QUALITATIVE ANALYSIS OF CANDIDATE BONDING AGENTS

TESTS CONDUCTED BY:

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INTRODUCTION

In the process of developing an aircraft a designer must choose materials and processes which best suit the manufacturing facilities, the company's line of expertise and other factors contributing to the overall fabrication and assembly effort. Our company is currently developing a line of composite aircraft which are designed to be safe, durable and simple to fabricate and assemble. Structural composites, our company's area of expertise, were chosen for these projects because we feel the performance gains justify the higher up-front cost of engineering and tooling development. As with aluminum aircraft, much of the durability and safety of the structure lies in the fabrication process but, unlike metal structures, the assembly of composite aircraft is a somewhat more complicated problem than just choosing rivets out of a catalog.

In order to realize the benefits of composite fabrication it is important to reduce conventional fasteners as much as reasonably possible, substituting bonding of primary components instead. The first step in this process is to design the structure as optimally as possible - the structure must be designed with composite concepts in mind. Too many of today's plastic aircraft still consist of I-beams, channels, reinforcing ribs, etc. - components which are commonly attributed to metal airplanes.

A composite airplane's structure (defined here as one made from fiber reinforced plastics) can be tailored to virtually any requirement by judicious selection and orientation of the directional material. Optimized, it should be able to be built as a monocoque shell with a minimal amount of internal reinforcement. Several years ago we developed a set of graphite wings for a biplane class racer (Reno Gold Cup winner 1994 and 1997) where the only internal structure were the two shear webs, and ribs at each mounting hard point. At the time, a few individuals questioned the lack of structure however, testing showed that the stressed skin concept worked just fine. The resulting wing was eight pounds lighter than the wood and fabric original, about ten times as stiff and more than twice as strong.

An important part of the development process for the optimum composite structure is the proper selection of bonding techniques and materials. In specifying the design criteria, one must examine not only the structural properties specific to the application but also those which will come into play over the life of the parts. In bonding, the significant properties are the peel strength and peel resistance of the bond. The bond strength (shear strength) is of course important too, but if the material is peel sensitive, structural endurance over the life of the part may be low.

In general, bonded components such as webs attached to wing skins, are loaded in shear, therefore it is important to initially examine the bonding agents' adhesion strength and its sensitivity to edge effects. But over the life of a part, variables other than load enter into play. These service factors could reduce the quality of the bond if the characteristics are not anticipated and designed for. Many bonding agents have some level of sensitivity to moisture absorption, a factor which could lead to delamination due to surface degradation (corrosion) or freezing (expansion of ice formation could initiate localized peel areas). Sensitivity to vibration or heat cycling could also physically weaken the bond through mechanical effects.

The tests presented herein examined a number of materials suitable for secondary bonding operations and qualitatively compared their properties and suitability for our purposes. This report covers two separate test procedures. The first examines bonding between two different materials, namely a vinylester/glass laminate and probably one of the most difficult materials to bond, aluminum.

The second series of tests also investigated aluminum bonding, but this time as a function of bonding agent and surface finish.

PURPOSE

The purpose of these tests is to qualitatively analyze candidate bonding agents and surface finish processes in order to ascertain their suitability for our assembly applications. By using a vinylester/glass laminate we are examining and comparing the bond quality of the baseline material chosen for our aircraft projects. In selecting aluminum, we are testing the bond strength of one of the most unbondable materials used in the aircraft industry. The tests will examine several different surface preparation techniques and examine their effect on the bond's peel strength. If the bonds prove practical, we may select aluminum for application to our shear webs and other internal structures, in conjunction with laminate structures for the skins, spars, and possibly ribs..

Using the results of the tests, we should be able to qualitatively select the best overall bonding agent and aluminum surface preparation procedure for all our applications. Since most suppliers have physical properties on file, the only critical information required is the comparison of bond quality and sensitivity to edge peel within the given material constraints.

Note: The peel tests done here do not conform to the ASTM methods of testing for similar properties. The procedures used here were strictly for obtaining comparative data, rather than numerical.

