®73M is more serious, because the knee reduction dominates the modulus reduction. The adhesive stress has gone slightly beyond the knee.

3) The designer has decisive information by this method, far superior to data from peel and lap shear tests. Should prudence dictate, he can:
a) Run repetitive load tests on skin-doubler specimens. b) Reduce the doubler gauge. c) Increase the skin gauge.

4) The data pleasantly reaffirms that the bonded attachment is superior to rivets, because of skin area lost to their holes.

Next, let us query the ability of these adhesives to outlive the skin metal in fatigue. If we begin by taking the metal endurance limit to be between 14,000 and 17,000 psi, we see the adhesives working at strains between .02 and .04 inches per inch. Following these strain lines upwards into the thick adherend graph, we see all three adhesives working below their knee stresses. The indication is that the attachment has a realistic potential to outlive the metal. Again, it is pleasant to realize that we speak of the metal at its full capability, not compromised by rivet holes.

6. F-18 AIRCRAFT, BONDED ATTACHMENT OF WING TO FUSELAGE

This aircraft has the ultimate in primary structure dependant on a bonded attachment. The wing is literally bonded to the fuselage.

Fig. 9 shows the aircraft and the wing joint detail in a schematic diagram. Graphite reinforced plastic is used for the wing bending material in the form of top and bottom wing cover plates or skins. These are bonded to titanium fittings at the sides of the fuselage. As seen in Fig. 9, the joint is a stepped lap shear configuration such that the load is gradually removed from the graphite over a series of shear areas.

Adhesive selection for this aircraft narrowed down to FM®400 and FM®300K because of elevated temperature requirements. Referring back to Fig. 8 for the shear stress-strain curves, we might deduce certain performance differences. Although FM®400 appears stronger, FM®300K might provide higher ultimate strength for a given joint, by virtue of its higher ultimate elongation. This elongation reduces shear peaks at the joint ends, provides high peel strength, and resists crack growth. From the fatigue standpoint, FM®400 has a higher "knee" stress, but the advantage is compromised because FM®400 is stiffer. On balance, FM®300K appears the winner in fatigue and residual ultimate strength after fatigue experience, because its higher elongation reduces stress concentrations. In the event, fatigue testing bore this out and FM®300K was selected as the adhesive.

6.1 FATIGUE TEST DATA, FM®400 vs. FM®300K

Fig. 10 shows the fatigue test specimen together with the test data. The specimen was very nearly the exact configuration as on the aircraft, except for width, which was reduced to allow a practical load level. The "spectrum" fatigue life means a selection of frequencies, stress levels, and number of cycles consistant with the mission of the aircraft. The 24,000 hours represents a requirement of four lifetimes of the aircraft. Residual static load capability means the load at ultimate failure after the specimen has seen four lifetimes of fatigue load. As can be seen, FM®300K was superior in fatigue life, and dramatically superior in residual static load capability.

6.2 ADHESIVE SHEAR STRESS STRAIN PROPERTIES

Fig. 11 presents typical shear stress-strain properties at R. T. for FM®300K adhesive. The spread in values shown was arrived at by adding plus or minus one standard deviation to the average properties. This same data is available from the adhesive manufacturer for all temperatures from -67°F up to +300°F. The F-18 designers devised a set of requirements for stress--strain properties of FM®300K adhesive to ensure proper performance of the bonded structure. These requirements are in use as a batch quality control procedure, as described in the following section.

