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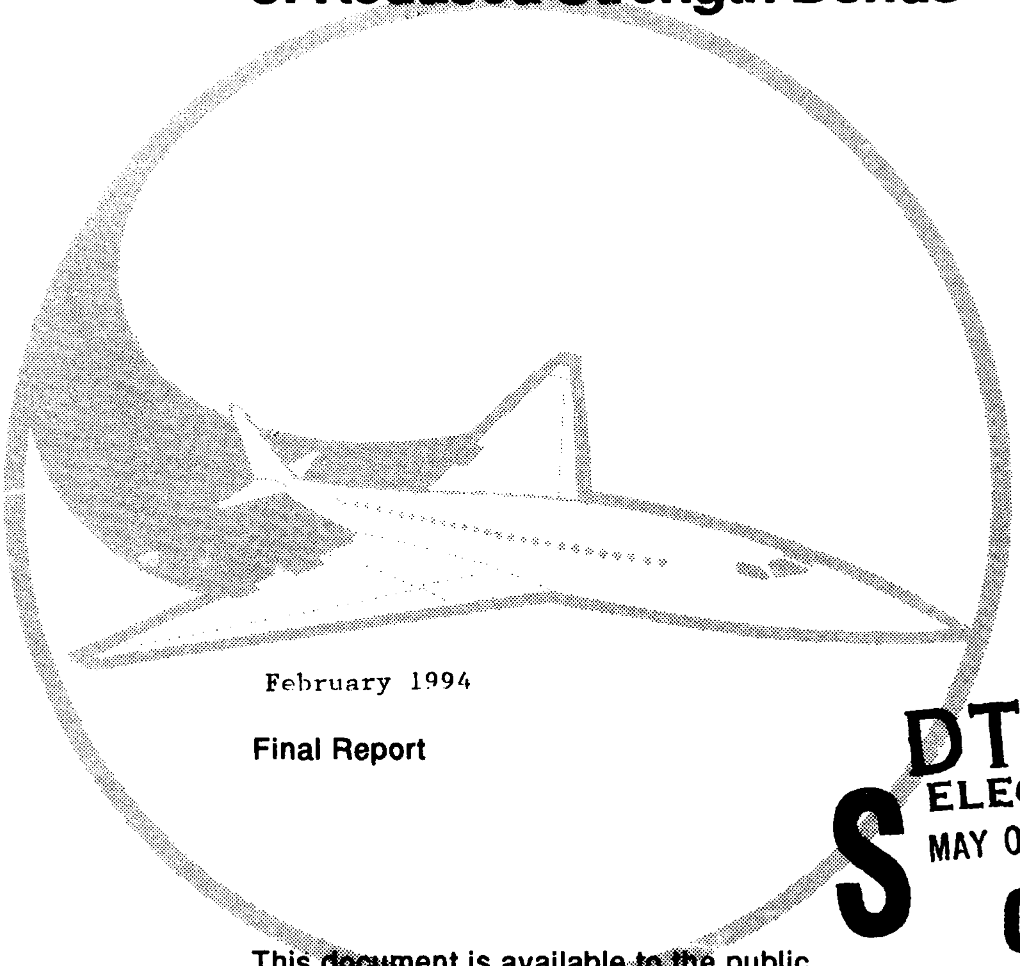
Nondestructive Inspection (NDI) of Reduced Strength Bonds



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Final Report

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16. Abstract

The goal of this project was to develop a nondestructive inspection technique capable of detecting weak adhesive bonds. The approach was to fabricate contaminated surface-induced weak bond specimens which were then used to evaluate candidate techniques and to further optimize the selected most promising technique. The results indicate that the ultrasonic resonance technique showed some success in detecting weak bonds as determined through destructive test correlations conducted using the representative weak bond specimens. The technique was 97 percent effective in detecting known weak bonds but was subject to false reject error ranging between 14 and 31 percent depending upon the evaluation criteria employed. Difficulties were encountered with the destructive test correlations due to the wide variation of results experienced with the flatwise tension tests that were conducted. The ultrasonic resonance technique and a recently emerged ultrasonic feature analysis/adaptive learning technique looked promising but will require further evaluation involving test specimens with large weak bond areas representing several weak bond mechanisms in addition to contaminated interfaces.

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PREFACE

This three-phase Federal Aviation Administration (FAA) Technical Center sponsored project is concerned with the development of a nondestructive evaluation system to detect reduced strength bonds. Phase I, specimen fabrication and preliminary technique evaluations, and Phase II, prototype development, have been previously reported on. This report summarizes the two previous phases and emphasizes the results of the third phase dealing with the quantitative evaluation of the prototype system.

The project was administered by the FAA Technical Center, Atlantic City International Airport, NJ. Lawrence M. Neri served as the FAA Technical Manager. Technical direction and support was also provided by Joseph Soderquist, FAA National Resource Specialist, Advanced Materials/Nonmetallic. The project was conducted by Grumman Corporation under the management of Richard F. Chance with technical participation by several personnel including K. Wongwiwat, J. Freese, J. Andre, and M. Horn.

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EXECUTIVE SUMMARY

A nondestructive evaluation prototype system and its associated procedure were developed to detect weak adhesive bonds created through contaminated interfaces. The system is based on the harmonic resonance technique identified in Phase I of this project and developed into a prototype in Phase II. The procedure using the prototype system is time consuming and complex but has been shown through destructive test correlations on known weak bond specimens to have some success for this very challenging problem. The degree of success is somewhat uncertain due to the considerable test result variation experienced with the flatwise tension destructive test correlations. Another recently emerged easier to use technique based on ultrasonic feature analysis and adaptive learning was investigated. This method looks promising but would require further evaluation to determine its effectiveness.

INTRODUCTION

This program was initiated to develop a nondestructive capability for detecting weak adhesive bonds. There is no currently available, proven method to reliably perform this function, although several available techniques routinely detect unbonds. The detection of weak bonds is an increasing concern in light of recent use of adhesive joints for primary structure applications. The biggest concern is for a condition commonly called a "zero strength" or "kissing" bond where the bond adherends are in intimate contact with the adhesive but with little or no developed mechanical bond between them, i.e., tension and shear strengths of the joint are negligible. This leads to "unzipping" (adhesive failure) when mechanically loaded. Other intermediate strength reduction levels are also a concern and were addressed by this program.

A significant ground rule during this effort was to emphasize use of "off-the-shelf" instrumentation to enable a rapid transfer of technology to the aircraft industry.

This is the final report of a three-phase program. The first phase involved the development of weak bond simulation techniques, the fabrication of test specimens, and the evaluation of candidate techniques. The second phase addressed the development, fabrication, and preliminary evaluation of a prototype system based on the Phase I findings. The third phase provided further evaluation of the prototype and a preliminary evaluation of a newly emerged, commercially available technique involving ultrasonic feature analysis combined with adaptive learning.