MATERIALS AND PROCEDURES - Test 1

The laminate used for the first set of tests consisted of a nine ounce fiberglass cloth (7781 weave), a six ounce boat cloth, graphite (unidirectional reinforcement to increase bending stiffness), and Reichhold VER 9100NP Vinylester resin. The wet lay-up was assembled on a sheet of glass and allowed to cure for five days before being removed and cut up into test coupons, each 4.985" wide and 13.75" long. The laminate schedule was: One layer of the six ounce boat cloth followed by two layers of 7781, a layer of graphite, finished off with a final layer of 7781. Although the schedule does not represent one to be used in our aircraft it does provide the identical bonding surface.

The theoretical thickness of the laminate is just under .06"; the actual thickness varied between .066" and .071". The average density of the panels was .065 #/cu. in.

The resin selected for our aircraft, Dow 411-45 Vinylester, was not immediately available for the purpose of this test therefore, a Reichold product was selected instead. The Reichold (VER 9100NP) resin has virtually identical properties of the Dow product and therefore was deemed suitable for this test.

Selection of the aluminum was also based more on availability rather than on similarity to our design however, since our primary goal in this test was to determine qualitative properties, the exact nature of the components was not considered a critical issue. The aluminum "T" extrusions were purchased from Boeing Surplus Sales in Kent, WA. The material was 6061-T6 (our proposed web material is 2024-T36).

The bonding agents selected for these tests represented a fair cross-section of those used in our industry today: Vinylester resin (Reichhold VER 9100NP), Jeffco 3102 epoxy, Hysol EA9430 epoxy, and Plexus MA330 Methacrylate adhesive. Vinylester for secondary bonding is commonly used by kits which use the same resin in their base laminate. This includes the Express aircraft and the Glasair line of airplanes. Similar to DOW's 411-45 resin, the Reichhold Dion VER 9100NP is a bisphenol epoxy vinylester resin which has historically demonstrated excellent structural properties. The high elongation resin has good corrosion resistance in a number of alkaline or acidic environments. FRP structures formulated with this resin have shown good stress fatigue resistance even when combined with thermal cycling. The resin has excellent wet out properties making it an excellent candidate for use with graphite materials.

Jeffco 3102 epoxy/hardener is described as a fast setting room temperature resin system. It has excellent working properties and sets relatively quickly even in thin films and low temperatures. A similar formulation is used by Lancair for bonding ribs to the wing skin and other less critical structural areas. The product, although a room temperature cure system, can be post-cured at an elevated temperature to achieve a higher service temperature resistance - HDT up to 214 deg. F.

Hysol's EA9430, the composite industry's favorite bonding materials for many years, has consistently proven to be superior to other products. The formulation is a modified epoxy adhesive that attains structural properties with room temperature cure. This two part adhesive is formulated to give very high peel strength coupled with excellent shear strength. Bonds are permanently flexible and resist water, salt spray, and many common industrial fluids. The tough, flexible nature of this adhesive makes it useful for bonding dissimilar substrates and for assemblies requiring a bond line up to one tenth of an inch thick. It is currently being used by the Lancair IV to bond wing skins to the spar and other primary structure applications. It is also used in the assembly of limited and unlimited hydroplanes, where impact and vibration stresses greatly surpass anything we see in aircraft applications. The only drawback to the resin is its significant working difficulty - unless warmed the resin has the consistency of taffy.

The last material is the Plexus MA330 Methacrylate Adhesive, an industrial bonding agent originally used in automotive assembly, but now making inroads into other applications due to its ability to bond many dissimilar materials with superior strength. It is a 1:1 ratio toughened structural acrylic with superior impact and peel resistance. It has been specifically formulated for applications requiring improved gap filling (to 3/8") and when sanding and painting of the bond line is necessary. It features room temperature cure, high shear strength and durability. It has good finishing characteristics and can be used as a supplement to other products for filling cosmetic imperfections. The resultant adhesive bond is resistant to weathering, humidity, and wide variations in temperature. On the negative side the system has a relatively short working time - on the order of five minutes when mixed by hand, ten to eleven minutes when dispensed from an electric gun with a mixing tip. For smaller components this is sufficient but may be a bit awkward when joining large components such as fuselage halves. The other drawback is the material's rather nauseating smell, something between well aged eggs and a dead opossum. When sanding the cured material one often feels the need to check one's shoes to make sure the smell is coming from the part and not something carried in from outside.

