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AN OBJECT LESSON IN FALSE ECONOMIES – THE CONSEQUENCES OF *NOT* UPDATING REPAIR PROCEDURES FOR OLDER ADHESIVELY BONDED PANELS

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ABSTRACT

A case is presented that a more complete response was needed to the recognition that the adhesive bonding used on American aircraft made between about 1965 and 1980 (in which the first generation of 250°F-cured epoxy adhesives was used on etched rather than anodized surfaces) produced bonded structures far less durable than those made with the earlier Redux bonding used in England and Europe. The next generation of adhesive materials and processes developed to overcome this problem should have also been applied to the older structures rather than only to new production. One measure of the consequences of not applying the new technology retroactively is discussed here. A recent survey, conducted at the RAAF's largest bonding facility where F-111 and some other fixed and rotary wing aircraft have been maintained, showed that over the past 18 years 52 percent of major structural defects reported were due to disbonds experienced in service. As if this were not bad enough, 42 percent of those 52 percent were associated with a defect which had been repaired at least once before. This happened because the repair procedures and technical orders were *not* changed once the aircraft had been delivered. Although airlines and other Air Forces have suffered similar fates, this practice *still* continues. It is shown here that even much of the very costly aging-aircraft programs can be attributed directly to the problem of not promptly addressing the corrosion which developed between disbonded skins, doublers, and splices. The widespread fatigue damage in pressurized fuselages would never have developed had the components not disbonded and thereby transferred fatigue loads to the rivets, which had been designed only for static strength. Good bonded panels have been built for almost 20 years since the processes validated by the PABST program were implemented in the *production* of *new* bonded structures. Some progress is reported in regard to using the new procedures for *repairing older* panels, which has convincingly demonstrated that the problem can be made to go away. The theme of this paper is that, for any parts to be kept in service, the time has come to repair or rebuild *ALL* of those older bonded structures which failed because of inad-equate environmental durability with these same new processes, so that they will never fail again.

KEY WORDS: Adhesives, Corrosion, Disbonds, Durability, Primers, Repair, Surface Preparation

HISTORICAL BACKGROUND

The manufacture of adhesively bonded metallic structures has passed through three distinct stages in terms of combinations of adhesive and surface treatment. There have also been three stages in the development of honeycomb core. Bonding started in England during the 1940s with the durable combination of phenolic adhesives on chromic-acid anodized aluminum alloy surfaces. These structures, and the similar ones built by Fokker in Holland, have proved to be almost impervious to environmental degradation. The one exception concerns honeycomb structures. Because of the great amount of steam generated during the cure of the adhesive, the core at that time was perforated to prevent it from being “blown”. Unfortunately, this meant that, once water could penetrate to *anywhere* in the interior of such a panel, it would soon penetrate *everywhere*. A one-way pumping action was established by the perforated cells, whereby water could condense and collect but only vapor be removed. Then, since the foil the core was made from was a magnesium-aluminum alloy, it would corrode rapidly if ever allowed to get wet.

The second generation of bonding began in America during the 1960s and involved the use of 250°F-curing modified epoxy adhesives, of great toughness, which were far easier to process than phenolics and generated virtually no volatiles during cure. This made it possible to use unperforated core, to delay the rate of corrosion even if the exterior seals of the panels were breached. This new class of materials was not tested thoroughly for durability, because there had never been any need to do so with the first generation of phenolic and 350°F-curing epoxy adhesives. Unfortunately, although it was not appreciated at that time, now there was a need! By the time these problems were acknowledged, there were years worth of production parts in service. Lower-cost surface treatments by etching alone, resulting in oxide coatings far less stable than those produced by anodizing, were introduced. Most of the first generation of 250°F-curing modified epoxy adhesives had a great affinity for absorbing moisture after being cured, and the aluminum surfaces had a far greater affinity for water (to form a hydroxide coating) than they did for epoxy adhesives. Consequently, water would eventually enter the panels even if they were not punctured in service. It would enter through unsealed cut edges of the panels and under the heads of fasteners which had not been installed with sealant. [The failure sequence is explained in Reference (1).] Unlike the first generation of bonded structures, the second generation has had lives varying from failure of the parts *before* they were even installed on the aircraft to outlasting the primary structure whenever the parts were perfectly sealed and kept free from water. Regrettably, there have been relatively few in the latter category. The problem was not confined to any one manufacturer. Douglas and Boeing made very similar secondary structures which did not please their Airline customers , and the corresponding parts on Lockheed military transports performed similarly for their various Air Force owners. In the middle 1970s, the US Air Force funded Douglas to solve the bonding durability problem with the Primary Adhesively Bonded Structure Technology (PABST) program, which lasted almost a decade.

The PABST program built on work begun by Boeing who, faced with the bulk of the problems, had the most to gain by working on them first. They, not Douglas, pioneered phosphoric acid-anodizing in America. One of their engineers developed the wedge-crack test, which is widely used around the world as the key process test for ensuring that the surfaces have been prepared properly for bonding and that the glue has stuck. Also, the new phenolic-based corrosion-inhibiting primer BR-127 had already been developed by American Cyanamid before work started on the PABST wide-body fuselage. What Douglas did do, and do very well, was to thoroughly research the processing variables, to do extensive bonded panel testing, to perform slow-cycle fatigue testing of bonded joints, to really prove their durability, and to build and test a large portion of a wide-body bonded fuselage [see Reference (2)]. At the end of this program, it was possible to use a second generation of more easily processed epoxy adhesives and yet attain the same durability in service as had previously been obtained only with the more difficult to use phenolic adhesives. Except for the continuance of existing programs, virtually all aircraft metal and honeycomb bonding since the PABST program has used this process, or Boeing's similar BAC 5555. Even so, switching from the early epoxy-bonding processes took far longer than it should have, with the result that metal bonding was given an undeserved reputation from which it has not yet fully recovered.