This report summarizes the efforts conducted during the first two phases and discusses in detail the efforts involving the concluding Phase III activities.

PHASE I SUMMARY

GENERAL DISCUSSION.

A key requirement in pursuing the development of a suitable weak bond detection technique is the availability of test specimens that are representative of reduced-strength bonds. A previously developed proprietary technique was the basis for preparing these specimens. The technique had been successful in producing reduced-strength bonds in metal-to-metal specimens and showed promise for composite-to-composite applications. Therefore, major Phase I tasks of this program were to duplicate the technique on metal-to-metal specimens and further develop it for composites.

The most likely nondestructive testing technique to be developed was anticipated during the proposal stages to be based on ultrasonic resonance principles. Preliminary studies indicated favorable results for this technique on metal-to-metal specimens; however, it was not evaluated for composites applications. Additional tasks of Phase I were, therefore, associated with further development of the ultrasonic resonance technique and evaluation of other emerging technologies.

Another task that was addressed in Phase I involved the evaluation of using external excitation to enhance the detectability of reduced-strength bonds. This approach was suggested as a result of the accidental discovery that defective areas in specimens evaluated after band saw cutting were more detectable. It was thought that a nondestructive technique for exciting the bondline might aid in the effectiveness of the selected test technique.

RESULTS AND DISCUSSION.

Test Specimens.

Initial Selection of Test Specimen Materials. Test specimen material variations representative of the typical adhesively bonded commercial aircraft structures were selected. A specimen combination using 0.030 and 0.100-inch-thick 2024T3 aluminum panels bonded together with an epoxy-based 250 °F cure adhesive was determined to represent typical metal-to-metal bonded structure. For composite structures, a specimen combination using 8-ply (0.040 inch) and 16-ply (0.080 inch) quasi-isotropic graphite/epoxy panels bonded together with either a 250 °F or 350 °F epoxy-based adhesive was selected. It was recognized that once candidate nondestructive inspection (NDI) techniques emerged, other specimens representing variable conditions that could affect the validity of those techniques might be required.

Fabrication of Metal-to-Metal Specimens. A proprietary surface treatment technique that had previously demonstrated the ability to generate reduced-strength bonds was further developed using an alternate commercially available compound. The adequacy of this technique was first demonstrated on specimens fabricated using a vacuum bag and oven cure procedure. These metal-to-metal specimens were subsequently evaluated using the conventional ultrasonic "C" scan reflector plate through transmission technique which revealed no unbond indications in 49 of the 72 areas treated by the proprietary technique. However, several areas (including 23 of the 72 treated areas) did reveal unbond conditions. In addition, a high frequency (50 MHz) pulse echo technique was used to measure bondline thicknesses which were found to range between 5.8 and 14.7 mils. Based on these results, it was concluded that the proprietary treatment technique was effective but that the vacuum bag/oven cure approach provided inadequate pressures which led to unbonds and widely varying bondline thicknesses.

Fifteen additional specimens were made that included the use of an optimized technique (vacuum bag/autoclave cure/3 bleed holes) and some variations in order to provide some intermediate strength bonds. These specimens were tested for unbonds with none found and for bondline thickness where the thicknesses ranged between 7.3 and 10.8 mils. Several of these specimens were accompanied by lap shear specimens which demonstrated that reduced strengths were achieved. In addition to the strength data, they all exhibited some degree of adhesive failure, which is considered evidence of a weak bond since cohesive failure indicates that the strength of the bond between the adhesive and substrate is greater than the strength of the adhesive.

Fabrication of Composite-to-Composite Specimens. Preliminary studies indicated that the proprietary surface treatment used on the metal-to-metal specimens had limited effectiveness on composites since it was diffused into the more absorbent graphite/epoxy surface (at cure temperatures). A modified procedure involving an additional application of the proprietary surface treatment was used in order to compensate for absorption effects. In addition, the originally proposed 8-ply to 8-ply configuration was changed to 8-ply to 16-ply in order to prevent warpage. Seven specimens were initially made using this technique, with good success achieved (no unbonds and lap shear strengths ranging between 440 and 900 psi). The next seven specimens were made using the same technique, except that a higher cure temperature adhesive and cure cycle (350 °F) was employed with no weak bonds evident. It was concluded that the higher cure temperature increased the absorption rate and made the technique ineffective. Subsequently, 19 additional specimens were fabricated using a duplication of the technique/adhesive employed for the first 7 and some variations in order to provide some intermediate strength bonds.

Technique Evaluations.

Emerging Technique Identification. A literature search and preliminary experimental evaluations were conducted in an effort to identify candidate techniques that showed sufficient feasibility to warrant further study. Preliminary metal-to-metal test specimens available from prior studies were distributed to various organizations that showed an interest or potential for detecting weak bonds. Georgetown, Ohio State, and Drexel Universities all exhibited potential feasibility using variations of the oblique incident angle ultrasonic technique. In addition, the ultrasonic resonance equipment available at Uniwest, Inc., showed potential feasibility, as had been expected, based on earlier studies. Other organizations were not successful in demonstrating feasibility, and the techniques they were promoting were eliminated from further consideration. Specific techniques that were initially considered and then eliminated included ultrasonic spectroscopy, leaky lamb wave ultrasonics, electronic X-ray backscatter imaging, and time-resolved infrared thermography.

Oblique Incident Angle Ultrasonics. The initial favorable Drexel University results were based on the use of two metal-to-metal specimens fabricated prior to this project and two specimens fabricated by Drexel. The results were not conclusive due to the possible influence of localized unbond conditions known to exist in the Grumman supplied specimens and unrealistically thick contaminated bondlines in the Drexel specimens. Three additional specimens with more realistic programmed weak bond conditions were submitted to Drexel to permit further evaluation of the technique.

The end result of these studies was discouraging. After optimizing their techniques on the earlier specimens, Drexel researchers reported a failure to detect three of the four weak bond areas they evaluated that were in a new specimen. The defect that was detected exhibited only a 2-dB signal difference from surrounding good areas. In addition, the technique employed was found to be extremely labor intensive and not very practical for routine applications. Based on the findings of this study, it was concluded that the oblique incident angle technique did not warrant consideration of further development in Phase II.

High-Frequency Ultrasonic Pulse Echo Reflection. A basic theoretical aspect of ultrasonic testing is that the size of a defect that will generate a reflection is directly related to the frequency (or waveform length) of the incident beam. At very high frequencies, very small defects can be detected; however, the rate of incident beam and reflected signal attenuation increases significantly. In the case of weak bondline defects such as very thin layers of contamination, it was thought that monitoring the amplitude of the reflected signal from the bottom interface of the adhesive to skin might be feasible. In pursuing this approach, it was recognized that the thickness of the adhesive would be a variable and have a large extraneous effect (due to attenuation) if not considered. Therefore, a technique using a 50-MHz normal incident beam (pulser and transducer) and a programmable digital oscilloscope (to automatically measure the adhesive layer thickness) was evaluated on the metal-to-metal specimens.