The following table is a brief listing of the tested bonding materials' available properties.

Property	Reich. 9100NP	Jeffco 3102	Hysol EA9430	Plexus MA330
Barcol hardness	35	84	(Shore D) 75	(Shore D) 78
HDT (deg. F)	220	214 *	140 +	250
Tens. Str. (psi)	11,600	9,450	5,300	NA
Tens. Mod. (psi)	460,000	493,000	380,000	NA
Flex. Str. (psi)	23,000	17,900	NA	NA
Flex. Mod. (psi)	500,000	377,000	NA	NA

* Post-cured at elevated temperature

Laminate surface preparation was identical for all the coupons: The surface was lightly sanded with eighty grit sand paper, then wiped clean with acetone and allowed to dry before the bonding agent was applied. In all cases the bonding agent was applied to the laminate coupon and the aluminum prior to assembly.

The aluminum samples were prepared three different ways. Test samples one through four were simply wiped clean with acetone prior to application of the bonding agent. Samples five through eight were lightly sanded with eighty grit sandpaper, then cleaned with acetone.

The third preparation of the aluminum coupons addressed the concern that all aluminum bonding takes place at the outside layer of molecules which are an oxidized form of the base metal. This aluminum oxide is considered weak and a poor substrate for bonding. In order to assure a bond to the aluminum itself we twice wet sanded the last six samples with a diluted mixture of the respective bonding resin and acetone, each time allowing the wetting agent to dry and completely cure before the second sanding. The first wetting mixture was about fifteen parts acetone to one part resin (by volume); the second cut that ratio by half to about seven to one. After the second sanding the parts were allowed to dry and cure for twenty four hours before proceeding with bonding to the test coupons.

All bonds were allowed to cure for seven days before testing.

Prior to the actual test it was discovered that the coupons were much stronger than anticipated - modifications had to be made in order to be able to conduct the tests within the capability of our existing fixture. Each coupon was cut down to a width of .67" to reduce the force necessary to initiate peel. A benefit of the trimmed pieces was the removal of excess resin flowing onto the aluminum edges, thus eliminating a possible cause of skewed data.

The setup for the test consisted of a vise which clamped each bonded assembly on the laminate .750" from the aluminum, and a five gallon steel drum which, by being filled with water, applied a load at ninety degrees to the bond line by pulling on the aluminum component near the clamped end (about .10" from the end). A cord connected the drum to the aluminum through a predrilled hole. The free end of the bonded assembly was supported so as not to allow the test coupon to bend over once the load was applied.

By clamping the substrate some distance from the aluminum, the applied load created an "S" shaped distortion in the laminate, setting up a peel condition at the bond interface. (Clamping at the interface would have created a pure tension condition.)

Upon reaching failure, the drum was detached from the fixture and weighed to determine the amount of force that was required to initiate peel failure. Each coupon was then examined for type and mode of failure.

A second set of tests were conducted on the pieces which were cut away from the main test samples. Here delamination was initiated by bending the laminate back from the aluminum, then with the aid of a wedge, forcing the aluminum up and away from the interface. The aluminum piece could then be slowly pulled away from the laminate a finite distance at a time. After a few of these coupons were delaminated it was found that the pieces that adhered the best formed a significant bend in the aluminum as it was being pried away from the surface. Coupons where the bond line was peel sensitive departed with little or no distortion. While far from precise, this test was used to back up the results obtained in the primary experiment.