At about the same time as the PABST program, there was also a response to the problem of corroding aluminum honeycomb core. The first step was the use of organic coatings, to keep whatever water entered the panel from making contact with the core. Such a product was Duracore. Later, even better core material was made by anodizing each layer of foil. This is known as PAA core, for phosphoric-acid-anodize. Its introduction, in comparatively recent times, should have put an end to the problem of corroding core. For the cores of highest specific strength, because they have the smallest cell size, there is such a great area to treat that the process is not applied for "economic" reasons. Faced with a choice between truly durable core of slightly greater weight and a less expensive structurally more efficient core with little or no protection, designers and purchasing agents continue to reach the wrong conclusion, even though each is convinced that he is doing the best thing for his employer. At one point, PAA core could not be used on government projects because of the requirement to minimize cost by purchasing only materials which were available from *multiple* sources. At one time, even when there was only one suitable material, made by a *single* supplier, multiple sourcing took precedence over the requirement to minimize cost by purchasing a durable product which would not need frequent replacement. There has been a long history of needing to repair and rebuild honeycomb panels after the earlier cores had corroded. Is saving a small increment in added cost of a "raw material" really more important than *not* having to periodically replace the entire finished panel costing hundreds or thousands of times as much? The same kind of thinking is evident in the obsession with specifying the minimum-weight core, which often needs extensive heavy and costly stabilization. The *overall* weight would usually be reduced appreciably by using a slightly heavier and stiffer core which did not *need* to be filled solid with potting compound.

Each of these changes in bonding processes and materials was intended to provide improvements over what had gone before, but not all of them succeeded. Nevertheless, there are some factories producing very reliable and very strong bonded structures. Unfortunately, most improvements were *not* applied *retroactively*; they affected only *future* production. The prime purpose of this paper is to ensure that they *are* applied retroactively, and that not even *one* bonded panel should ever be repaired again using procedures known to ensure that the same panel will need repairing yet again. Despite all of the publicity given to the testing during the PABST program, and the excellent service record of post-PABST bonded metal structures, not all of the structural repair manuals for these older structures have been fully updated to reflect the modern practices. So the problems have been perpetuated. Parts already designed and manufactured using older procedures and materials, which had been found wanting, continue to this day to be manufactured *and, more importantly, repaired* according to the original specifications. They then fall apart again, for exactly the same reasons as they fell apart the first time.

A survey by the Royal Australian Air Force for the 18 years leading up to 1995 [see Reference (3)] showed that, at the RAAF's largest repair facility, 52 percent of *major* structural defects in their fleet of F-111 and other fixed and rotary wing aircraft were for disbonds caused by unsuitable surface preparations on aircraft made in America. In addition, 42 percent of these repairs were made to previously "repaired" areas! This is a typical part of the legacy of not having gone back and updated the repair manuals and technical orders. It is a tale repeated at Airlines and Air Forces all around the world. As is explained later in the paper, the senior author would also submit that most of the aging-aircraft program, despite its focus on cracks from rivet holes which appear to have nothing to do with bonding, is an additional legacy. The great majority of widespread fatigue damage in aircraft structures has been associated with bonded splices and bonded doublers which had been manufactured using the earlier bonding systems. This is one measure of the cost of failing to respond promptly once the problem had been solved by the technical community. Had the splices and doublers been bonded properly and the glued stayed stuck, the interfaces would never have corroded, the rivets would never have seen any loads, and the skin cracks would never have occurred.

Why, one may ask, were repairs not made in accordance with the greater wisdom accumulated since the first parts had been made? It certainly cannot be that the need for change had been less than convincing. Otherwise, costly improvement*s* would *not* have been implemented in future production. A small part of the problem may be laid at the division of responsibility between those who are authorized to design aircraft and those responsible for keeping them flying. However, the major reason would seem to be artificial constraints of the budget process whereby, once a design budget is spent, there is no mechanism to add to it to repeat the task. Then, since no one else is authorized to make changes on drawings, when spare parts are made 20 years after original production ceased, they will be "built-to-print," even when doing so incurs great additional cost to replace the superior contemporary processes by the long outmoded methods which had been disbanded may years earlier.

The situation is little different in regard to repairs. Repair manuals cost money to prepare. How is this to be paid for? It ought to come from the savings realized by not needing to *repeat* every repair if each is done correctly, rather than as specified. Unfortunately, the savings and expenditures do not accrue in the *same* department, and sometimes not even within the same organization. When production of a particular kind of aircraft has ceased, traditional accounting procedures do not permit opening charge numbers for additional work with no possibility of being paid for it. When a purchasing agent has bought all of a particular kind of aircraft which some operator is ever going to use, no money is available to modify the specifications. It would be wrong to imply that even poorly bonded structures survive beyond their warranty, even though there is plenty of evidence that well-bonded structures survive indefinitely. The problem with poorly bonded structures is that it is impossible to tell *how long* they will last. Unfortunately, it is known that thoroughly protecting them from the environment can convert a part which would otherwise have failed *within* the warranty period into one which fails *beyond* it.