A total of 13 specimens were "mapped out" using the high frequency technique. The adhesive layer thickness and amplitude of the bottom interface were noted on the specimen. The interface amplitudes from common thickness areas having good and weak bonds were compared with somewhat encouraging results. However, further investigation of the few areas having poor correlation revealed that the bond interface amplitudes were severely affected by probe pressure and coupling efficiency at the skin surface. The investigation further revealed that the thickness of the primer coating on the surface had a major effect on the bond interface signal due to attenuation effects. In order to eliminate these unwanted variables, one of the specimens was rerun with the primer coating chemically removed and the probe pressure maintained constant by normalizing to a common amplitude for the top adhesive to skin interface. The results were no longer that encouraging with only a slight difference evident between good and weak bonds in only some of the areas.

Ultrasonic Resonance. This is an established ultrasonic technique used to detect unbonds. It is based on the fact that two well-bonded skins will tend to resonate at a frequency and amplitude similar to that for one piece of the same material representing the combined thickness of the two skins. When very thick bondlines or unbonds are present, the resonance frequency will tend to approach that of the top skin. When phenolic-based adhesive systems are used, variations in adhesive layer thicknesses can be directly correlated to adhesive bond strength. However, when epoxy-based adhesive systems are used (a current common practice), there is no direct correlation of bond strength to adhesive thickness. Early experimental studies found that the amplitude of the resonating frequency from metal-to-metal specimens appeared to differ depending on the adhesive strength of the epoxy adhesives. Further studies involving various techniques for inducing the resonating frequencies and for analyzing the signals were recommended.

The optimization efforts performed in Phase I related to evaluating inducement, signal analysis, and scanning techniques. The three methods of inducing the resonant sound waves in the material that were investigated included mechanical, piezoelectric, and electromagnetic. The signal analysis techniques evaluated were amplitude and phase shift. The scanning technique optimization addressed the effect of probe pressure and part holding concepts.

Several metal-to-metal test specimens were used to evaluate the three methods of inducing resonant sound waves. Table 1 illustrates the typical results that were obtained. The results indicate that the mechanical method of inducing the sound wave was most effective. The mechanical probe utilized a transmitting element having a coil resting in an aluminum cup with a rod touching the base of the cup. When excited, the coil induces an interactive opposing eddy current field in the base of the cup and, consequently, mechanical vibrations. The electromagnetic probe induced vibrations by an alternating current-driven coil that generates an electromagnetic field in the skin with the interaction of opposing and transmitted fields causing vibrations. The piezoelectric probe induced the vibrations in the material using a piezoelectric crystal. In all the probes, the resultant sound wave induced in the skin was sensed by a piezoelectric crystal.

The same metal-to-metal specimens used to evaluate the probe types were used concurrently to evaluate the effectiveness of amplitude and phase signal analysis techniques. In all cases, the phase analysis technique was found to be ineffective, while variations in amplitude were much more informative. A possible explanation for these results is that the phase shifts that would be detected would reflect changes in resonating frequencies which are probably very subtle or nonexistent in the case of weak bonds.

Based on the initial results on the metal-to-metal specimens, further evaluations of the ultrasonic resonance method were restricted to a technique based on the use of a mechanical excitation probe and amplitude signal analysis. A total of 36 metal-to-metal specimens and 33 graphite-to-graphite specimens were then evaluated, with the results shown in tables 1 and 2. The asterisk (*) symbol indicates that the area was not available for test due to its assignment to perform a peel test.

TABLE 1. ULTRASONIC RESONANCE ELECTROMECHANICAL PROBE/AMPLITUDE ANALYSIS TECHNIQUE ON METAL-TO-METAL SPECIMENS SHOWING RELATIVE AMPLITUDE (IN %)

SPECIMEN		DEFECT NO.									GOOD AREA
NO.	TYPE	1	2	3	4	5	6	7	8	9	
M1	ZERO	62	60	65	62	55	55	55-60	70	55	40-45
M2	ZERO	75	80	75	50	75	62	65-70	55	55	40-50
M4	ZERO	68	75	100	65	65-70	75	65	80	60	35-50
M5	ZERO	75	65-85	82	70	60	90	60	80	60	20-50
M6	ZERO	62	68	75-90	65-70	80	70	82	65	75	35-45
M7	ZERO	70	70	80	80	70	70	55-60	90	75	35-50
M8	ZERO	69-80	82	72	70	50	75	63	90	70	30-40
M9	ZERO	62	68-72	70	*	70-75	65-72	*	65	*	40-60
M10	ZERO	70	70-85	70	90	90	60	85	60	95	40-55
M11	ZERO	70	65-75	70-80	80-90	75	65-70	65-75	65-70	65-72	40-50
M12	ZERO	70	75-82	65-70	85	75-85	65	70-80	68	100	40-60
M13	ZERO	**	75-90	85	80	**	80-90	90	80-90	90	60
M14	ZERO	82	70-75	75-80	75	72	75-80	70	70	70	40-50
M15	INTERMEDIATE	65	70-90	65-85	70-80	90-95	65-70	85	70	70-80	40-60
M16	INTERMEDIATE	72	65-75	70	70-82	80-85	60-85	70-80	75	95	40-60
M17	ZERO	90	65-70	75	80-90	70-80	65-70	80	65	80-90	45-50
M18	ZERO	75-90	65-80	70-80	**	70-80	85	75	80	**	45-50
M19	ZERO	70	65-80	72	72	90	82	75	70	70	50-55
M20	ZERO	70	70-85	70-95	70	65-70	60	65-70	70	90-100	40-50
M21	ZERO	65	65-70	65-70	75-90	65-70	65-85	75	65	65-80	40-50
M22	ZERO	65-70	70-85	70-85	65-70	65-85	70	65	65	75-90	40-50
M23	ZERO	70-75	75	75-90	75-80	50	50	60	60-70	80	40-50
M27	ZERO	70-90	65-72	65-70	90	70-80	55	65-70	50	70-80	40-50
M28	ZERO	65-75	65-72	70	90	60-65	70	65	65-72	70-95	40-50
M29	ZERO	65-70	90-100	75	80	75	60	75	65	90-100	40-60
M30	ZERO	70	70-80	72	80-90	72	75	70	65-70	100	40-65
M31	ZERO	70	65	70-72	75-85	75	70	65	65	80	30-50
M33	ZERO	65	72	75	75	70	60	65	55-60	80	40-60
M34	ZERO	75	70	65	75	50	50	80	65	85	40-60
M35	ZERO	80	72	90	65-90	75	70	80	75	70	40-65
M36	ZERO	90-95	80	70	75	90	50	65	70	80	40-60
M37	ZERO	70-90	80-100	85-95	90	70	80-90	80	70	80-85	40-65
M38	ZERO	80	90	80-90	90	75	60	75	80	70-90	40-65
M39	INTERMEDIATE	65	90	70	70	70	60	70-90	70	85-90	40-50
M40	INTERMEDIATE	65-70	75	70-80	70-90	80	70	65-72	60	70-75	40-50
M41	INTERMEDIATE	70-90	65-75	70	70	70	55	70	70-75	100	40-60

