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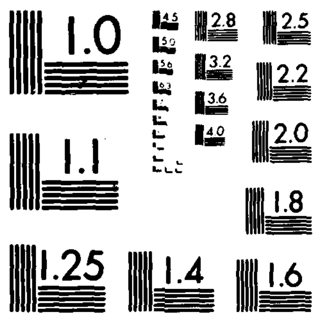

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Durability of Adhesive Bonded Structures Subjected to Acoustic Loads

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

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AGARD Report No.701

DURABILITY OF ADHESIVE BONDED STRUCTURES SUBJECTED TO ACOUSTIC LOADS

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PREFACE

At its Fall 1980 Meeting in Aix-en-Provence, France, the AGARD Structures and Materials Panel (SMP) decided to reconsider the topic of sonic fatigue, particularly for new aircraft structural materials and fabrication concepts.

The development of high strength adhesives, integral damping, advanced composite materials and lower cost manufacturing techniques has led to structural concepts quite different from the conventional riveted configurations. These new structural concepts are finding widespread interest in aircraft design and application and they must survive high intensity acoustic excitation for the service life of the aircraft. Acoustic fatigue prediction information for advanced composite and adhesively bonded structures is rather limited, and since these concepts represent a significant change in dynamic characteristics and failure mechanisms, prediction methods based on riveted technology may not be valid.

This report constitutes a review of the potential problem by the SMP and an effort to determine if there was sufficient concern in several NATO countries to warrant further activity.

JAMES J.OLSEN
Chairman, ad hoc Group on
Acoustic Fatigue Lifetime Prediction

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DURABILITY OF ADHESIVE BONDED STRUCTURES SUBJECTED TO ACOUSTIC LOADS

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SUMMARY

Acoustic fatigue damage to riveted metallic structures in aircraft due to high intensity noise has been recognized as a problem and design criteria have been developed to prevent such damage. However, very little design criteria are available for bonded structures subjected to high intensity noise. A summary of the work completed in acoustic fatigue prediction techniques for weldbonded aluminum, adhesive bonded aluminum and adhesive bonded graphite-epoxy structures is discussed. These structures are more complex than riveted structures, more difficult to analyze and exhibit many different modes of failure which require a more detailed study to predict the sonic fatigue lifetime. Adequate performance under static loading did not guarantee adequate performance under dynamic loading. Some prediction methods have been developed for certain failure modes in adhesive bonded aluminum and graphite-epoxy bonded skin-stiffened structures. Further investigations are needed to adequately predict the acoustic fatigue life of adhesive bonded aircraft structures.

INTRODUCTION

Acoustically induced fatigue failures in aircraft operation have been a design consideration for over 25 years. The problem was introduced with the advent of the turbojet engine which produced high intensity acoustic pressure fluctuations on aircraft surfaces. As engine performance requirements increased, the intensity of the acoustic pressures increased. Airframe minimum weight requirements resulted in higher stresses in structural components. The number of acoustic fatigue failures began to grow at a rapid rate until adequate design criteria were developed and used in the design process.

Similar fatigue failures have occurred in other regions of high intensity pressure fluctuations. These have occurred in regions of separated flow, behind protuberances such as air brakes, and in surface areas near the plane of propeller rotation. Failures have also occurred from the fluctuating pressure induced when bomb bay doors are opened during high speed flight.

The oscillating pressures from various noise sources produced a resonant response of the structural component such as external skin panels, frames, ribs and spars which results in rapid stress reversal in the structure. If these stresses have sufficient magnitude, fatigue failures occur.

Acoustic fatigue failures have resulted in unacceptable maintenance and inspection burdens associated with the operation of the aircraft. In some cases, sonic fatigue failures have resulted in major redesign efforts of aircraft structural components.

Accurate prediction methods are needed to determine the acoustic fatigue life of structures. The approach has been semiempirical using analysis, acoustic testing of panels and vibration shaker testing of cantilever beam coupons. This combination of theoretical relationships, statistical relationships and test data for a particular structural configuration and material is used to predict the acoustic fatigue life of aircraft structures.

Three types of structural joints are discussed in this paper. These are the conventional riveted joint, the weldbonded joint and the adhesive bonded joint. The primary components of the joints are shown in Figure 1.

CONCERNS IN PREDICTION TECHNIQUES

Many advanced structural concepts were developed to save weight, reduce production cost and reduce maintenance cost by increasing fatigue life. Some of these concepts such as adhesive bonded stiffened skin aluminum structures and stiffened skin graphite-epoxy (G/E) structures are being applied to new and future aircraft. Two questions should be addressed to insure that acoustic fatigue problems do not become unmanageable. Will the acoustic loads on advanced structures be sufficiently high to cause concern and do we know enough about the advanced structural concepts to prevent acoustic fatigue problems? To answer the first question, a look at the sound pressure levels that have resulted in acoustic fatigue problems in military aircraft indicates a history of high sound pressure levels well above the damage thresholds as shown in Figure 2. The second question is the focus of this paper.

A broad base of general design information for riveted structures in the form of nomographs and equations based upon combined analytical and experimental approaches was developed and is summarized in AGARDograph No. 162, Reference [1]. Experience has shown that these design data and prediction techniques are generally adequate for riveted structures and form a basis for developing prediction techniques for advanced structural concepts. Problem areas encountered with riveted structures generally can be remedied by changing skin thickness or stiffening the structure. The question then is whether or not adequate methods are available to prevent sonic fatigue failures in bonded aluminum and graphite-epoxy structures and whether or not the riveted technology base is applicable to these structures?