The RAAF is faced with maintaining their fleet of F-111 aircraft in operation long after the USAF will have retired their aircraft, when there will no longer be easy access to spares from the original manufacturer. The RAAF has faced this challenge squarely and is actively considering completely rebuilding the bonded panels with more modern processing. Doing so would be far less expensive, even at this late date, than waiting until the next century when there is nothing left to salvage. A few other organizations have shown such wisdom in the past. Ironically, these repair facilities have done their work so thoroughly, and the problem has been eradicated so successfully there, that these organizations now face the threat of redundancy because their existence is no longer perceived as economically justified by those who allowed such problems to grow to such proportions in the first place.

THE MECHANISM OF FAILURE

The key to attaining durability in adhesively bonded metallic structures, with bold old and new processes, is simple. Keep the glue stuck to the adherends! One approach, the traditional one for treating large areas in chemical solutions, has required a relatively *inert* oxide coating which will *not* react with water and readily be converted into a hydroxide, which is what one sees on corroded aluminum surfaces. This approach seems to preclude a chemical bond, so the surface must be perforated to create a strong interlock with the primer (or adhesive resin in the case of Redux). The primer must have a low viscosity to fill the pores. In addition, it should be such as to act as an impermeable barrier to water. All of this was known and studied thoroughly *before* the first adhesives were used on metallic aircraft structures. The success of Redux bonding was no accident. Unfortunately, many of those who followed the pioneers failed to understand the importance of this homework and did not repeat it. Dilute solutions of the basic adhesive, as used with some of the first generation of 250°F-curing adhesives, were not effective barriers. Those which have succeeded are either phenolic based, in which case absorbed water results in further cross-linking of the resin, or contain sacrificial sites like chromium or strontium ions to tie up the water molecules. Thorough curing also helps, by making the primer less prone to absorbing moisture.

Another approach, pioneered by the Aeronautical Research Laboratories in Melbourne, Australia, as part of their successful boron-epoxy crack-patching program, *requires* the creation of a surface chemical bond so strong that water cannot break it. This is achieved by the use of silane coupling agents applied very soon after a *reactive* surface has been created by grit blasting, as explained in Reference (4). The strength of the bond does not decrease with time, provided that the bonding is performed while the surface is still reactive. However, even the short-term strength is degraded if the prepared surface is left too long to re-oxidize *before* bonding. In much the same manner, primers must be sprayed on anodized or etched surfaces before the micropores all fill in as the morphology of the exposed surface changes. Priming is best done within half an hour. *After* priming, however, this surface remains bondable for a day or two, if necessary, to fit into the assembly and bond schedule. It also gives time to verify, per the wedge-crack test, that the panels *should* be bonded or that they should be reprocessed *before* they are irretreviably bonded into an expensive structure destined to fail in service. The cured primer is far more tolerant than the bare metal surface. The reason why both of these approaches achieve *durable* bonds is that they prevent the oxide coating on the aluminum alloys from being converted to a hydroxide. They provide a *strong* bond either by a mechanical interlock over a proportionally very large porous area or by an impervious chemical bond. In either event, both the bond strength and the durability are achieved by *special* surface treatment, *not* by cleanliness alone.

While the water absorbed by the first generation of 250°F-curing adhesives definitely played a part in the interfacial failures of the bonds, the same adhesives have since been used quite successfully with the PABST primers and surface preparation. It is not the water *in* the adhesive which does the harm, it is water allowed to penetrate to the aluminum *surface* which fails the bond. Significantly, not all of it gets there through the adhesive layer itself. Some passes along continuous fibers in woven or knitted carriers in the adhesive film, which is why mat carriers made from discontinuous whiskers are to be preferred. The most common initiation points for interfacial bond failures, however, have been fastener holes and edges trimmed on assembly. In both cases, the protection of both the primer and anodize (or etch) has locally been removed. Coating these areas with rubber-based sealants creates a new water-impervious barrier. Without it, the interface will fail progressively unless the surface is so inert as not to react with water. Absorbed water first separates the substrate from the primer (or adhesive). This creates a crevice in which far larger quantities of free-standing water accumulates. This area will then corrode, as the water permeates further forward, creating more disbonds, which are initially free from corrosion. The problem has been found to be particularly bad with clad 7075 alloys and 250°F-cured adhesives. In this case, the cladding acts as a sacrificial coating, like galvanizing on corrugated steel roofs. The corrosion is easily visible, but the defective bond extends far ahead of it. Indeed, when this phenomenon is observed, there are three conditions present in the structure; those areas which have already corroded, those which have disbonded but are yet to corrode, and the remainder which is *about to fail*, no matter how many times it is inspected ultrasonically. These phenomena are illustrated in Figures 1 and 2, taken from PABST reports and the more recent Reference (1), in which it was recommended that the only sensible response to this condition is a total disassembly, replacement of corroded components where necessary, reprocessing of each and every detail using *new* processes (not the ones which had led to the corrosion in the first place), followed by a *total remanufacture*, *NOT* a *local* repair.