6.3 QUALITY CONTROL OF FM®300K ADHESIVE BASED ON SHEAR STRESS-STRAIN PROPERTIES

In the past, adhesive quality control was based on conventional lap shear and peel testing. As we have seen, these tests do not relate to the stresses on the adhesive in "real-life" designs. Such tests show little more than that the adhesives has the same ultimate strength as previous batches. To improve correlation with fatigue, creep, and ultimate strength of a specific design, the strain properties must be known. Accordingly, the designers of the aircraft devised limits for stiffness and ultimate elongation, which, if met, would ensure that design stresses would not be exceeded on the actual aircraft. These values are agreed by the adhesive manufacturer and are used as batch acceptance-rejection quality control tests. Fig. 12 presents these requirement plotted on the shear stress strain curve of Fig. 11. Stiffness is controlled by defining secant modulus limits, (high and low) when such modulus is taken at a point on the curve at 67% of UL strength. This ensures that the adhesive will produce the same stresses on the airframe for each batch of adhesive. Fatigue life is contolled by ultimate elongation. As seen in Fig. 12 this control is done by a lower limit for elongation over the range of ultimate strength.

7. CONCLUSIONS

In an objective way, it is concluded that proper stress analysis exists for bonded joints in aircraft primary structure. This concludes that satisfactory test instrumentation exists and, most important, that such testing is germane to the analysis and so is used as a quality control procedure.

In a more subjective way, it is concluded that the foundation of proper stress analysis is firm and will lead to even more improvements in testing. Specifically, this means that improved testing to produce allowable stresses for fatigue and creep are possible, Ref. 5. Finally, the benefits of structural bonding will be more widely enjoyed because of the confidence engendered by proper stress analysis.

ACKNOWLEDGEMENTS

The author wishes to express gratitude for the assistance and cooperation ot the United States Navy, Naval Air Systems Command, and the McDonnell Aircraft Company, St. Louis, Missouri for providing test data and other information presented in this paper.

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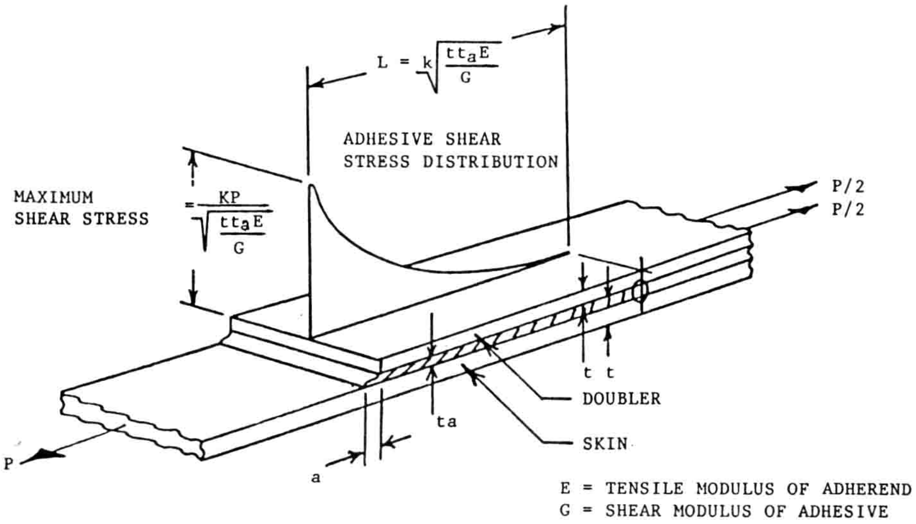