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TABLE 2. ULTRASONIC RESONANCE ELECTROMECHANICAL PROBE/AMPLITUDE ANALYSIS TECHNIQUE ON COMPOSITE-TO-COMPOSITE SPECIMENS SHOWING RELATIVE AMPLITUDE (IN %)

SPECIMEN		DEFECT NO.						GOOD AREA
NO.	TYPE	1	2	3	4	5	6	
G1	ZERO	90-100	80-100	90-100	90	90-100	60	50-60
G2	ZERO	85-90	80	90-100	100	80-90	80-95	40-65
G3	ZERO	90-100	75	85	80-90	90-100	90-100	50-60
G4	ZERO	95-100	80	95-100	90	95-100	80-85	40-60
G5	ZERO	80-90	80	80-90	100	100	95	45-55
G6	ZERO	80-85	85	85-90	85-90	95-100	90	30-50
G7	INTERMEDIATE	85	85-100	100	100	100	85-90	50-60
G9	ZERO	95	100	90	80	100	80-100	50-60
G10	ZERO	90	90	80-85	90	80-95	90-100	50-60
G11	ZERO	100	75-80	85	90	80-100	100	40-60
G20	INTERMEDIATE	85	70	80-85	70	80	85	50-60
G21	INTERMEDIATE	75	80	85-100	85-90	80-95	80	50-60
G22	INTERMEDIATE	80-90	80-90	80-100	90-100	80-100	90-100	50-60
G23	INTERMEDIATE	75	80-100	90	75-100	75	90	50-60
G24	ZERO	90-100	75	90	70	80-95	80	40-60
G25	ZERO	75	80	70	75	70-90	75-90	50-60
G26	ZERO	100	85-100	100	90-100	90-100	90	50-60
G27	ZERO	90-100	95-100	90-100	100	100	100	50-70
G28	ZERO	80	65	75-85	100	100	95	40-60
G29	ZERO	80-85	70-75	95	80-100	80-95	90	50-60
G30	ZERO	70-75	80	90	70-85	75-85	85	40-50
G31	ZERO	75-85	70	75-85	80	85	80	40-65
G32	ZERO	70-75	70	75	80	65	65	35-50
G33	ZERO	80	75-80	70	60	85	85	40-45

REMARK: SPECIMENS G8, G12-19 WERE FABRICATED WITH NO CHEMICAL IN DESIGNED DEFECTS.

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A significant refinement to the technique used for subsequent evaluations was the use of "bubble wrap" packaging material between the specimens and the table surface. This approach was determined to be necessary based on the observation that nonrepetitive readings were always found from some areas of some samples. An investigation of these samples revealed that they were slightly warped and that, depending on the probe pressure, the back surfaces of the specimens had varied contact with the table top which, in turn, would alter the specimen's resonating characteristics. The bubble wrap was found to be an effective method of eliminating this specimen peculiar variable.

A unique characteristic of the technique used during the specimen studies was the increased sensitivity involving defect boundaries. All the data reported reflect the maximum signal observed, which always occurred at the boundary between the good and defective areas. Very small signal differences were observed from areas in the middle of large defective areas and "good" areas. Based on this, the personnel gathering the data scanned very slowly and from multiple directions across the boundary areas. Further studies of this factor indicated that scanning at the rate of approximately 60 inches per minute and from perpendicular directions would be effective in detecting the defects. However, it should be noted that, due to this limitation of the technique, it would not be effective if the entire part was weakly bonded.

The results of the ultrasonic resonance (electromechanical probe/amplitude) analysis studies indicated that it was the most effective technique for detecting reduced-strength bonds. In almost all cases, the programmed defect areas were detected and distinguishable from "good" areas. However, the effects of varying skin and adhesive layer thicknesses on the technique were identified as areas requiring further study before determining feasibility.

Effect of Other Variables. The effect of skin thickness variations on the feasibility of the optimized ultrasonic resonance technique was studied using the specimens listed in table 3. For both types of specimens, it was found that as the total thickness increased, additional amplification of the signal was required in order for the defect to be detectable. For metals, the total thickness limitation was found to be 0.8 inch where an additional 10 dB of gain was required in order for the programmed weak bond defects to be marginally detectable. For the composite-to-composite specimens, the total thickness limitation was found to be 60 ply (approximately 0.3 inch).

The effect of adhesive thickness variation on the optimized ultrasonic resonance technique was also studied using several basic metal-to-metal specimens that had variations of bondline thicknesses in the defect areas. A general trend (figure 1) was found in which the signal amplitudes decreased as the bondline thickness increased. A probable explanation of this trend is that the thicker adhesive layers would have a damping effect on the induced ultrasonic wave. These data indicate that the technique would tend to give false acceptable indications when a nominally assumed 10.0-mil-thick bondline exceeded 12.0 mils in thickness since the amplitudes would begin to approach those observed for good areas (40 to 65 percent). In addition, with bondline thicknesses that are much less than nominal, the possibility for the whole part to exhibit defect indications would exist.

TABLE 3. ADDITIONAL TEST SPECIMENS REPRESENTING SKIN THICKNESS VARIATIONS

SPECIMEN NO.	DESCRIPTION
METAL-TO-METAL	
M42	0.250 in. Al BONDED TO 0.100 in. Al
M43	0.375 in. Al BONDED TO 0.050 in. Al
M44	0.125 in. Al BONDED TO 0.125 in. Al
M45	0.125 in. Al BONDED TO 0.100 in. Al
M46	0.100 in. Al BONDED TO 0.032 in. Al
COMPOSITE-TO-COMPOSITE	
G34	30-PLY GR/EP TO 30-PLY GR/EP
G35	30-PLY GR/EP TO 16-PLY GR/EP
G36	16-PLY GR/EP TO 16-PLY GR/EP
G37	16-PLY GR/EP TO 8-PLY GR/EP