The purpose of *this* paper is to *encourage* this proper response to corroded bonded structure, by highlighting the costs being incurred today through *not* having responded to these messages years ago, when the cumulative savings would have been far greater. Even at this late stage, more than a decade after the completion of the PABST program, considerable money will be saved and more flying time made available if the recommendations made here are followed. If not, locally repaired bonded structures will continue to need repairing.

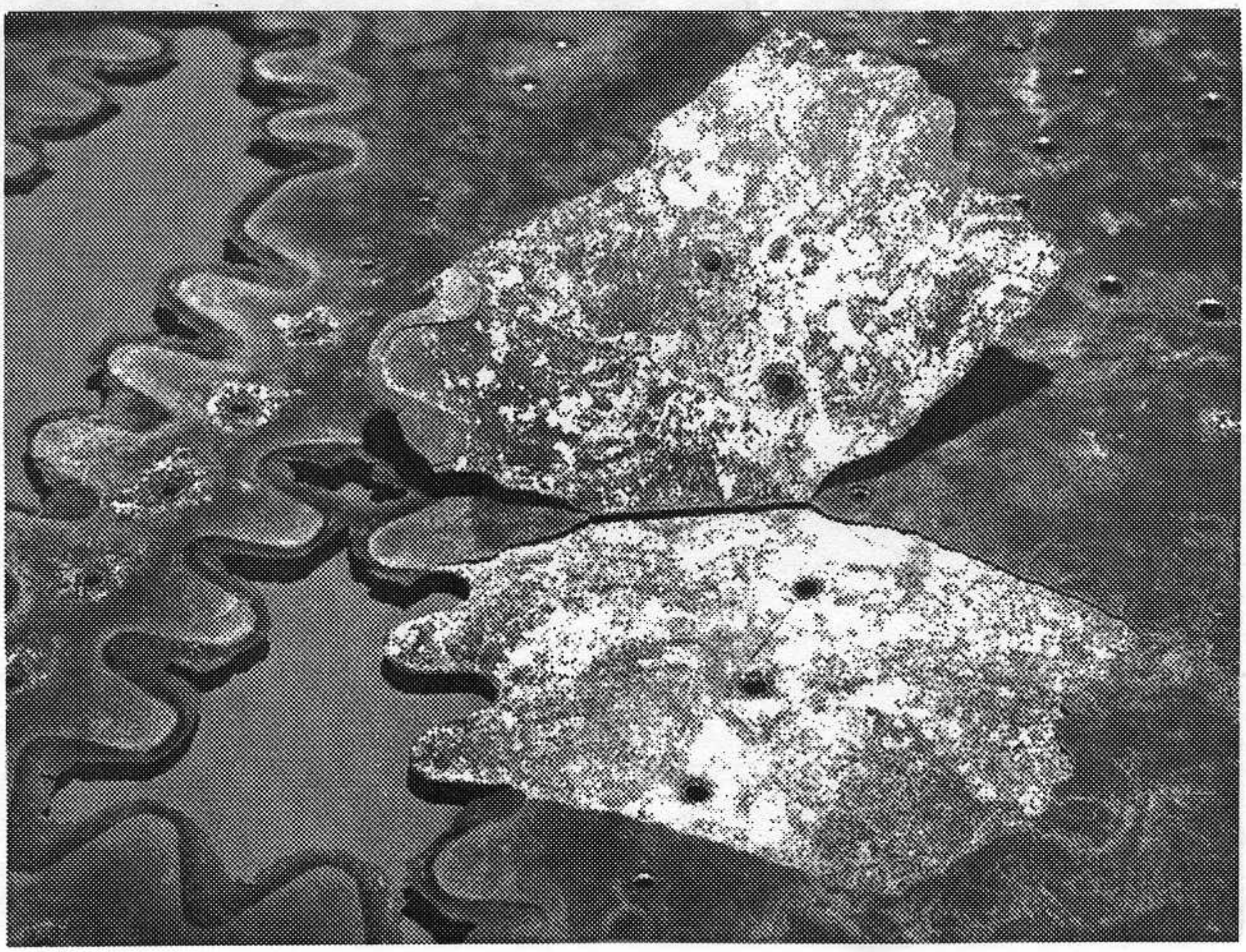

FIG. 1 CORRODED ADHESIVELY BONDED PANEL MANUFACTURED WITHOUT ANODIZING THE SURFACE, USING THE ORIGINAL UNCONTROLLED FPL ETCH