The setup and numbering of the test coupons is as follows:

Test Piece	Surface Preparation	Bonding Agent
Coupon 1	Acetone Wipe	Vinylester
Coupon 2	Acetone Wipe	Jeffco Epoxy
Coupon 3	Acetone Wipe	Hysol Epoxy
Coupon 4	Acetone Wipe	Plexus Acrylic
Coupon 5	Dry Sand / Acetone Wipe	Vinylester
Coupon 6	Dry Sand / Acetone Wipe	Jeffco Epoxy
Coupon 7	Dry Sand / Acetone Wipe	Hysol Epoxy
Coupon 8	Dry Sand / Acetone Wipe	Plexus Acrylic
Coupon 9	Resin Wet Sand Prep.	Vinylester
Coupon 10	Resin Wet Sand Prep.	Jeffco Epoxy
Coupon 11	Resin Wet Sand Prep.	Hysol Epoxy
Coupon 12	Resin Wet Sand Prep.	Vinylester w/ glass
Coupon 13	Resin Wet Sand Prep.	Jeffco Epoxy w/ glass
Coupon 14	Resin Wet Sand Prep.	Hysol Epoxy w/ glass
Coupon 14b	Resin Wet Sand Prep.	Hysol Epoxy w/ glass

MATERIALS AND PROCEDURES - Test 2

The second, and most recent, set of tests were conducted on a series of aluminum samples, finished in five different surface treatments. The base material for all these coupons was 6061-T6. The first set of coupons were bare and smooth with only an acetone wipe for surface preparation prior to application of the bonding agent.

The second set of coupons were sanded with 120 grit sand paper and wiped down with acetone. In this case, the bonding agent was applied to the sanded surfaces within ten minutes of the wipe, well before the oxidation process had a chance to reform on the abraded surface.

The third set of coupons were acid etched and anodized. Each surface was cleaned with acetone prior to applying the bonding agent.

The forth coupon set was hardcoat anodized. An interesting side-effect of this process was the substantial embrittlement of the aluminum material as a result of the surfacing process. Care had to be taken when forming the tang (for attaching to the line coming from the bucket which supplied the pulling weight) so that the material would not crack and/or break off.

The last set of coupons were nickel coated (Alclad). The theory was that a better bond may be achieved with an oxide free nickel surface. The surfaces were only cleaned with acetone but otherwise untouched.

All the coupons were 4.0" wide and 6.0" long, bonded in pairs. Once the bonding agents were cured, the coupons were sheared into one inch wide segments.

This second test examined four different bonding agents. The first was the best agent of the first set of tests, the Hysol EA9430 epoxy. To date, we have used this epoxy (and a more user friendly formulation thereof - EA9412) with great success in secondary bonding applications and even limited wet layup.

The second bonding agent was an epoxy manufactured in Canada by Industrial Formulators of Canada. According to the company rep, this material was originally developed to aid in fastening concrete roadways to steel bridge structures. The formulation includes a measure of a vulcanized rubber compound which aids flexibility and impact resistance.

The third bonding agent was a Polyurethane material commonly used in coating truck beds and other surfaces which expect harsh treatment and weather. The material's capability to adhere to a wide variety of substrate materials and its relatively easy working properties were considered a major advantage for this application.

The last agent was Polysulfide, a material commonly used as a tank sealant. Its ability to stick to a variety of surfaces under extreme conditions made it a suitable candidate for application for bonding and sealing primary airframe structures.

The setup and procedures for the second series of tests were nearly identical to the first. By clamping one coupon and pulling on the second at ninety degrees to the bond surface, a peel situation was created which, when a critical load was reached, separated the two strips of metal. The load required to initiate the peel was then recorded.

By running these two sets of tests, we were able to identify the best candidate for our bonded structures, as well as select the best material surface treatment to achieve the strongest bond.

RESULTS AND OBSERVATIONS - Test 1

The following are observations of the failed coupons. The failure mode is divided into three types: Limited, partial and complete. The limited bond failure refers to those coupons where peel was initiated under load but, as the delamination progressed, the coupon failed rather than the bond line. This usually resulted in a total break or a interlaminar failure within the laminate itself.

The partial failure is where the continuing motion of the drum load delaminated the coupon but did not separate the two components. In these situations, a partial bond or parts of the laminate remain on the aluminum surface.

The complete failure was where sensitivity to peel delaminated the entire bond-line in one quick, almost brittle fashion.

Coupon 1 - Complete failure of bond to aluminum. Initiation of peel resulted in instantaneous delamination of entire coupon - no resin residue remains on the aluminum material.

Coupon 2 - Complete bond failure similar in nature to Coupon 1. Delamination was also instantaneous however some resin remained attached to the aluminum test piece. The remaining material however was towards the middle of the coupon - ends were free of any residue - less than thirty percent of the bonding agent remained on the aluminum.