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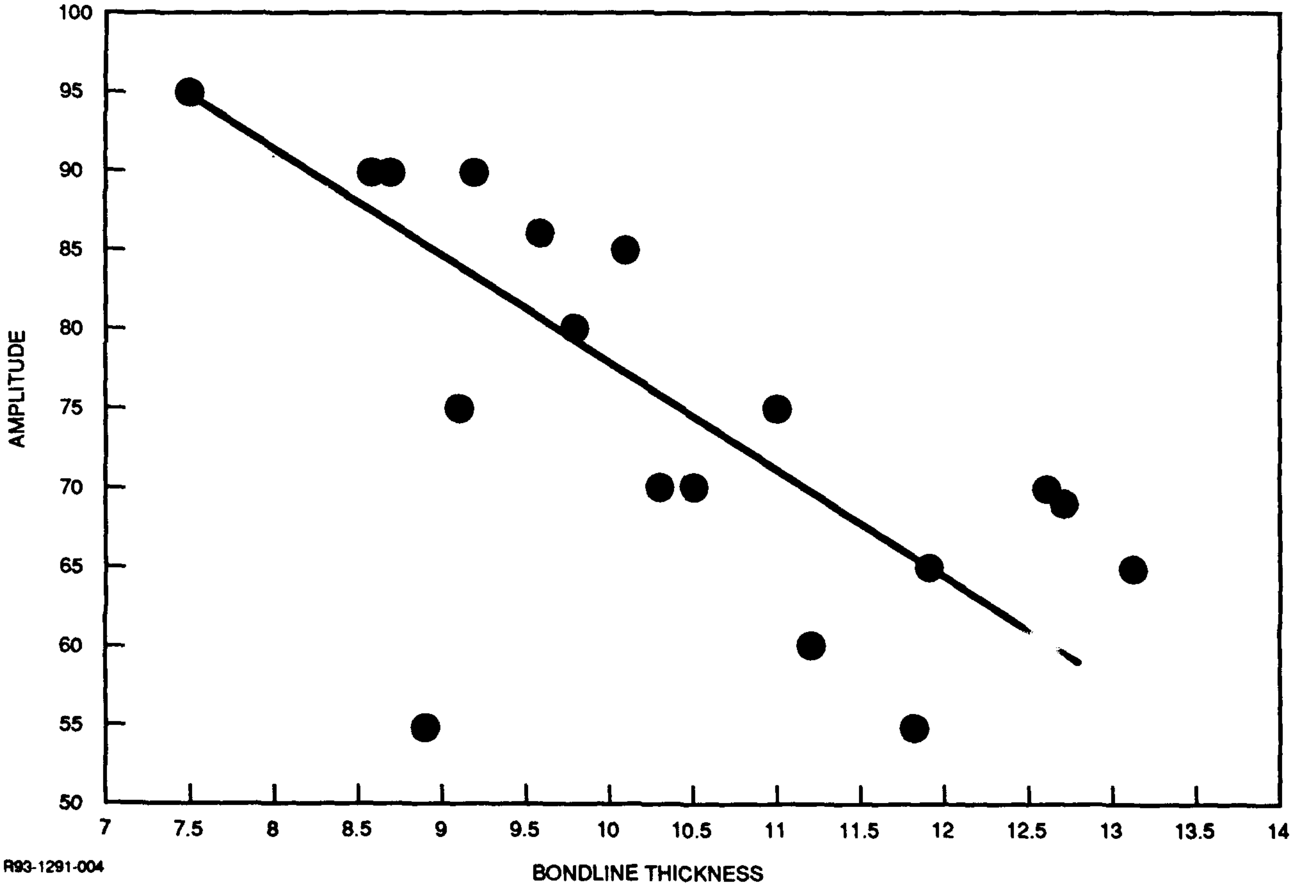

FIGURE 1. EFFECT OF BONDLINE THICKNESS

External Excitation.

Characterization of the "Band Saw" Effect. Preliminary studies indicated that inadvertent band saw cutting of specimens enhanced the detectability of weak bond defects. An evaluation of the band saw operation was conducted to help identify the requirements for a nondestructive approach that would enhance detectability. A measurement of the blade teeth per inch and blade speed indicated that a load frequency in the range of 15 cycles/second was induced in the samples. The amplitude of the vibrations varied with the sharpness of the band saw blade, with essentially no observable vibrations evident with a new/sharp blade and deflections of more than 0.050 inch observed when using an extremely dull blade. It was concluded that it would be highly desirable to identify a candidate technique that would operate in a similar frequency range and have a highly variable amplitude capability.

Survey of Potential Excitation Techniques. Loading techniques that were initially investigated included thermal, capacitive discharge, electromagnetic, acoustic, and mechanical. The thermal approach using either conventional heat sources (i.e., quartz rods, hot air, lamps) or a high-energy laser was eliminated from further consideration due to the damping effect thermal conductance would have on efforts to achieve a frequency in the range of 15 cycles/second. The capacitive discharge and electromagnetic techniques were eliminated due to the requirement that the applicable materials be restricted to electrical conductors. The acoustic technique was considered undesirable since it would require massive and costly transducers to achieve the amplitudes desired. It was therefore decided to pursue the mechanical vibration approach since it was most similar to the band saw effect, was not restricted to the type of material, and would not require high-cost equipment.

Evaluation/Optimization of Mechanical Excitation Technique. A subresonant frequency system used to stress relieve-welded assemblies was located that possessed a variety of characteristics and controls that were very suitable for the desired studies. The system has frequency control, interchangeable force inducers with varying load capabilities, and force-monitoring system to measure the induced loads. The standard system setup involves locating the force inducer on a large steel baseplate and placement of the force-monitoring probe on the part or specimen being treated. However, the system can also be operated in a portable mode without the baseplate, which would enable applicability to "in-service" applications.

Initial studies were conducted using 7- by 14-inch metal-to-metal specimens that had marginally detectable weak bond indications (using ultrasonic resonance) prior to treatment. The specimens were mounted on the steel plate which was then excited to its subresonance frequency (which is the frequency at which the power level is 1/3 of the maximum achievable power). The specimens were then reevaluated using the same ultrasonic resonance technique with several of the defective areas appearing to be more detectable.

Further optimization of the technique was sought by attempting to isolate the specimen. A 7- by 14-inch specimen was clamped to the steel plate with aluminum blocks placed between the edge of the specimen and the steel plate. The force-monitoring transducer was then alternately placed on the specimen and the steel plate while operating the force inducer at the same frequency. No difference in the power level readings was observed, indicating that isolation was not achieved. An alternate approach of attaching the force inducer to the specimen was determined to be unfeasible due to the large size of the inducer and the small size of the specimen.

CONCLUSIONS (PHASE I).

1. The most suitable technique for reduced-strength bond detection was found to be ultrasonic resonance, using mechanical excitation for inducing sound waves and amplitude signal analysis.