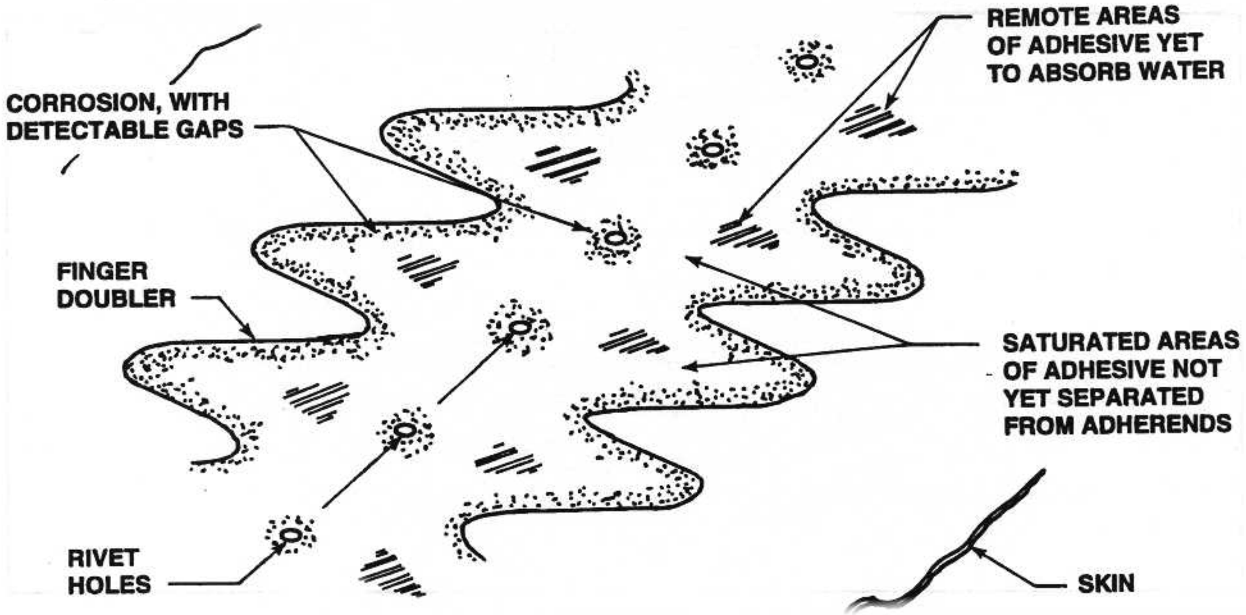

FIG. 2 PROGRESSIVE FAILURE PROCESSES AS WATER PENETRATES ALONG THE BOND

A NEW ILLUSTRATIVE EXAMPLE OF THE PROBLEM

Figure 1 is typical of the corroded bonded panels made by etching the surface in the solutions used *before* the development of the optimized FPL etch. Figures 3 and 4 show a different kind of failure, with absolutely no sign of corrosion, on which more will be said later in the paper. In the short term, the resin injected through the many holes drilled in the facings may have concealed the disbond for long enough to pass the ultrasonic inspection to which the panel would undoubtedly have been subjected. However, when they failed again, at the same time as the surrounding areas which had not yet fallen apart when the previous repairs were made, the repairs lifted cleanly off the surface, leaving no adhesive behind. This is the classic sign of bond failure not by mechanical fatigue but by environmental attack. The only thing new about Figure 4 is the combination of such a widespread area of disbonding and the lack of corrosion. Even the core is intact.