Sonic fatigue tests and service experience have shown adhesive bonding to be a highly effective joining process. For some types of structures such as aluminum or composite honeycomb sandwich, co-cured and integrally cured composites, it is the only viable attachment method. In stiffened metal structures, the effectiveness of bonding compared to mechanical fasteners will depend upon the skin thickness. As skin thicknesses decrease, 0.04 in (0.102 cm) and less, adhesive bonds become more effective whereas riveted structures begin to encounter "knife-edges" and the fatigue notch factor increases. With thicker skins, 0.080 in (0.203 cm) and up, the fatigue resistance of riveted joints increases, and adhesive joints begin to become less fatigue resistant. Consequently, it seems that any comparison of the two design methods should account for skin thickness.

Sonic fatigue programs and service experience have revealed that the sonic fatigue life of adhesive bonded joints is dependent upon two important factors. One is the quality of the joint process parameters and the other is the structural properties of the selected adhesive system. In reviewing this experience in detail, it becomes apparent that the joint quality is the most critical consideration for the sonic fatigue designer. Most failures of well designed adhesive bonded structures are a direct result of bond process problems affecting joint quality. The selection of adhesives and formulation of process specifications are established by Materials and Process Engineers and Chemists prior to utilization by the Structural Designer. This is typically the case in the aerospace industry. The problem of joint bond quality is aggravated by the lack of a nondestructive test method which can determine joint strength. Good static strength properties do not guarantee good sonic fatigue properties. Consequently, the sonic fatigue designer has no way of knowing the fatigue life of the joint without performing dynamic tests. Since sonic fatigue design is usually more critical for lighter structures, subjected to low-load, high cycle random loading, the importance of joint quality becomes a critical factor.

WELDBONDED STRUCTURAL CONCEPTS

Weldbonded structural joints in this paper are defined as thin plates or skin attached to back-up structures or stiffeners using a combination structural adhesive and spot welds. In general, weldbonded structures offer reduced manufacturing costs and improved fatigue life. This paper addresses the sonic fatigue life which can be quite different than the fatigue life under mechanical loading.

In 1972 three full scale A-7 wing outer panel trailing structures were tested which in service are subjected to buffeting loads [2]. These loads were acoustically simulated in a test chamber shown in Figure 3. Three identical structures were fabricated using two weldbonding techniques and one structure using the conventional rivet methods for comparison purposes. Fatigue failures in the riveted structure initiated around the rivet head as shown in Figure 4. Fatigue failures in the weldbonded structures were located in the skin along the edge of the stiffeners as shown in Figure 5. The failures shown resulted from testing for a period of time equivalent to about 15 lifetimes exposure to service excitation. The comparisons of weldbonded structures with riveted structures are dependent on the criteria selected and the type of weldbond system. One criterion is the test time until first failure. First failure is defined as the visual observation of a crack without the aid of magnification. The test times to first failure for both weldbonded structures and the riveted structure were observed to be approximately equal. Another criterion is the amount of cracking. Both weldbonded structures exhibited less cracking at the end of five to ten lifetimes than did the riveted structure. Although the fatigue failures of the weldbonded structures were quite different from the riveted structure, the fatigue lifetimes were relatively close.

Several programs with test coupons and test panels were conducted to develop prediction techniques for weldbonded structures similar to those developed for riveted structures. A combination of theoretical relationships, statistical relationships and test data for a particular weldbond system is used to predict the acoustic fatigue life. The fatigue life of the material and the response of the structure are usually determined using cantilever beam coupons and panels. A typical stiffened skin coupon is 12 in (30.48 cm) long and 2 in (5.08 cm) wide with the stiffener fastened in the middle as shown in Figure 6. The cantilever beam coupon test provides fatigue and damping data. The test coupons are a section of the more complex panel, including the stiffener. These coupons are vibrated at resonance on an electro-mechanical shaker to generate alternating bending stresses in the beam representative of the bending stresses produced by acoustic excitation. A typical shaker test set-up is shown in Figure 7.

Strain gages are installed on the skin at locations of maximum strain. A low level sine sweep is usually made to determine the natural frequencies and modes of the beam. Fatigue tests are usually conducted using a narrowband random excitation centered at the first or second bending modal frequency. The root-mean-square (RMS) strain level is held constant. The test article is inspected frequently to determine the time of failure. The cycles-to-failure is determined by multiplying the time to failure by the average frequency. Stress versus cycles-to-failure (S-N) curves are developed for each weldbond system. The cantilever beam coupon tests are simpler and less costly than panel tests. The coupon fatigue data are considered supplemental to the data from panel tests. These tests have been extremely beneficial in screening candidate weldbonded systems before fabricating full-scale and much more costly test panels.

S-N curves were developed for the following weldbond system: Whittaker X6800 adhesive with a spot weld etch surface preparation. The curves, developed using cantilever beam coupons, are shown in Figure 8. The skin thickness for each curve is noted, since the peel stress in the adhesive is dependent upon the skin thickness. Fatigue failure initiated with a delamination of the adhesive along the bondline followed by a crack in the spot weld. A change in the surface preparation significantly affected the fatigue life of the beam coupons tests as shown in Figure 9. The weldbonded coupon with metal bond etch surface preparation produced longer lifetimes than those with the spot weld etch surface preparation. Therefore, the steps in the fabrication process became very important in the fatigue life. The fatigue data is shown in terms of bending moment to permit a direct comparison of different skin thicknesses. Very little benefit was gained by using the spot weld with this type of loading, since crack initiation depended on the adhesive system.

Three and four bay, flat and curved test panels were fabricated identically to the C-140 aircraft fuselage construction except that rivets were replaced by weldbonding with a spot weld etch surface preparation. These panels were tested in an acoustic test chamber with a wideband random excitation similar to that produced by the engines. The S-N curve developed from test panels is shown in Figure 10. Comparing the S-N curve obtained from the weldbonded panels with the riveted data, a shorter fatigue life can be expected with this type of surface preparation. Most of the weldbond sonic fatigue work sponsored by the U.S. Air Force is summarized in Reference [3].