Fig 1 Adhesive shear stress distribution for skin-doubler specimen

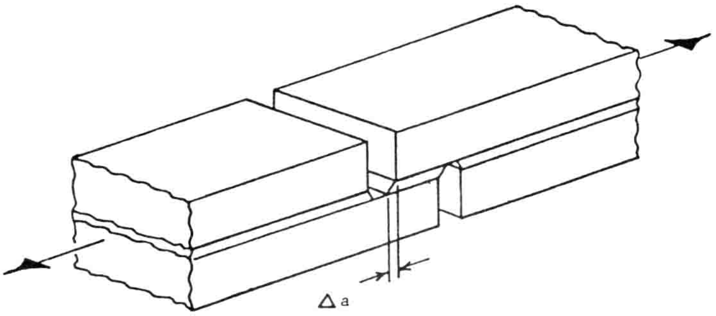


Fig 2 Thick-adherend lap shear specimen

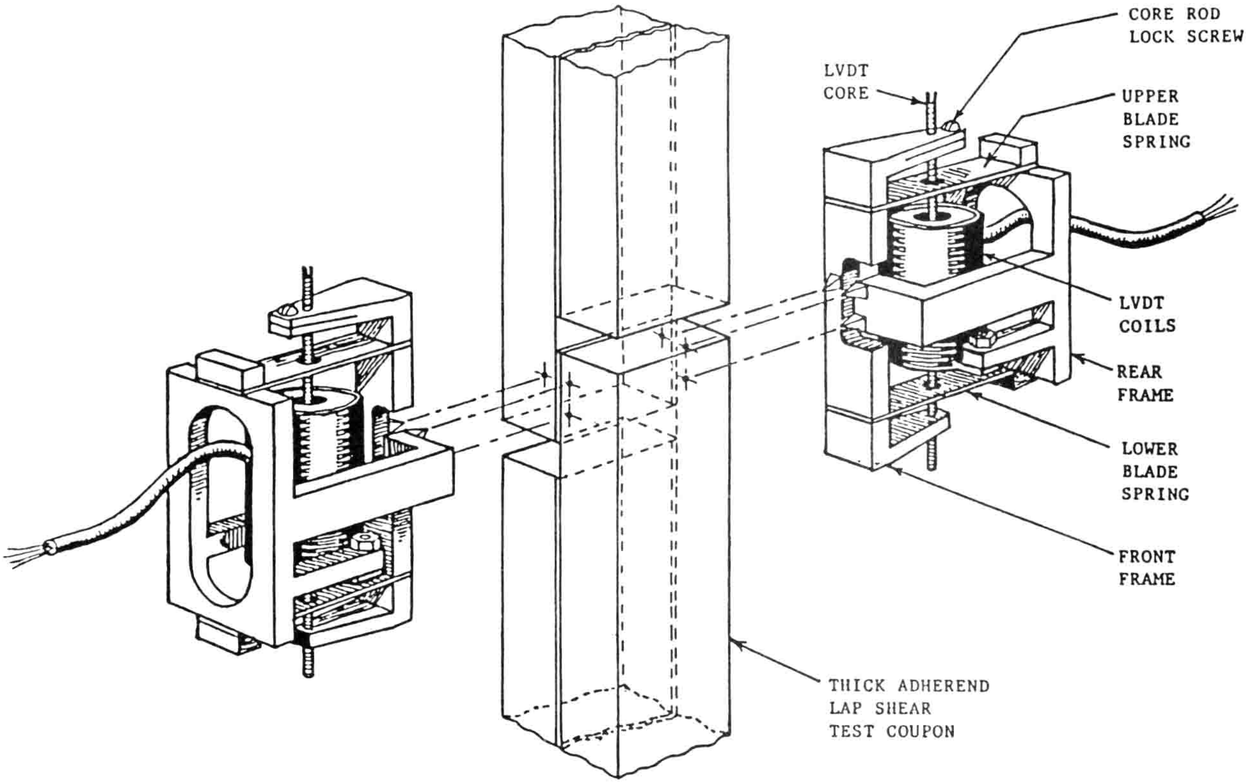


Fig 3 KGR-1 extensometer