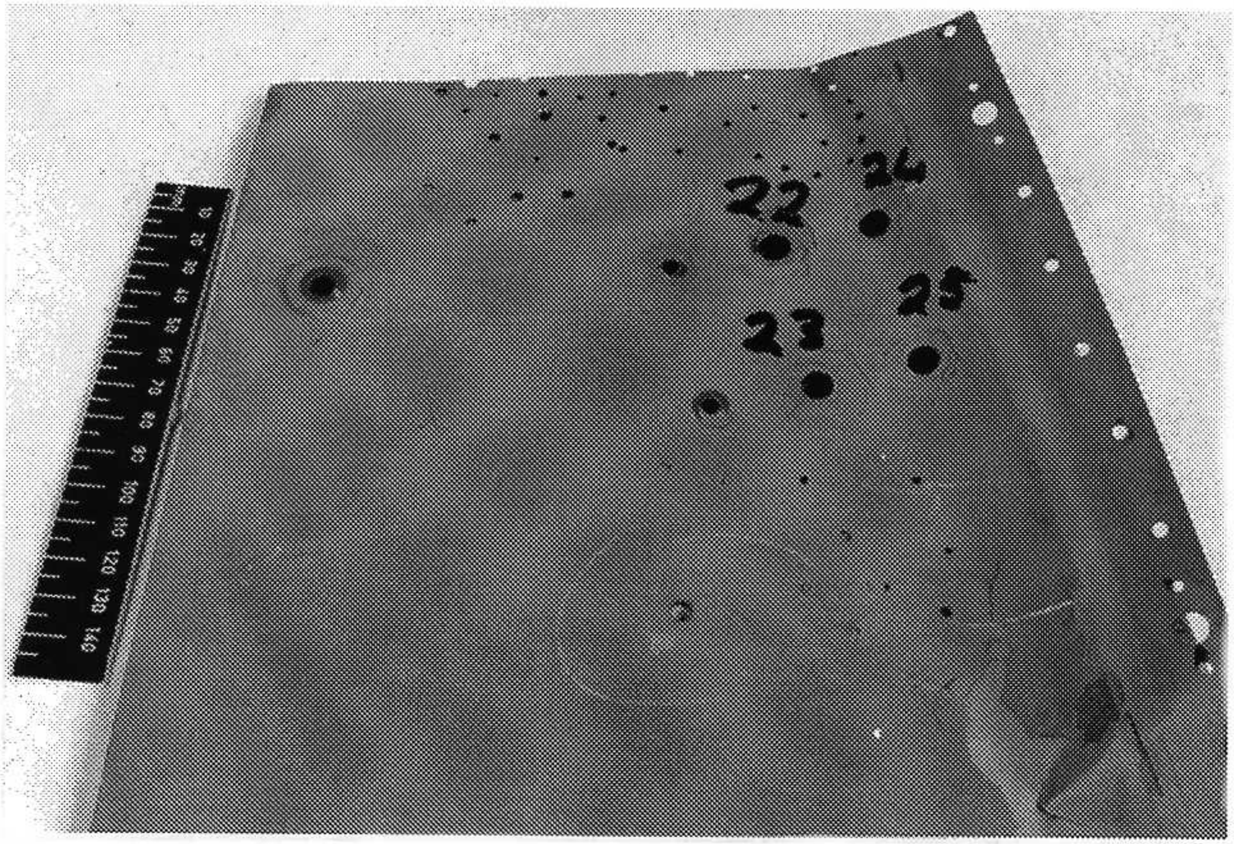

FIG. 3 EXTERIOR OF SUPPOSEDLY BONDED HONEYCOMB PANEL, SHOWING INNUMERABLE SMALL HOLES USED TO INJECT RESIN TO MAKE IT IMPOSSIBLE TO DETECT THE DISBONDS (UNTIL THEY HAD OPENED UP AGAIN)

The exterior of the skin shown in Figure 3 gives little indication of the extent of the internal damage. In the lower right corner, the exterior skin is seen to have cracked by acoustic fatigue once a sufficiently large area had become detached from the core. Otherwise, this skin (and the opposite one which is not illustrated here) look in quite good condition. However, virtually the

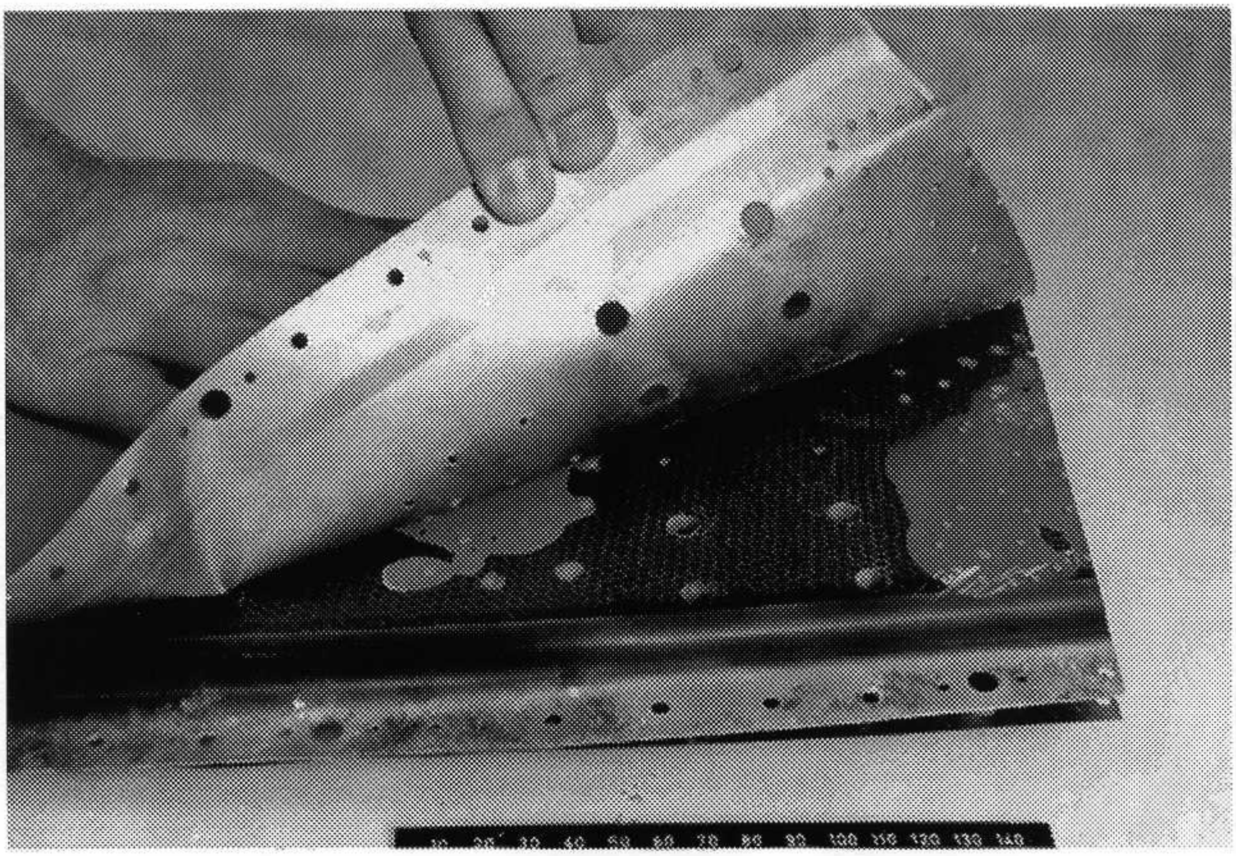

FIG. 4 INTERIOR OF THE SAME PANEL, SHOWING HOW THE INJECTED RESIN (TWO LIGHT GREY AREAS) HAD FAILED TO ADHERE ANY BETTER THAN THE ORIGINAL BOND, TO A SEALED CHROMIC-ACID-ANODIZED SURFACE

entire right-hand half of the skin in Figure 3 was actually detached from the core, as revealed by peeling it back in Figure 4. The lower-right corner of Figure 4 corresponds with the upper-right corner of Figure 3. The larger holes in Figure 3 are bolt holes. So are the smaller holes against a white background along the right-hand edge. The small black holes in Figure 3, mainly at the far end, look as if they were drilled to inject repair resin, in accordance with the specified procedures of the day. Actually, as can be seen in Figure 4, most of them were drilled at a far later date, to map the extent of what was at first believed to be a "new" disbond when it was discovered at the *most recent* inspection. However, almost as many of these holes were in the previously "repaired" area as are to be found alongside in the previously unrepaired areas. Most of the holes in the old repair have passed through the skin into the repair adhesive, clearly visible in two areas in Figure 4, so they could not possibly have been left over from the original repair.