ADHESIVE BONDED ALUMINUM STRUCTURAL CONCEPTS

To establish a data baseline for high strength structural adhesives, American Cyanamid FM137 adhesive/BR127 primer with a metal bond etch surface preparation was selected for evaluation. This was a common adhesive system used in production including the L-1011 wide body aircraft.

Mode shapes are generally obtained experimentally to determine response frequencies and locations of maximum strain. An example of a contour plot obtained for one modal pattern of a three bay adhesive bonded aluminum panel is shown in Figure 11. Comparisons were made with similar riveted construction. No major differences were noted in the dynamic response of the bonded and riveted panels tested. This was also the case in the modal analysis comparison with similar weldbonded panels. The S-N curves developed from cantilever beam coupon tests using FM137 adhesive are shown in Figure 12. Two types of failures were encountered: skin failures and cohesive bond failures. A cohesive bond failure is defined as one in which part of the adhesive remains on both adherends after failure. An adhesive bond failure is defined as a complete separation of the adhesive from one adherend while remaining on the other adherend. Generally, adhesive failures are considered undesirable, since they are unpredictable. A much lower fatigue strength resulted from adhesive failure modes than cohesive failure modes.

Adhesive bonded panels using the C-140 fuselage design were tested in an acoustic test chamber. Fatigue cracks in the stiffeners, as shown in Figure 13, ended the test before the bond system could be evaluated. The fatigue life of the stiffener was about equal to that obtained with riveted construction; however, to prevent this mode of failure, a much stiffer design will be needed.

As additional stress durable adhesive systems were developed, more programs were undertaken to determine the benefits of adhesive bonded structural concepts. One program that advanced the state-of-the-art of adhesive technology was called Primary Adhesively Bonded Structural Technology (PABST). The sonic fatigue part of the program investigated the following adhesive/primer bond systems: American Cyanamid FM73/BR127, Narmco M1133/BR127, 3M AF55/XA3950, and Hysol EA9628/EA9202 with phosphoric acid anodized aluminum adherends. Two failure curves were developed from cantilever beam coupon data. A fatigue curve for skin failures in the aluminum adherend is shown in Figure 14. Compared with riveted data, a higher fatigue life in the skin can be expected at the lower stress levels. At the higher stress level, the fatigue life is about equal. A fatigue curve for the cohesive bond failure is shown in Figure 15 in terms of bending moment. Included in these data is a weldbonded coupon using Goodrich PE-130 adhesive, which showed a comparable life with the other adhesive systems tested. No general comparison with riveted design can be made until the skin thickness is known, which also determines the mode of failure in the adhesive bonded structure. Increasing the skin thickness in a bonded structure increases the peel stress in the adhesive which can shorten the fatigue life of the adhesive while increasing the fatigue life of the skins.

Very little panel data are available for adhesive bonded metallic structures. The results of the panel tests in one program are shown in Figure 16 [3]. The structural model was an adhesive bonded fuselage section designed for the loads of the YC-15 aircraft, a prototype short take-off-and-landing medium cargo aircraft. Some of the failures were in the adhesive and some were in the stiffeners. Failures occurred at a much lower bending moment or stress in the panels than in the beam coupons. Multimodal response of the panel is one reason for the difference in the stresses obtained from the two types of tests. More investigations are needed to determine the relationship of the coupon data and the panel data when the panels are exposed to a wideband acoustic load. Beam coupon tests alone are not sufficient to predict the lifetime.

A sonic fatigue analysis of the PABST structure, using the acoustic loads for the take-off condition from measured YC-15 flight test data, indicated that the structure would not withstand the 50,000 hour service life. This was based upon coupon data with a correction factor for panel data. The critical structure was a large bay size with a heavy gage thickness [2 ft (60.96 cm) by 2 ft, 0.070 in (0.178 cm) thick]. Further testing of this type of adhesive bonded structure is continuing. Preliminary results of the panel tests show that the prediction with the coupon data was fairly accurate. A typical example of the panels tested is shown in Figure 17. Fatigue failures were found in the adhesive bondline and in back-up structures.

The bonded surfaces were examined after fatigue failure by separating the joint under static load. The bonded surfaces produced under dynamic excitation were noticeably different from those produced under static loading as shown in Figure 18. Under static load, the failure was characterized by separation midway through the thickness of the adhesive film; whereas, under dynamic load, the adhesive separated closer to the surface of the adherend. While the reason for the crack location is not known, consistent and predictable behavior was found whenever the failure was cohesive within the adhesive and not in the primer, oxide layer or adherend.

Some of the fractured adhesive surfaces were evaluated using a scanning electron microscope (SEM). The adhesives, primer and oxide layers have distinct morphological features easily distinguishable. An example of a cohesive bond failure is shown in Figure 19. A full range of fracture mechanisms were found: cracking, cavitation and shear banding, which indicated that the adhesive performed satisfactorily.

Another area of concern was quality control since different results often were obtained when test structures were fabricated by different manufacturers using the same standard. Since bond failures within the primer were a common problem, an investigation was conducted with cantilever beam coupons with different primer thicknesses, adhesive thicknesses and surface preparation. The fatigue results are shown in Figure 20. The fatigue data indicated that the FM73/BR127 adhesive/primer system was essentially insensitive to variation in primer thicknesses and the type of adherend surface treatment. The thicker adhesive samples showed a somewhat shorter fatigue life and showed evidence of interfacial failure, namely, adhesive to primer failure and primer to oxide failure. Most of the adhesive bonded stiffened skin sonic fatigue work is summarized in Reference [3] and [4].