2. The ultrasonic resonance technique is applicable to metal bonded assemblies with a total thickness up to 0.8 inch and to composites with a thickness up to 60 plies, assuming 0.005 inch per ply.

3. The ultrasonic resonance technique is effective for bondline thicknesses of 10.0 mils ± 2.0 mils.

4. A limitation of the ultrasonic resonance technique is its reliance on the presence of boundaries between good and reduced-strength areas.

5. Intermediate strength bonds appeared to be detectable by the ultrasonic resonance technique but were not readily distinguishable from near-zero-strength bonds.

6. The subresonance frequency excitation technique appeared to enhance the detectability of weak bonds when employed using a large baseplate. However, efforts to employ the vibrating inducer directly on the specimens were not successful.

PHASE II SUMMARY

GENERAL DISCUSSION.

The Phase I findings indicated that the preliminary feasibility of the ultrasonic resonance technique for detecting weak bonds warranted the further development of the technique into a prototype system. The further development of the subresonance external excitation technique was not pursued in Phase II based on its nonapplicability to small parts and specimens. Further evaluation of the ultrasonic resonance technique after the prototype was evaluated was considered very important since it would remove the subjectivity associated with the initial evaluation.

RESULTS AND DISCUSSION.

Assembly of Prototype.

Based on the Phase I results, the initial prototype system recommended was to include a resonance-type instrument, a resonance probe based on mechanical excitation, a probe scanner, and a recorder. Such a system was assembled and evaluated using test specimens fabricated during Phase I. The instrument employed was a Shurtronics Composites Tester which has phase and amplitude display outputs. The probe was a Shurtronics Model ST-3014 which has a transmitter (based on an eddy current coil exciting a metallic cup attached to a rod impactor) and a membrane microphone receiver attached to a rod (figure 2). The probe scanner had a small DC motor that drove a lead screw having a probe holding fixture attached. A 2-channel, high-impedance strip chart recorder was included in the system to provide outputs of amplitude and phase characteristics.

This early prototype system was unusual in that it provided the capability for controlled incremental scanning with a technique that has normally been used in a hand held, manual mode. The data collected during Phase I were based on the manual approach, where the operator was required to hand-scan over a "suspect area" until maximum signals were observed. The purpose of the scanning system was to eliminate the subjectivity inherent with the manual approach.

The test specimens fabricated during Phase I were used to evaluate the initial prototype system and its subsequent improvements. The configurations of these specimens and the

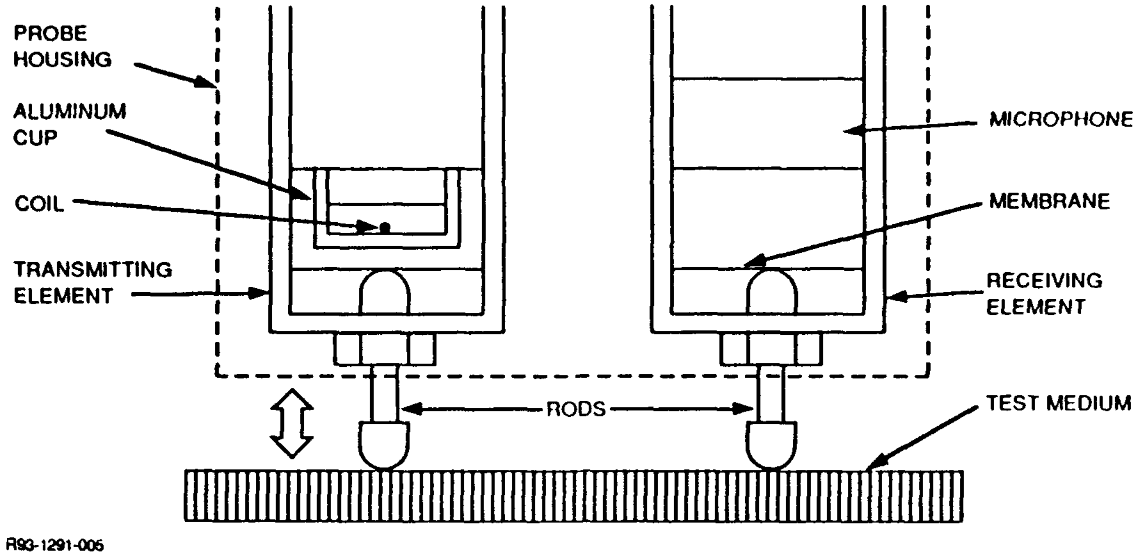

FIGURE 2. TRANSMITTING AND RECEIVING ELEMENTS

locations of the programmed weak bond areas are shown in figures 3, 4, and 5. It should be noted that the two latter designs contain bleed holes in the skin that were necessary to achieve consistent adhesive bondline thickness. These bleed holes cause a localized change in the resonance patterns and often result in resonance amplitude peaks (i.e., antinodes) that are similar to defect indications.

The initial evaluation of this prototype system addressed consistency. Multiple scans over the same area on a specimen were conducted to provide recorded scans that could be analyzed for repeatability. The results were poor, with a wide variation of signal amplitudes evident. This was due to the tilt of the probe which fluctuated due to nonrigidity of the holding fixture. It was further discovered that the optimum (maximum) signal was achieved when the probe was not flat but at a 3-degree tilt angle. An interim fix of the probe scanner was made by removing the probe from the holding fixture and merely using the attachment off the lead screw to push the probe, which had a 1-pound weight placed on top in an off-center position (to provide a 3-degree tilt angle). A more rigid scanning device would be required in order to permanently overcome these problems.

The prototype system with the interim fix implemented on the scanning device was then used to scan several specimens in order to evaluate the effectiveness of the instrumentation and recorder. A periodic pattern of vibration amplitude, consisting of minimums (nodes) and maximums (antinodes), across the