The more troubling information contained in Figure 4 is the total absence of the corrosion, which was so unmistakable in Figure 1, and the lack of damage to the core as the initial disbond was opened up to photograph it. A properly formed and bonded adhesive fillet along the ribbons in the honeycomb is more than strong enough to rip the core apart. Yet, here, it simply lifted off the skin, just as the explanation in Figure 2 suggests that it would. The absence of small holes in the skin suggests that the area between the two old repairs (in the middle and the right of Figure 4) had passed the most recent ultrasonic inspection. Yet it was clearly not bonded. Unfortunately, the circumstances whereby someone concluded that the extent of the internal damage was far more widespread than inspection from the outside had indicated it is not recorded. It is obviously a very good thing that this "someone" did not merely perform more repairs like the *second set*, only to have them fail yet again. Yes, this panel had *already* been repaired *TWICE – IN THE SAME PLACE!* Although the demarcation line is not clear in the reproduced photograph in Figure 4, the repair at the right hand end is actually *two* repairs. The tear-drop shaped piece of visible core in the lower right corner of what seems to part of a *single* blob of injected repair adhesive is part of this demarcation. Also, the skin in the bottom right of Figure 3 did not shake itself to death until *after* it had separated from the core.

The reason for the lack of corrosion was explained 20 years ago during testing performed during the PABST program.. The details were chromic-acid anodizing to create a stable oxide surface covered with closely spaced pits for the primer or adhesive to grip onto. Then in accordance with the specifications under which the panel was manufactured, they was dunked in very *hot* water. The reason for doing so was to *seal* the pores to prevent corrosion. This techniques obviously works very well for that purpose; but it does *not* permit the glue to stick, which *should* have been the reason for the anodizing in the first place. It was only while investigating these two figures that the senior author learned that Robert Schliekelmann, Fokker's famous bonding expert, was well aware of this phenomena. He deliberately chose *not* to seal the chromic-acid-anodized surfaces on his bonded panels during processing. This allowed the phenolic resin to lock into the pores on the surface where the bonding *was* to occur and the steam generated at 350°F during the cure of the phenolic adhesive to seal the *rest* of the surface to protect it against corrosion where the bonding was *not* required. What more could one ask for in the form of a durable bond and a structure protected from corrosion? For precisely analogous reasons, *100 percent* of the phosphoric-acid-anodized surfaces treated in accordance with the PABST processing are covered with corrosion-inhibiting primer. Otherwise, the waffle grid formed by the bonded areas would survive for ever, but the unbonded areas in between would all corrode far faster than if they had been left as bare aluminum alloy.

Although this is not part of the basic theme of this paper, it may be noted that recent tests on water-based primers for adhesives curing at different temperatures are showing that the surface morphology of some anodized panels can be adversely affected by bonding at 350°F, by changing the grain structure. This had already been noted during the PABST program. What is now known is that some primers perform as well on some alloys as they do badly on others and that excellent performance with 250°F-cured adhesives is no guarantee of even adequate performance with 350°F adhesives. In short, there is *no single universal best answer* to the riddle of how to guarantee that the glue will always stick. The *entire* process must be assessed to identify the best course to follow, if we are to preclude a repeat of the great leap forward in the 1960s and 1970s. Conversely, past experience makes it clear that diligent homework has consistently been rewarded by easily manufactured trouble-free bonded components, no matter how much the publicity has focused on the consequences of skipping the homework.

EFFECT OF POOR BONDING ON AGING-AIRCRAFT PROGRAM

There was widespread disbonding in service associated with American-made metal-bonded structures in the late 1960s and early 1970s prior to the Primary Adhesively Bonded Structure Technology (PABST) program, Reference (2). There was no warning of this from the short-term tests made during production, which indicated that the bonds had excellent shear and peel strengths. However, these bonds did not *stay* stuck. They did not fail from mechanical fatigue; they disbonded as the result of environmental attack. The bonded joints simply fell apart once moisture had migrated to the adherend surfaces, the oxide coating on which had a greater affinity for water than for epoxy. The solution found for this problem was a more stable oxide, of the type produced by anodizing, a phenolic primer to act as a barrier, or both. This situation arose because the new procedures and materials were introduced *without* the thorough durability testing which would have been needed to expose the problem beforehand. Since there had been no environmental durability problems with the adhesives and surface treatments used *prior* to the introduction of the first generation of epoxy adhesives and the original (unoptimized) Forest Products Laboratory etch, there was no precedent calling for such tests. A short-term *durability* test was developed to discriminate between those metal-bonded joints which would fail in service and those which would not. This Boeing wedge-crack test is now a standard part of virtually all quality assurance programs for bonded metal structures.