ADHESIVE BONDED ALUMINUM HONEYCOMB

Adhesive bonding is the conventional method of joining the face sheets and the core for aluminum honeycomb sandwich structures. Extensive sonic fatigue tests have been performed on such structures in progressive-wave tubes (PWT) [5]. These tests have involved various adhesives having widely varying peel strengths and lap shear properties. The results of these tests and the subsequent service history in high intensity acoustic environments (above 170 dB for 50,000 hours) have consistently shown that the adhesive bond is not the mode of failure. This is not to imply that adhesive bonds never fail nor that an adhesive's structural properties are unimportant. A properly designed honeycomb panel utilizing one of the current widely used aircraft structural adhesives will not experience adhesive bond failures unless there is a bond quality problem. Variations in peel strength and lap shear strength, within the range of typical adhesives, will not affect sonic fatigue life. However, if the bond quality is degraded due to moisture or porosity for example, it has been found that rapid fatigue failures occur in the adhesive bond even when static tests such as lap shear, peel and flatwise tension indicate good bond quality. This problem is discussed further in the next section.

ADHESIVE BONDED GRAPHITE-EPOXY (G/E) STRUCTURES

Recent extensive sonic fatigue and shaker testing on bonded G/E structures [6] demonstrated the importance of adhesives in developing light-weight aircraft structures. Comparisons between the sonic fatigue resistance of riveted aluminum and bonded graphite structures showed the bonded graphite offers a 2:1 weight savings. While this structural advantage is due largely to the graphite material, rather than the joining process, it could not be achieved without effective fatigue resistant adhesives. Since composite structures exhibit much larger deflections than metal structures, the adhesives used must display a combination of high strength and good elastomeric properties.

The adhesive selected for the program described in Reference 6 was 3M's AF147. The graphite pre-preg was Hercules AS-3501. AF147 is an elastomeric adhesive with a high fracture toughness. It cures at 350°F and has a lap shear strength of 4,500 lb/in^2 (3.10 X 10^7 Pascals) based on the manufacturer's literature. A corresponding value of

3,430 lb/in^2 (2.37 X 10^7 Pascals) was measured from specimens cut from a sonic fatigue test panel.

Test specimens were skin-stringer configurations, typical of aircraft fuselage structures, consisting of G/E zee stiffeners and skins secondarily bonded together. These specimens comprised sub-element shaker test specimens [3 in by 9 in (7.62 cm by 22.9 cm) skin section with a 3 in long zee section bonded along the center] and multi-bay panels [2 ft by 3 ft (61 cm by 91 cm) skins with various stiffener spacings, skin thicknesses and curvatures]. The shaker specimens were subjected to random mechanical loading and the sonic fatigue test panels were subjected to random acoustic loading in a PWT. Early shaker and PWT results were characterized by premature delamination of the stiffeners from the skins, with no damage occurring to the graphite fibers. This type of failure clearly indicated inadequate strength in the adhesive joint. Visual inspection of the failed joints revealed some porosity. Since these specimens had met or exceeded the usual industry adhesive acceptance criteria, it became apparent that these criteria were not adequate to determine the sonic fatigue capabilities of an adhesive joint. Quality acceptance criteria applied to the failed specimens included percent weight of resin, void percent by volume, flatwise tension and lap shear. Also an ultrasonic inspection was made.

The observation that the static strength properties of bonded joints do not adequately reflect the dynamic high cycle fatigue characteristics is substantiated by Reference 4, in which identical specimens exhibited different modes of failure under static and dynamic loads. Under static loads failures occurred in the adherend, whereas under dynamic loads the failures occurred in the adhesive itself. Also, small variations in static strength properties often resulted in large variations in sonic fatigue life, but only when the static strength variations are due to process and/or quality variables. Corresponding static strength variations due to the basic strength characteristics of the adhesive system do not appear to affect sonic fatigue life. Similar observations have been made on other joining methods such as brazing and diffusion bonding.

When the graphite specimens experienced premature dynamic fatigue failures, with visual evidence of porosity, an investigation was carried out to determine the cause of failure and the relationship between the porosity and static strength. Modifications were made to the bonding process which reduced the porosity by 75%. However, the corresponding increase in lap shear strength was only 2%. Nevertheless, when sonic fatigue tests were performed on panels before and after modifying the bonding process, there were dramatic changes in fatigue lives and also in the mode of failure. Figure 21 shows a failed sonic fatigue test panel prior to modifying the bonding process. The failure is in the adhesive, and the photograph shows the sub-structure separated from the skin without any significant graphite fiber damage. Figures 22 and 23 show the two faces of a failed panel after modifying the bonding process. Here the mode of failure has shifted to the skin laminate, evidenced by the extensive graphite fiber damage and broken skin fibers attached to the sub-structure. Figure 23 shows that the skin damage propagated through the entire skin thickness without failure of the adhesive joint. Neither lap shear, peel strength or flatwise tension values predicted this result. The sonic fatigue life of the two panels ranged from virtually instant failure to 10^7 cycles. The strain-versus-cycles-to-failure data from the panels and beam coupons are shown in Figure 24. The acoustic life of stiffened skin G/E structures can be predicted using this curve and the technique developed to predict the maximum RMS strain [6].

Although the static tests did not indicate the sonic fatigue life nor mode of failure, the sub-element shaker tests did predict the mode of failure and gave good fatigue life versus strain data. Based on the work performed in Reference 6, shaker testing of sub-element specimens appears to be the simplest and least expensive test to establish good bond quality relative to sonic fatigue resistance.

RECOMMENDATIONS AND CONCLUSIONS

Very little benefit in sonic fatigue life was gained by the spot weld in the weldbonded structures compared to the adhesive bonded structures. A change in the surface preparation significantly affected the sonic fatigue life of the weldbonded structure tested. The acoustic fatigue life of the weldbonded aluminum structure with the Whittaker X6800 adhesive and spot weld etch surface preparation was significantly shorter than the metal bond etch surface preparation. Apparently the acoustic loads produce a peel stress in the adhesive. Most adhesives have a low peel strength.

The adhesive bonded aluminum panels tested until destruction generally failed in the stiffener. The stiffener design used was identical to riveted design. The design was inadequate to prevent sonic fatigue damage to the stiffeners in adhesively bonded metallic structure. More acoustic fatigue data are needed covering a wider range of stiffener designs.