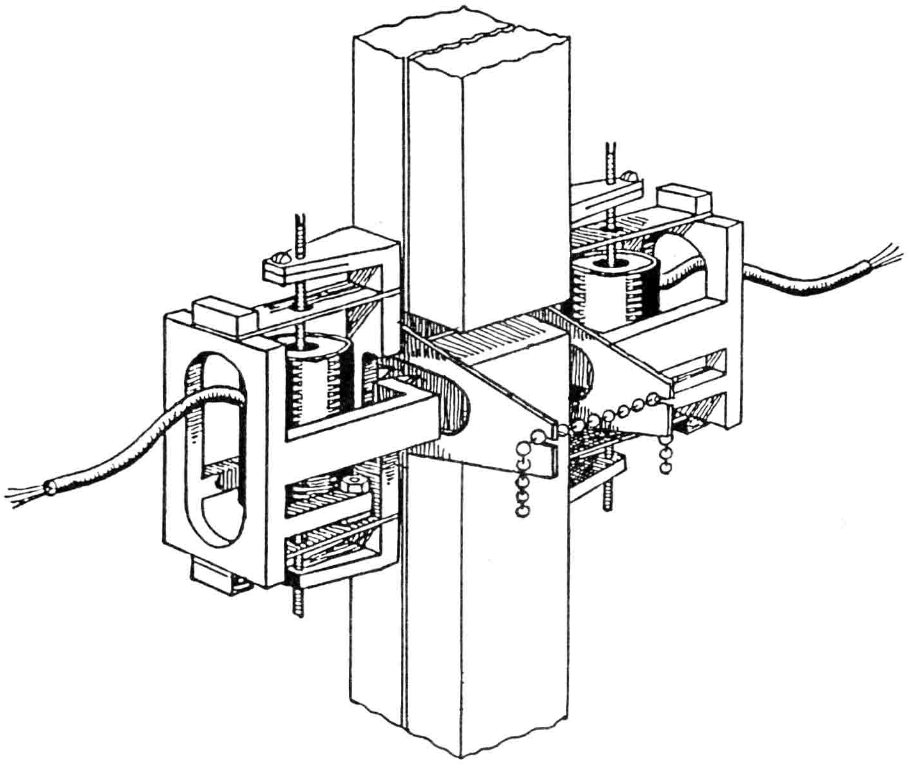


Fig 4 KGR-1 extensometer mounted on thick-adherend lap shear specimen

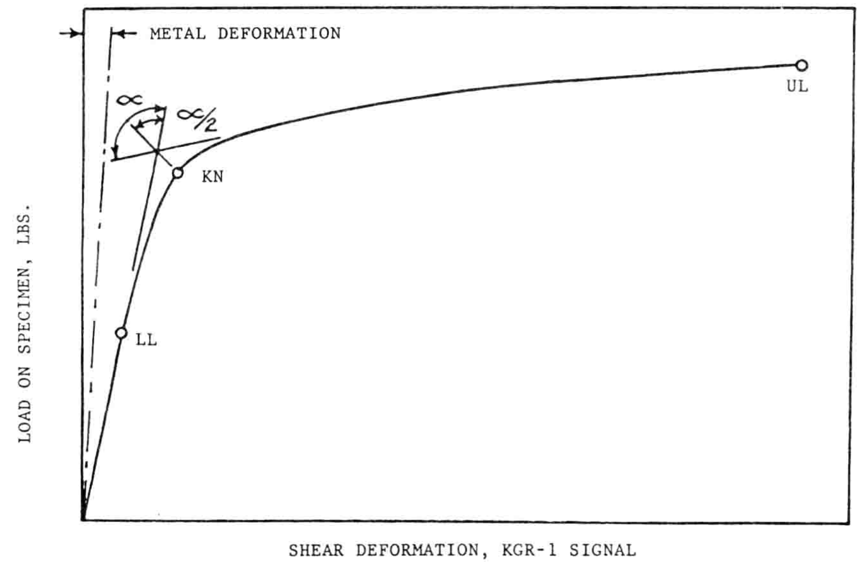


Fig 5 Shear stress—strain curve produced by KGR-1 extensometer