Coupon 3 - Limited bond failure, primarily on the laminate side - adhesion to aluminum remained strong. Peel was from laminate side but coupon did not delaminate - failure resulted in breaking of laminate. Remainder of unfailed laminate is virtually intact.

Coupon 4 - Complete bond failure; a substantial amount of bonding agent remains on the aluminum sample, covering approximately seventy percent of the area. Aluminum bond is virtually intact at onset of peel.

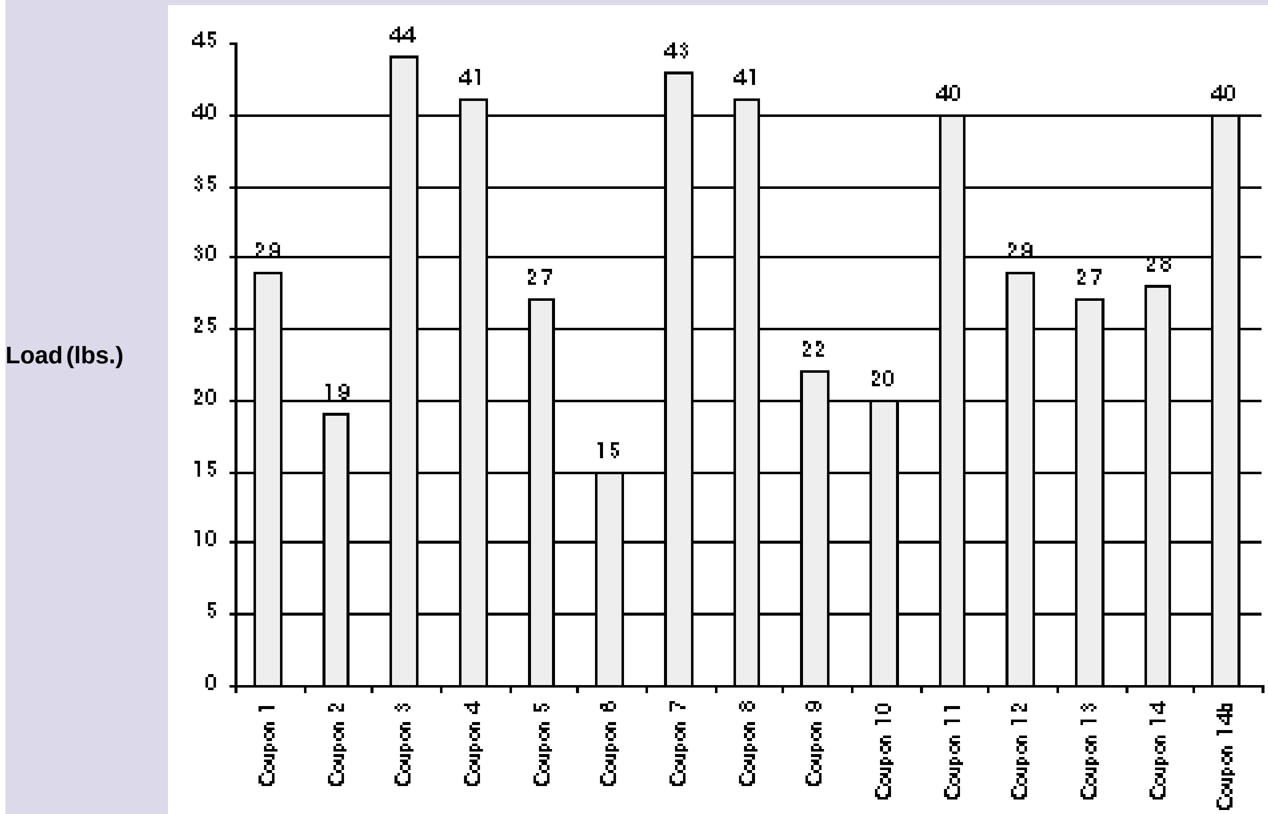
Coupon 5 - Partial bond failure. Bond failed on aluminum side at peel onset however as the peel continued failure is primarily on the laminate side. Some damage to laminate; complete delamination was possible with only minimal effort. Bonding agent remained for the most part on the aluminum covering more than ninety percent of the area.