Double cantilever beam coupon data have been developed for two modes of failure of an adhesive bond aluminum joint: cohesive bond failure of the adhesive and metal fatigue failure of the adherend. The cohesive bond fatigue curve is for a very narrow range of adhesives, generally high strength, brittle and are curved at 250°F (121°C). More work is needed to include a wider range of adhesives and to correlate cantilever beam coupon data with panel data.

Investigations have shown that the static strength properties of bonded graphite-epoxy (G/E) joints do not adequately reflect the random bending fatigue characteristics.

Shaker tests of G/E beam coupons have shown virtually a zero random bending fatigue life for an adhesive system while static strength tests and quality control inspections are all acceptable. The non-destructive test techniques available are not sufficient to ensure adequate performance under dynamic loading. Shaker tests or other suitable dynamic tests must be performed on any candidate adhesive bond system to ensure adequate performance under acoustic loads.

A prediction method has been developed for laminated graphite-epoxy stiffened skin design with the adhesive bonded stiffeners. The method is applicable for the design of the skin only. More work is needed to predict the life of other design configurations and other materials. The shaker tests with random mechanical loading augmented by selective progressive-wave tube tests appear to be the best approach.

Riveted technology prediction methods in general are not valid for adhesive bonded metallic structures and advanced composite structures. Modal analysis techniques are applicable, however, the magnitude and location of the maximum stress in the structure will be different. Many failure modes are possible with the adhesive bonded structures which must be understood. Fatigue curves are needed for each failure mode of interest. Adequate design methods must be produced to prevent the undesirable failure modes. Some of the methods used to solve sonic fatigue problems in riveted structures are not applicable to adhesive bonded structures. For example, increasing the skin thickness to reduce the stress in the skin can increase the peel stress in the adhesive and other stresses in the joint, shortening fatigue life.

The methodology associated with predicting the acoustic fatigue life is more complex in adhesive bonded metallic structures and composite structures since the failure modes and mechanisms are quite different and more sensitive to design and manufacturing methods than are riveted configurations. The testing requirements should be identified and defined in greater detail. Standardized test methods should be established to permit comparisons among the different investigators. Manufacturing methods, process control, quality control techniques and nondestructive evaluation techniques should be standardized to ensure consistent performance of the structures.

REFERENCES

1. Thomson, A. G. R. and Lambert, R. F.; "Acoustic Fatigue Design Data" Parts I through IV; AGARD-AG-162, Advisory Group for Aerospace Research and Development, 7 Rue Ancelle 92200 Neuilly Sur Seine France, November 1972.

2. Craddock, J. M.; "Evaluation of Weldbonding for Joining Thin Gage Aircraft Structures", Vought Systems Division, LTV Aerospace Corp. Report No. 2-22320-3R-4 (AD-918-212L), November 1973.

3. Wentz, K. R. and Wolfe, H. F.; "Development of Random Fatigue Data for Adhesively Bonded Weldbonded Structures Subjected to Dynamic Excitation", Journal of Engineering Materials and Technology, Transactions of the ASME, January 1978.

4. Wolfe, H. F.; Rupert, C. L. and Schwartz, H. S.; "Evaluation of Several Bonding Parameters on the Random Fatigue Life of Adhesively Bonded Aluminum Joints", AIAA Dynamics Specialists Conference, Paper No. 81-0627-CP, Atlanta, Georgia, April 1981.

5. Ballentine, J. R. et. al. "Refinement of Sonic Fatigue Structural Design Criteria", AFFDL-TR-67-156, AF Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, January 1968.

6. Holehouse, I.; "Sonic Fatigue Design Techniques for Advanced Composite Aircraft Structures", AFFDL-TR-80-3019 (AD-A084897), AF Wright-Aeronautical Laboratories, Wright-Patterson AFB, Ohio, April 1980.