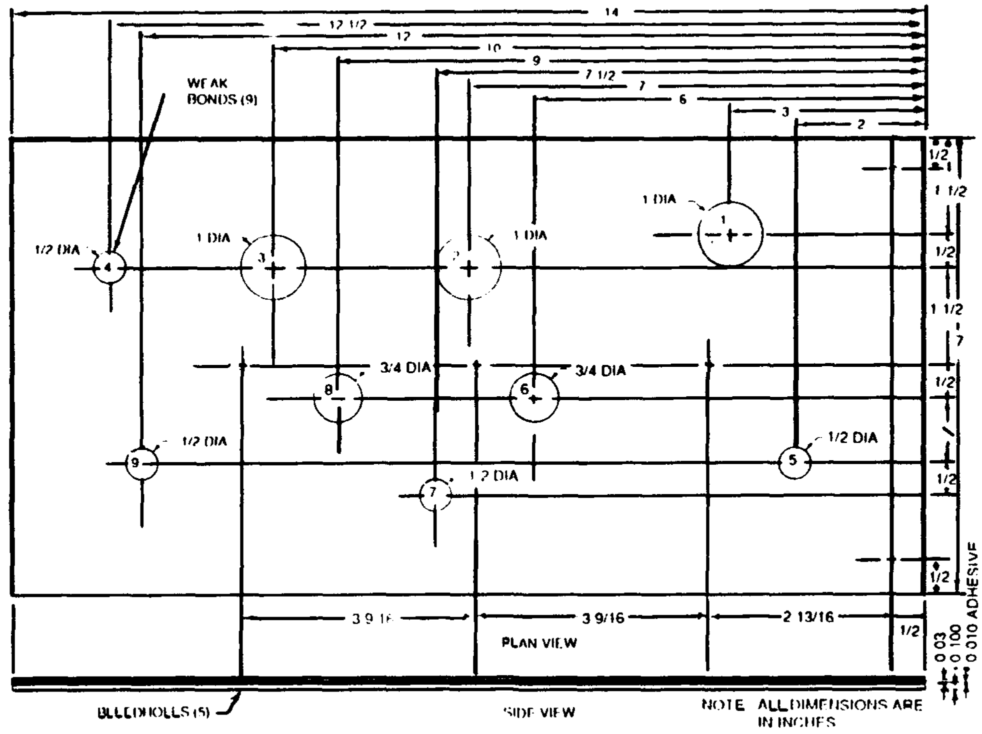

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FIGURE 3. SPECIMEN DESIGN FOR M1 THROUGH M16

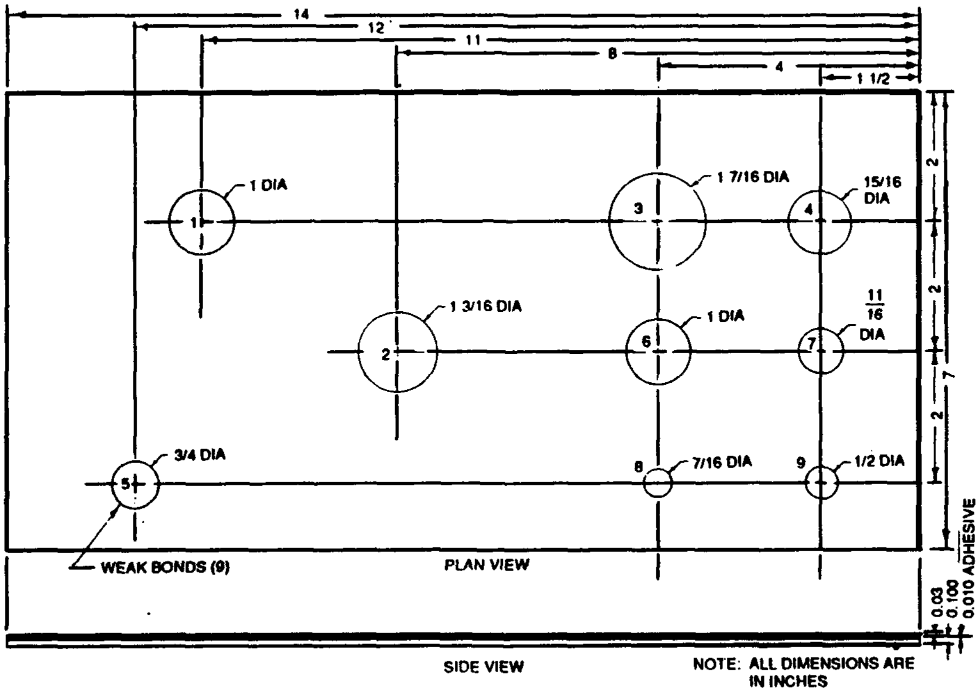

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FIGURE 4. SPECIMEN DESIGN FOR M17 THROUGH M41