Coupon 6 - Partial bond failure. Bond failed on aluminum side at peel onset however as the peel continued failure is primarily on the laminate side. Complete delamination was possible with only minimal effort. Bonding agent remained for the most part on the aluminum covering more than seventy percent of the area.

Coupon 7 - Limited bond failure with break occurring on laminate side. One and a half inches from peel onset the laminate failed, leaving a layer on the aluminum. Laminate failure (coupon broke) three inches further on. Complete delamination not possible.

Coupon 8 - Partial bond failure with separation on laminate side. Virtually all bonding agent remained on aluminum except at peel onset where the agent remained on the laminate. Significant effort was required to complete delamination.

Coupon 9 - Partial bond failure with separation occurring on aluminum side. As delamination progressed along the length of the test coupon, failure transferred to laminate side. More than eighty percent of bond remained on aluminum. Complete delamination was not possible – laminate broke near the opposite end.



Summary of loads required to initiate peel

Coupon 10 – Partial bond failure with separation occurring on aluminum side. As delamination progressed along the length of the test coupon, failure transferred to laminate side. More than ninety percent of bond remained on aluminum. Delamination of remainder of coupon required little effort.

Coupon 11 – Limited bond failure with separation initiating on laminate side. One and a half inches from peel onset the laminate failed, leaving a layer of glass on the aluminum. Laminate failure (coupon broke) three inches further on. Complete delamination not possible.

Coupon 12 – Partial bond failure with break initiating on laminate side. No bonding agent loss from aluminum. Considerable effort was required to continue delamination – laminate coupon broke near opposite end.

Coupon 13 – Partial bond failure with break initiating on laminate side. No bonding agent loss from aluminum. Minimal effort was required to continue delamination.

Coupon 14 – Ragged failure at initiation of peel – with some fibers remaining on the aluminum. Coupon broke within three inches of the peel end. Load to failure appears to be suspect - closer examination reveals a possible poor bond since the treatment that was applied to the aluminum appears to have stayed intact upon failure. In all other coupons the treatment either peeled off leaving bare aluminum or the bond failed on the laminate side - no other coupon failed between the preparation and the bonding.

Coupon 14b - Minuscule bond failure on laminate side - laminate failed.

The following chart and table summarize the test coupons, their preparation, bonding agent and the load at failure.

Test Piece	Surface Preparation	Bonding Agent	Pounds to Fail
Coupon 1	Acetone Wipe	Vinylester	29
Coupon 2	Acetone Wipe	Jeffco Epoxy	19
Coupon 3	Acetone Wipe	Hysol Epoxy	44
Coupon 4	Acetone Wipe	Plexus Acrylic	41
Coupon 5	Dry Sand / Acetone Wipe	Vinylester	27
Coupon 6	Dry Sand / Acetone Wipe	Jeffco Epoxy	15
Coupon 7	Dry Sand / Acetone Wipe	Hysol Epoxy	43
Coupon 8	Dry Sand / Acetone Wipe	Plexus Acrylic	41
Coupon 9	Resin Wet Sand Prep.	Vinylester	22
Coupon 10	Resin Wet Sand Prep.	Jeffco Epoxy	20
Coupon 11	Resin Wet Sand Prep.	Hysol Epoxy	40
Coupon 12	Resin Wet Sand Prep.	Vinylester w/ glass	29
Coupon 13	Resin Wet Sand Prep.	Jeffco Epoxy w/ glass	27
Coupon 14	Resin Wet Sand Prep.	Hysol Epoxy w/ glass	28
Coupon 14b	Resin Wet Sand Prep.	Hysol Epoxy w/ glass	40

In the second part of the test, where the aluminum was forced to peel from the laminate with the aid of a wedge, all samples peeled with a minimal amount of distortion with the exception of those bonded with the Hysol EA9430. The Plexus bonds also exhibited good adhesion but in general failed with significantly less distortion then that of the Hysol.