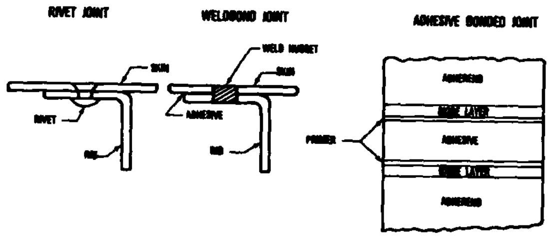

FIGURE 1 COMPONENTS OF A RIVETED JOINT, WELDBOND JOINT AND ADHESIVE BONDED JOINT

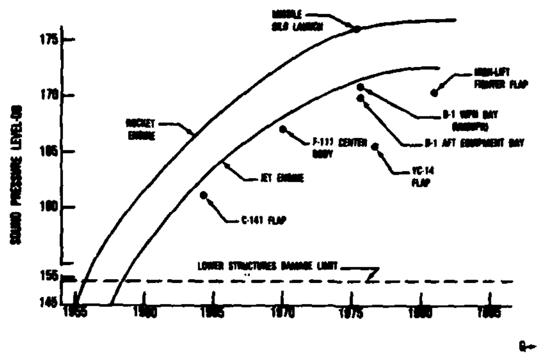

FIGURE 2 SOUND PRESSURE LEVELS ABOVE DAMAGE THRESHOLDS

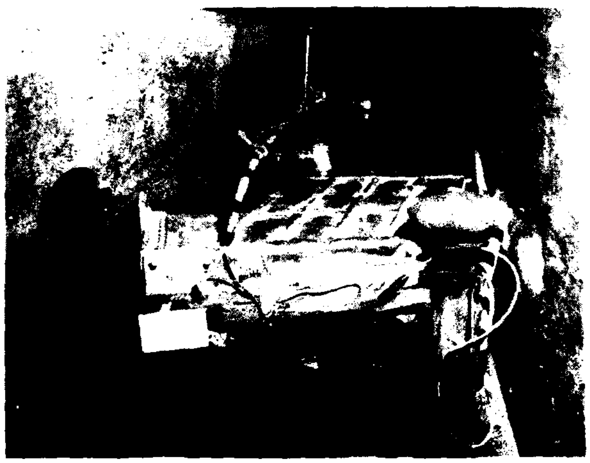

FIGURE 3 A-7 WING TRAILING EDGE SECTION IN ACOUSTIC CHAMBER

FIGURE 4 A-7 SECTION RIVETED FATIGUE FAILURES

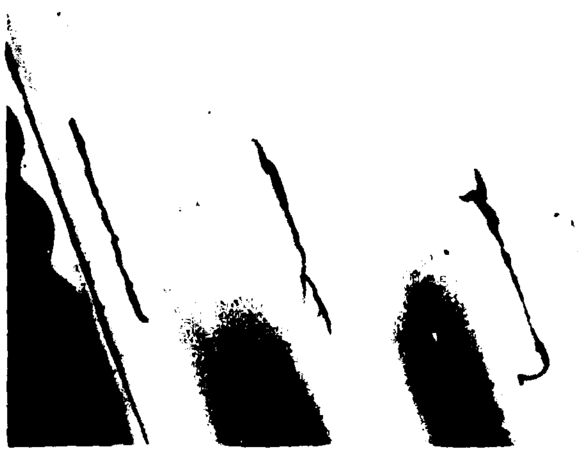

FIGURE 5 A-7 SECTION WELDBOND FATIGUE FAILURES

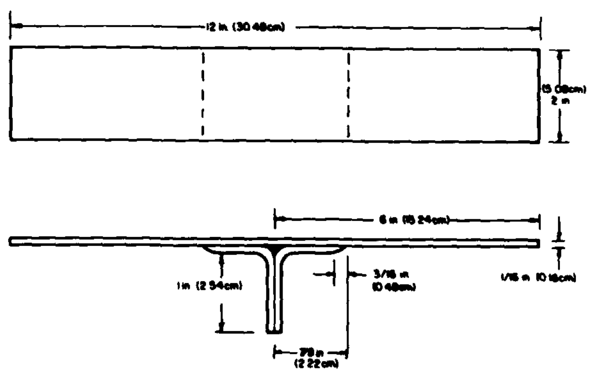

FIGURE 6 BEAM COUPON DIMENSIONS

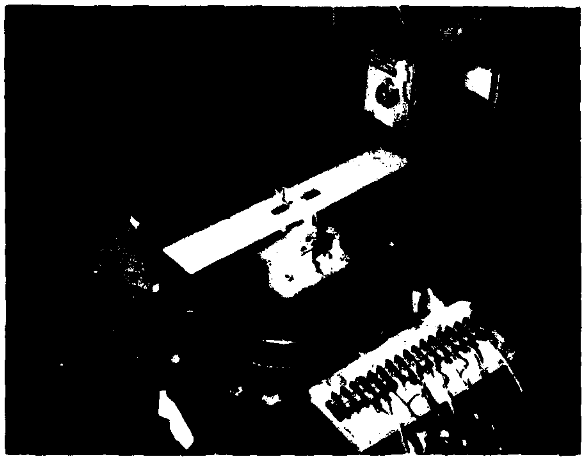

FIGURE 7 TEST SET-UP FOR BEAM COUPONS

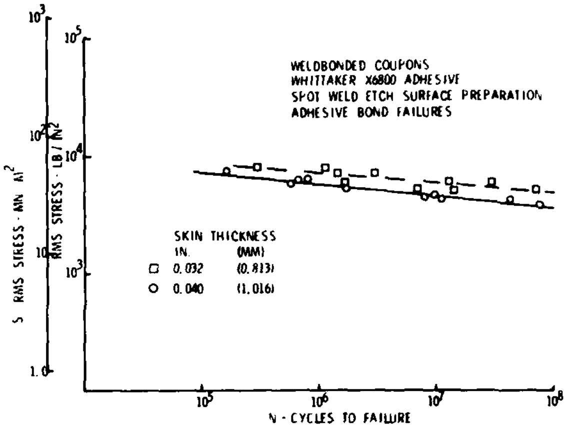

FIGURE 8 WELDBONDED COUPON S-N CURVE WHITTAKER X6800 ADHESIVE, SPOT WELD ETCH SURFACE PREPARATION