Some bonded *composite* joints appeared to have adequate static lap-shear strength at the time of manufacture, but have failed interfacially in service. The symptoms match the old metal-bond problem precisely. The analogy is so complete that, both times, changing the adhesives was tried before it was acknowledged that surface preparation was the problem. The big difference is that there are *no* quality assurance tests for *durability* of bonded composite structures. There should be, if there is not to be a repetition of the metal-bond problem, the delayed response to which caused the following problems to persist for far longer than necessary.

Some bonded metal panels separated at the adhesive-to-metal interface *during* the roughly two-year span of the production cycle, and millions of dollars were spent replacing such parts *before* delivery. However, the far higher costs, in tens and hundreds of millions of dollars, were *deferred* until later in service, when many more panels failed. Those operators who were diligent in guarding against corrosion by keeping fasteners and panel edges well sealed merely succeeded in delaying the need for repairs until after the warranties for secondary structures had expired. Actually, a strong case can be made that, had the adhesive bonds been stuck properly in the splices and doublers of the fuselage skins of the Boeing 727s, 737s, and 747s manufactured during that period, the airline industry would have been spared most of the burden of today's aging aircraft programs. The sequence of events was that the adhesive came unstuck from the metal, which caused higher than planned loads to be transmitted by the fasteners, resulting in fatigue cracks, and crevice corrosion promoted by the liquids trapped between the faying surfaces. With these specific but widespread problems separated from the total aging aircraft problem, the remaining incidence of fatigue cracking in aircraft structures would have been quite small.

In the case of the bonded metal structures, research by Krieger, of American Cyanamid, and Bethune, of Boeing, [see Reference (1)] was able to *explain* the mechanism of failure in such a way as to account scientifically for the variable delay between the manufacture of such parts and their disintegration. These failures could *NOT* be correlated with degradation under applied loads; they were shown to be the result of inappropriate surface preparation for bonding. Even so, several years were to elapse before the new durable adhesive bonding materials and processes were implemented in production, adding appreciably to the number of poorly bonded structures which would eventually need to be repaired or remanufactured.

Reference (5), by DeRosa of United Airlines, gives some idea of the magnitude of the problem created for the operators as the result of this primary structural bonding which did not stay stuck. This may be contrasted with the virtually infinite resistance to both corrosion and fatigue displayed by the earlier Redux bonding used in England and Europe, which permits de Havilland Comet airframes built decades ago to be updated with modern electronics and remain in service for decades yet to come. Fortunately, at Douglas, metal bonding was not used on the primary structure, and disbonding problems in this regard have been limited to more easily repaired or replaced secondary structures. The more recently manufactured bonded metal structures, using PABST technology or an equivalent, also have an excellent service record. Unfortunately, this good news has yet to become as well known as the bad image of problems associated with earlier systems.

CONCLUSION

This paper has revealed some of the consequences of applying the best and latest bonding procedures *only* to subsequent production and *not* to the repair and rebuilding of panels manufactured according to *older* processes. In one case, a thorough survey by the Royal Australian Air Force, performed by technical specialists to show the need for improved repair practices, revealed that disbonding was responsible for over half of the major structural defects found at the RAAF's largest bonding facility. The bonds *never* failed as the result of mechanical fatigue the way basic structure does. It was *always* the result of environmental attack. Better yet, military and commercial operators in America had already shown that, with complete rebuilding using modern processes, it was thereby possible to *prevent* the failures from ever happening again.

Their potential cost savings which could have accrued by doing total rebuilds as soon as the need for doing so first became evident, are actually even greater than avoiding the 42 percent of the repairs which were actually *re-repairs of the same disbond.* Every panel needing to be repaired was either keeping an aircraft on the ground, removing it from the operational fleet (causing the *purchased* fleet of aircraft to be larger than otherwise necessary) or required the purchase of additional spares to be rotated through the fleet as each disbonding panel was being repaired. There is no reason to believe that the RAAF's experience in this regard would be any different from that of any other Air Force, except that theirs will eventually be *better* than most because of a belated willingness to eradicate the problem rather than to tolerate it. (If still possible, it might be helpful to quantify the savings to the USAF of having rebonded the outer wings of the C-130 fleet with PABST bonding at Warner-Robins AFB, Georgia, to justify this course of action.)

Given the higher utilization of commercial transport aircraft, the USAF experience is likely to *underestimate* the impact on airline operations. The Douglas Aircraft Company has already endorsed the concept of replacing old bonding processes by new, in the Structural Repair Manuals, and is in the process of revising the individual sections. The same improvements need to be made for the manufacture of spare parts and all subcontracted structural parts as well as for cowlings and the like which are controlled by the engine manufacturers.

By far the most costly consequence of not applying the better bonding techniques retroactively must surely be the *billions* of dollars still being incurred as part of the aging-aircraft program. Had the adhesive bonds been stuck properly in the splices and doublers of the fuselage skins of the Boeing 727s, 737s, and 747s manufactured prior to the introduction of PAA surface preparation for bonding, or had this problem been addressed as soon as its consequences could be foreseen, the airline industry would have been spared most of the burden of today's aging aircraft programs.

Even though it is standard business practice to defer expenses wherever possible, one must surely question the wisdom of having done so in regard to environmental disbonds. The only question left to ask is how much *more* will it cost if all involved *still* do not respond promptly now that the various consequences and potential benefits have been explained.

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