RESULTS AND OBSERVATIONS - Test 2

As previously described, this second test was an evaluation of bonding agents and finishes as applied to aluminum-to-aluminum bonds. The following brief descriptions will be organized by bonding agent - surface treatments will be discussed within each section.

The following numbers represent only the median averages for the test coupons and should not be used for design purposes. Most of the test results had a substantial variety of load magnitudes, a function not only of the surface treatments but also of the bond quality and completeness of contact (thicker bonding agents tended to create voids).

Hysol EA9430

Consistent with the previous set of data, the Hysol test coupons tested with the highest results out of all the combinations (with one exception). Although the peel loads were higher than with the other materials, the strength for the plain, scuffed and Clad aluminum surfaces are deemed to be inadequate for any structural applications. The highest properties were seen by the two anodized material sets, although the plain anodized coupons delivered the highest performance. The median averages are as follows:

Clean surface	Scuffed surface	Anodized (plain)	Hard-coat anodized	Alclad surface
3.57	5.93	14.2	10.2	2.57

CR Epoxy

Although slightly better than the Hysol when used on the scuffed material, the overall properties were consistently lower. If however the working properties of the Hysol were deemed to be too restrictive or difficult, the CR Epoxy could serve as an adequate substitute.

Clean surface	Scuffed surface	Anodized (plain)	Hard-coat anodized	Alclad surface
3.03	9.83	11.57	6.37	2.4

Polyurethane (Morton Truckbed Liner)

Although the polyurethane is a fantastic material for surface application, this test determined that the material is unsuitable for bonding, especially nonporous substrates. One possible explanation for its poor performance may be due to its inability to outgas in the aluminum laminate. The trapped material may be the cause of the detrimental effect on the cured physical properties.

Clean surface	Scuffed surface	Anodized (plain)	Hard-coat anodized	Alclad surface
1.65	3.32	1.05	0.25	1.87

Polysulfide

Based on input from several individuals who have used this material for a number of service applications, this sealant was expected to do quite well however, this was only true for the hardcoat anodized samples. It did do better on the Clad coupons but the remainder of its performance was less than would be required. The big surprise was its performance with the hardcoat surfaced material. Although a guess at this time, it is assumed that the Polysulfide also requires a certain amount of outgassing in order to achieve its highest strength. This is evidenced by the poor adhesion on the remainder of the samples. It seems however, that on the coated coupons, the trapped material reacted with the treatment used in the hardcoat process, and thus adhered to the base material better than any of the other bonding agents. At this point however this is not considered conclusive.

Clean surface	Scuffed surface	Anodized (plain)	Hard-coat anodized	Alclad surface
1.75	1.9	4.15	22.2	9.07

Again, it should be noted that these tests are not set up as the ASTM defined peel test. Therefore, although the above numbers are in pounds per inch, they should not be used as a comparison to the ASTM derived values. The purpose of these tests was more qualitative and comparative, not quantitative and therefore the numbers should not be used for design purposes.

DISCUSSION AND CONCLUSIONS

One of the popular kits available today has a spar carry-through structure which is laminated outside of the fuselage then, through secondary bonding, is attached to the side-walls and floor. A few years ago, as one of the factory technicians was installing the spar stubs into this added structure, the act of tapping the attach bolt through the carry-through hole caused a loud bang. The cause of this was not immediately apparent even though a concentrated search and inspection was initiated - nothing was found out of place nor damaged. Some time later however, when the work was resumed, the act of installing the wings revealed movement in the entire carry-through assembly.

Subsequent investigation revealed that the loud bang was the secondary bond between the carry-through structure and the fuselage laminate delaminating itself in a brittle and catastrophic fashion. Since then the company has been reinforcing the joint with steel plates and bolts. The secondary bond, as well as the structure, used vinylester as the binding resin. This was an excellent example of what can happen in a secondary bond application when improper surface preparation techniques are used or when an improper choice of materials is made.

Vinylester, while an excellent laminating resin with good high temperature resistance, is not as good in a secondary bonding application, especially when joining parts which have been allowed to cure more than two or three weeks. Historically, manufacturers have found that secondary bonds of vinylester structures have been satisfactory if assembled within one week of the parts' lay-up. When assembling later however, bonds were found to be degraded due to the surface characteristics of the fully cured resin. In those application, where assembly of parts takes place much later, after the full cure of the laminate, it is often necessary to undertake extensive surface preparation procedures and/or use a resin system specifically formulated for secondary bonding. This is not to say that the current techniques of assembly are dangerous however, there are superior materials for bonding, regardless of the laminate resin formulation.