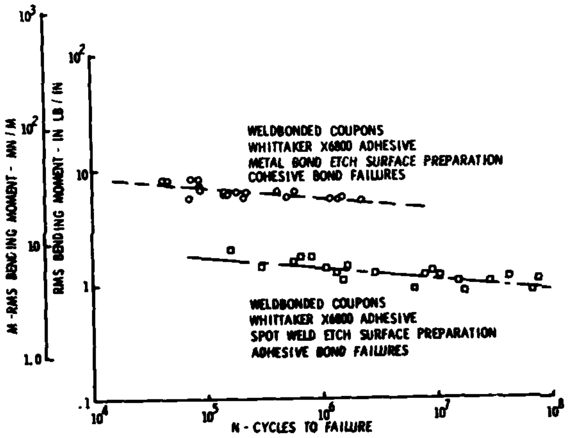

FIGURE 9 WELDBONDED COUPON M-N CURVE, COMPARISON OF TWO ADHESIVE SYSTEMS

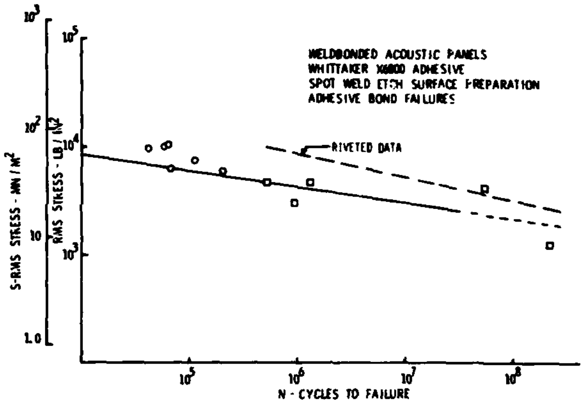

FIGURE 10 WELDBONDED PANEL S-N CURVE, AFFDL DATA, WHITTAKER X6800 ADHESIVE, SPOT WELD ETCH SURFACE PREPARATION

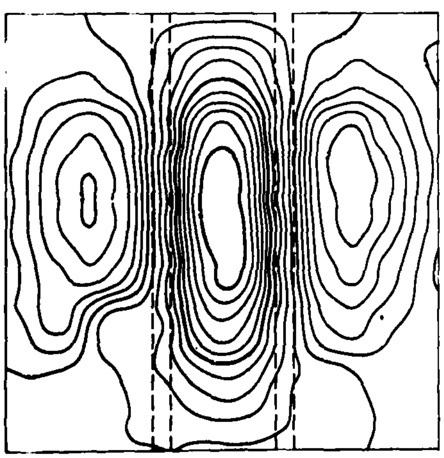

FIGURE 11 CONTOUR PLOT OF THREE BAY ADHESIVELY BONDED PANEL MODE SHAPES

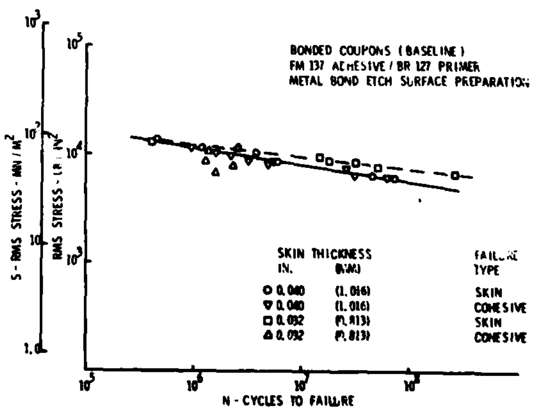

FIGURE 12 BONDED COUPON S-N CURVE, FM-173 ADHESIVE BR-127 PRIMER, METAL BOND ETCH SURFACE PREPARATION

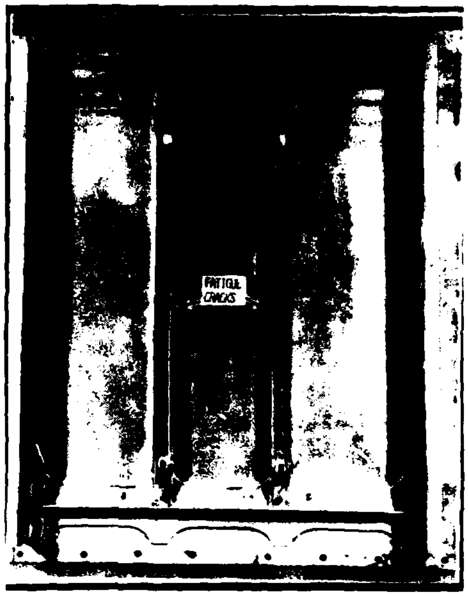

FIGURE 13 INTERMEDIATE SEGMENT FAILURES, BONDED ACOUSTIC TEST PANEL, FM-173 ADHESIVE BR-127 PRIMER, METAL BOND ETCH SURFACE PREPARATION