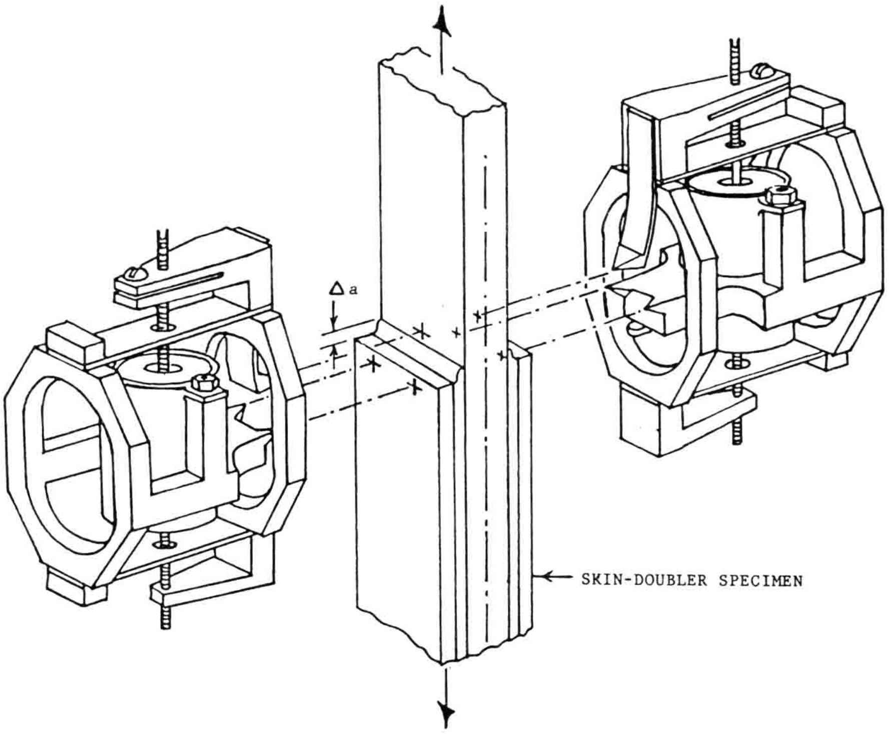


Fig 6 KGR-2 extensometer

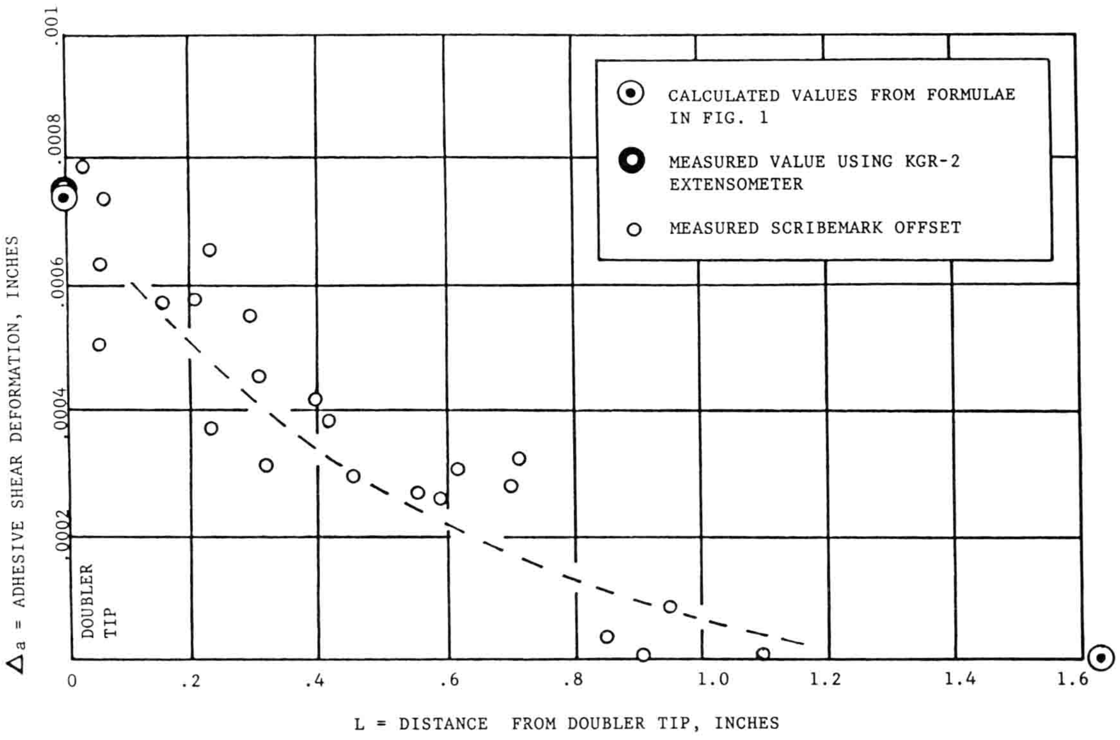


Fig 7 Skin-doubler shear stress distribution, calculated and measured data

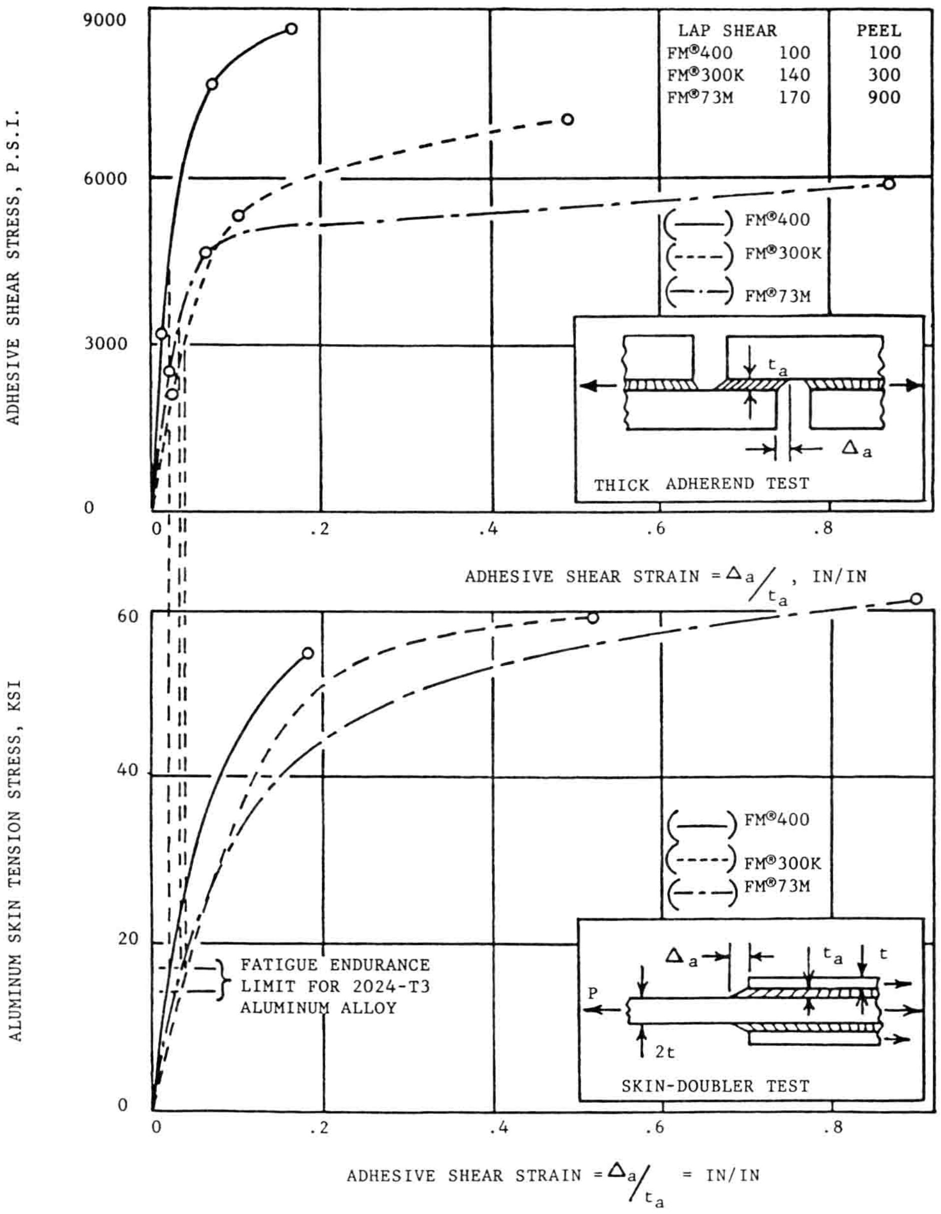