In general our test results were consistent, but with some surprises. While it did delaminate in each case in a brittle fashion (peel sensitive), the vinylester bonds proved to be stronger in peel onset than anticipated. On the other hand, the Jeffco epoxy bond, which was expected to be as good if not better than the vinylester, was much poorer. The Plexus bonding agent was anticipated to be the best but that too was not the case, the Hysol resin surpassing the Methylcrylate by a significant margin.

Bonding properties of aluminum decreased (as expected) on the sanded specimens although the wet sanding procedure seemed to aid the case of the vinylester and the Jeffco epoxy. Adding fibers to the bonding agent seemed to help the vinylester and Jeffco resins but was inconclusive for the Hysol. In two cases the added fibers restrained the resin from forming contact over the full area, causing small areas of void. These voids could have been the cause of lower strength numbers for the Hysol resin.

These results lead to the following recommendations:

1) If constructing secondary bonds with vinylester, make sure to eliminate any possibilities of peel onset. Peel can be caused by any number of circumstances including vibration (engine vibration; rough field operation; turbulence; etc.), impact (hangar rash; minor ground accident; etc.), and environmental damage (water absorption and subsequent freezing thereof; differential expansion due to heating; hail impact; etc.). Minimizing the chance of peel onset can be accomplished with at least two ways:

1 - Reinforce the bonded area or components with fabric laminations. For instance, in bonding a spar or shear web to the wing skin add laminate onto the web (or cap) and the skin - try to avoid depending

on the bond alone. The number of plies will depend on the service loads. The laminated plies increase the area of contact therefore reducing the stress magnitude (load per unit area). They also constrain the edges of the bond, reducing the chance of local delamination or contamination by foreign matter.

2 - If possible, reinforce edges, corners or ends with mechanical fasteners. Often referred to as "chicken rivets", these little insurance policies reduce the chance of edge delamination forming and in the case of small bond failures, will prevent edge delamination from continuing throughout the remainder of the bond.

3 - Try to form the secondary bonds well within one week of the part layup. If the parts will sit for a longer period of time before being assempbled, use peel-ply and/or make sure to extensively prepare the surfaces prior to joining.

2) This test and industry experience provides support for using Hysol EA9430 for all primary structure secondary bond applications. Although parts of recommendation "1)" do have application here too, the concerns due to edge peel with this material are much lower. Should be a good material for all applications, especially those which require some alignment or repositioning in the first hour or so. While some may show concern over the lower heat distortion temperature than that of the vinylester or elevated temperature cure systems, analysis and tests show that the effects of heat are minimal, especially when used on interior and/or shielded components (composites conduct heat poorly, even graphite). Even if the surface temperature does rise, it is unlikely that any significant heat flow will reach to the interior components.

3) The Plexus Methylcrylate Acrylic adhesive seems to posses excellent bonding properties but due to its extremely short pot life, can be best utilized only in smaller and/or self jigging applications.

4) The Polysulfide and the Polyurethane are best used as topical coatings and should not be used in bonding. Although there are specially formulated Polyurethane adhesives, none has been tried, as of yet, for these applications. (A subsequent series of short tests is planned to investigate the use of other bonding systems - a follow-on report will be presented at the time.)

5) The CR epoxy does show promise, especially as it is much more user friendly and easier to apply. Further testing of this material will be done in the near future.

6) In all cases of secondary bonding of laminate structures, it is important to use peel-ply in laminating the substrate, in order to develop bond-ready surfaces. Most resin systems tend to leave a thin film once cured. This is usually removed with the use of a peel-ply material. Without it, the fabricator will be forced to allow the part to cure for several weeks, before conducting an extensive amount of grinding prior to any secondary bonding operations. This applies to all resin systems.

6) All aluminum bonding should be accompanied by a certain amount of physical fasteners in order to remove any chance of edge degradation and peel onset.