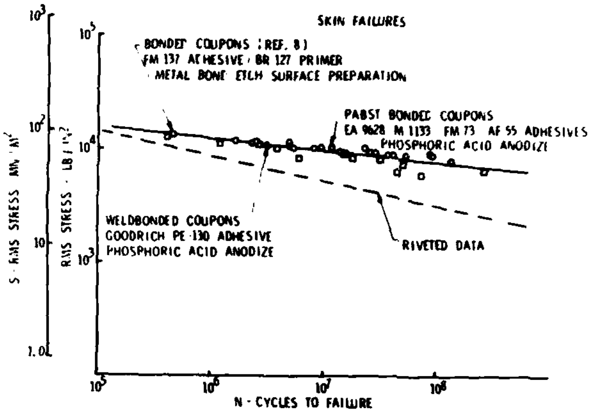

FIGURE 14 SKIN FAILURE DATA, THREE ADHESIVE SYSTEMS

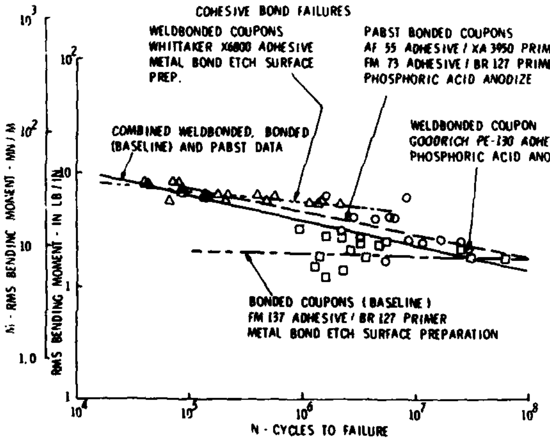

FIGURE 15 BONDED COUPON M-N CURVES AND COMBINED COHESIVE FAILURE CURVE

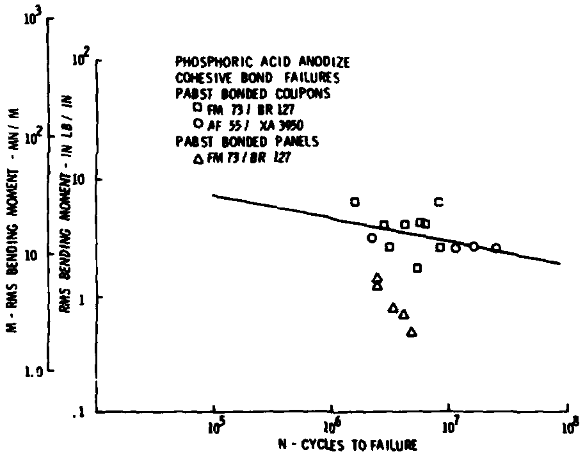

FIGURE 16 PABST COUPON M-N CURVE AND PABST PANEL M-N DATA

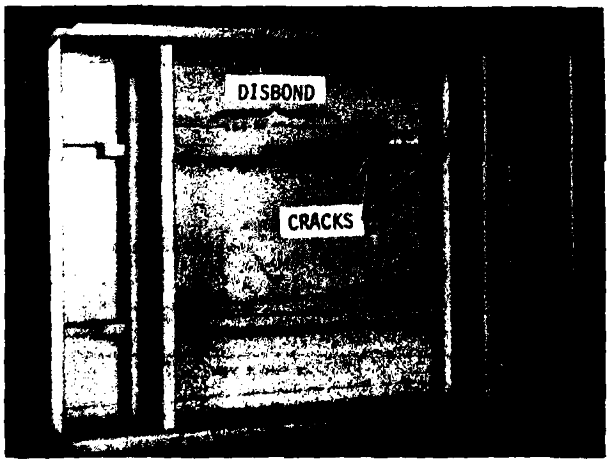

FIGURE 17 ADHESIVELY BONDED TEST PANEL

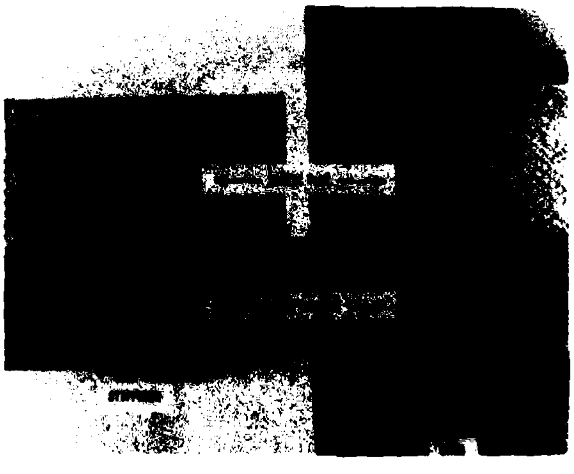

FIGURE 18 EXAMPLE OF FRACTURED ADHESIVE SURFACES UNDER STATIC AND DYNAMIC LOADS

FIGURE 19 PHOTOMICROGRAPH EXAMPLE OF COHESIVE BOND FRACTURE OF FM-73/BR-127 BOND SYSTEM

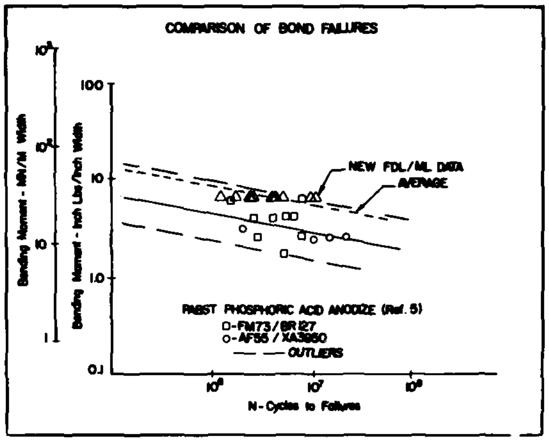

FIGURE 20 COMPARISON OF FDL/ML BOND FAILURES WITH PABST DATA

FIGURE 21 GRAPHITE-EPOXY PANEL WITH ADHESIVE BOND FAILURES

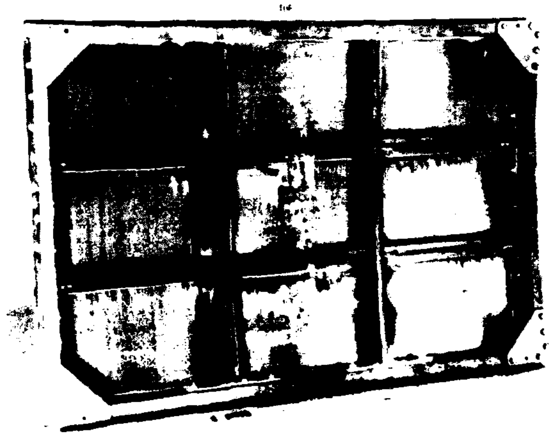

FIGURE 22 GRAPHITE-EPOXY LAMINATE FATIGUE FAILURES, BACK FACE

FIGURE 23 GRAPHITE-EPOXY LAMINATE FATIGUE FAILURES, FRONT FACE

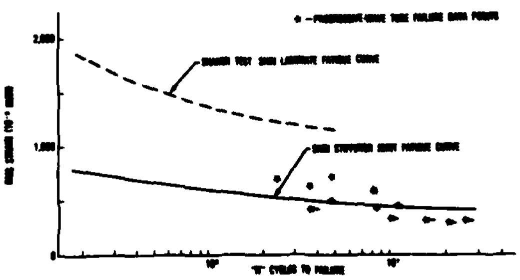

FIGURE 24 STRAIN VERSUS CYCLES-TO-FAILURE, PANEL & COUPON TESTS, GRAPHITE-EPOXY LAMINATE

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14. Abstract

The development of high strength adhesives, integral damping, advanced composite materials and lower cost manufacturing techniques has led to structural concepts quite different from the conventional riveted configurations. These new structural concepts are finding widespread interest in aircraft design and application and they must survive high intensity acoustic excitation for the service life of the aircraft. Acoustic fatigue prediction information for advanced composite and adhesively bonded structures is rather limited, and since these concepts represent a significant change in dynamic characteristics and failure mechanisms, prediction methods based on riveted technology may not be valid.

This report constitutes a review of the potential problem by the SMP and an effort to determine if there was sufficient concern in several NATO countries to warrant further activity.

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