Fig 8 Shear stress–strain data at room temperature for three adhesives on thick-adherend and skin-doubler specimens

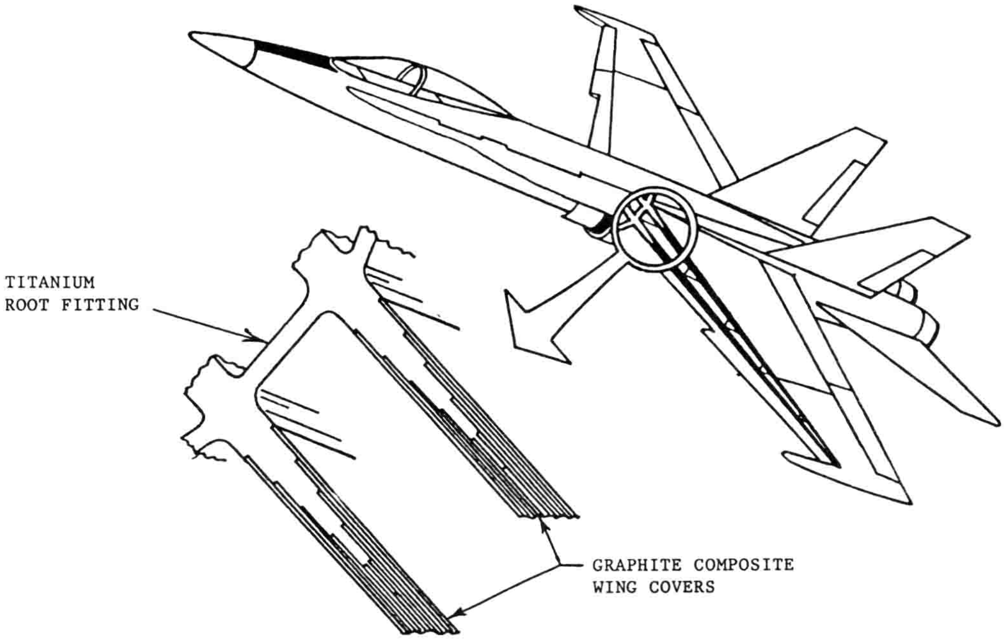
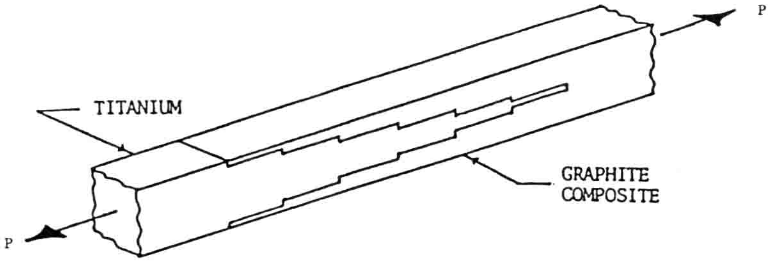


Fig 9 F-18 wing to fuselage attachment



ADHESIVE	SPECTRUM FATIGUE LIFE (HRS)	RESIDUAL STATIC LOAD CAPABILITY POUNDS
FM® 400	24,000 24,000 2,000	60,000 Avg. --
FM® 300K	24,000 24,000 24,000	130,000 Avg.

Fig 10 F-18 wing attachment fatigue specimen