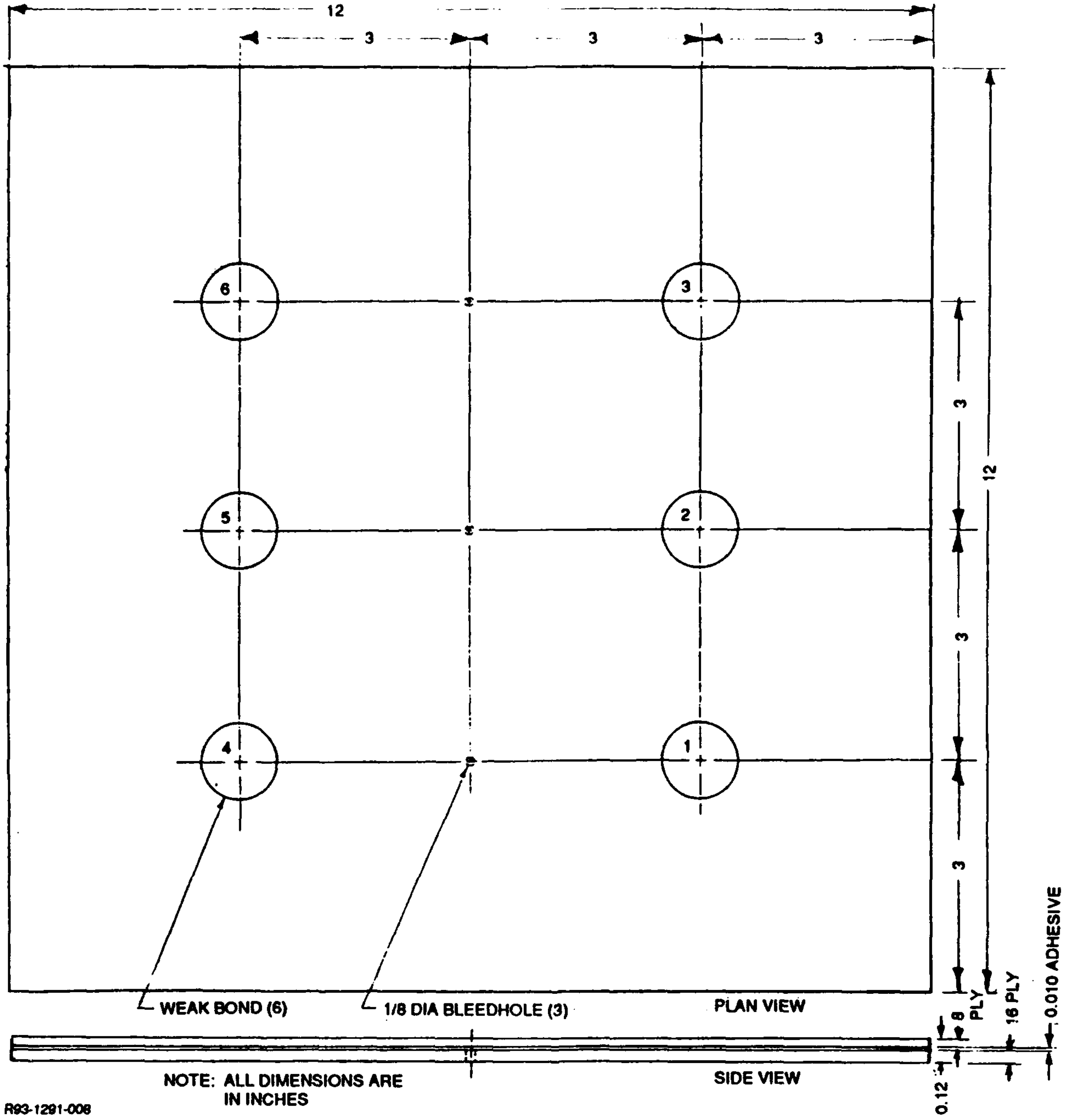

FIGURE 5. SPECIMEN DESIGN FOR GRAPHITE COMPOSITES G1 THROUGH G33

specimens was recorded as scanning took place in both good and programmed weak bond areas (figure 6). This was found to be consistent with resonance theory that suggests that a resonance wave will travel through material with hills and valleys similar to ocean waves. The nodal patterns were quite regular on the amplitude recordings and irregular for the phase output. It was first thought that the contrary pattern of the phase signal could

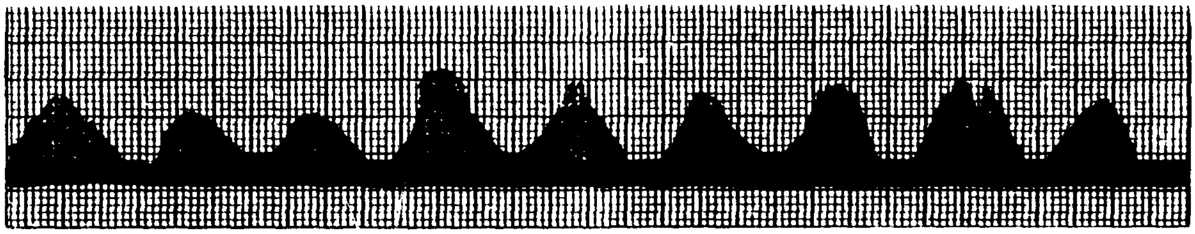

FIGURE 6. TYPICAL RESONANCE PATTERN OF PERIODIC VALLEYS (NODES) AND PEAKS (ANTINODES) IN AMPLITUDE OF VIBRATION

be related to the presence of defects, but further specimen scans revealed that this was merely an intermittent malfunction of the instrument. However, subtle increases in the antinodes (peaks) for the amplitude output were observed when the probe scanned over the programmed weak bond areas and the node coincided with the locations of the defect.

The significance of the nodal effect was further investigated by scanning the specimens from various directions. A graphite composite specimen was scanned at six different angular directions (0, 45, 90, 180, 270, and 315 degrees) using 1/8-inch index. All six programmed weak bond areas exhibited at least one antinode in excess of 24 mm. However, three areas away from the programmed defects also exhibited antinodes greater than 24 mm. It was concluded that several additional specimens would have to be evaluated in this manner in order to further understand the significance of the nodal effect.

It was found that testing with the initial prototype scanning device was not practical due to its slow speed. It took 37 hours to scan one specimen at six angles, due to the low torque motor (which would not operate at a higher rate of speed) and the need for manual intervention (the operator had to index the specimen 1/8 inch after each scan). A new scanning device was therefore designed to provide an even pressure on top the probe, a more rigid probe holding fixture, a high-speed/high-torque motor speed control, and XY-indexing capability.

Evaluation/Optimization of Prototype System.

The modified scanning equipment was fabricated and installed into the prototype system (figure 7). The scanning bridge can be used in conjunction with a specimen table for small specimens up to 14 inches square or placed directly on top of larger specimens or parts. The table contains a specimen platform that enables indexing the specimen a total of 13 inches in the Y-direction underneath the motorized bridge that parallels the X-axis. In

FIGURE 7. PROTOTYPE SYSTEM

addition, the probe-holding fixture attached to the carriage on the bridge can be indexed in the Y-direction a total of 2 inches which enables the larger specimens or parts to be scanned. The probe-holding fixture has two additional adjustments which permit the probe to be tilted and oriented at either of two angles. A high-torque, high-speed permanent magnet DC motor enables scanning speeds in both directions up to 73 in./min. - a significant improvement over the 7.6 in./min. unidirectional capability of the initial scanner. Using this scanning equipment, a 12- by 12-inch composite specimen was scanned at 1/8 inch increments in less than 1 1/2 hours per angle.

The modified prototype system was then used to do multi-angle evaluations on several specimens representing an assortment of conditions. Initially, the Composites instrument was used but was soon replaced by the Harmonic Bond Tester after fluctuating amplifier gain performance was observed but was not readily repairable. The replacement instrument was found to be as effective as the Compositest.

The metal-to-metal specimen, No. M35, was scanned at eight different angles with eight of the nine programmed weak bond areas detected. When the gain was increased to a level that gave an indication for the previously undetected programmed weak bond area, an additional two apparently good areas also exhibited indications. An investigation using an unbond specimen revealed that the probe detects defects within a 1 1/16 inch radius of its receiver. The location of the programmed weak bond areas were then examined and their peripheries found to be within 2 inches of each other in the apparently good areas that exhibited indications. It was concluded that the unknowingly overly close location of the programmed defects in the metal-to-metal specimens would limit the usefulness of these specimens for further evaluation of the prototype system.

The prototype system was then evaluated using the Phase I graphite composite-to-composite specimens where the programmed weak bond areas are spaced further apart (3 to 6 inches center-to-center). Initially, three specimens (G9, G10, and G11) containing weak bond areas and one "good" specimen (G8) were evaluated using a relative gain setting approach in which the gain was set individually for each. Using this approach, several preliminary scans were made on each specimen to identify a gain setting just below that which would exceed a predetermined threshold when scanning over an apparently good area. Using this procedure, all the programmed defect areas exhibited multiple indications (at least two) within a varying number of angular scans (figure 8). However, similar indications were observed for the good specimen which suggested that natural resonance antinodes characteristic of the specimen geometry were also being detected.

An alternative approach based on the use of the good specimen as a standard was established. At the gain setting established as above, various threshold settings were tried until a combination was found that did not result in a large number of indications on the known good test specimen (G8). It was decided not to seek a combination of settings that would result in no indications on the known good specimen in recognition of the natural resonance peak (antinodes) effect. A threshold of 8 mm was selected based on this approach.

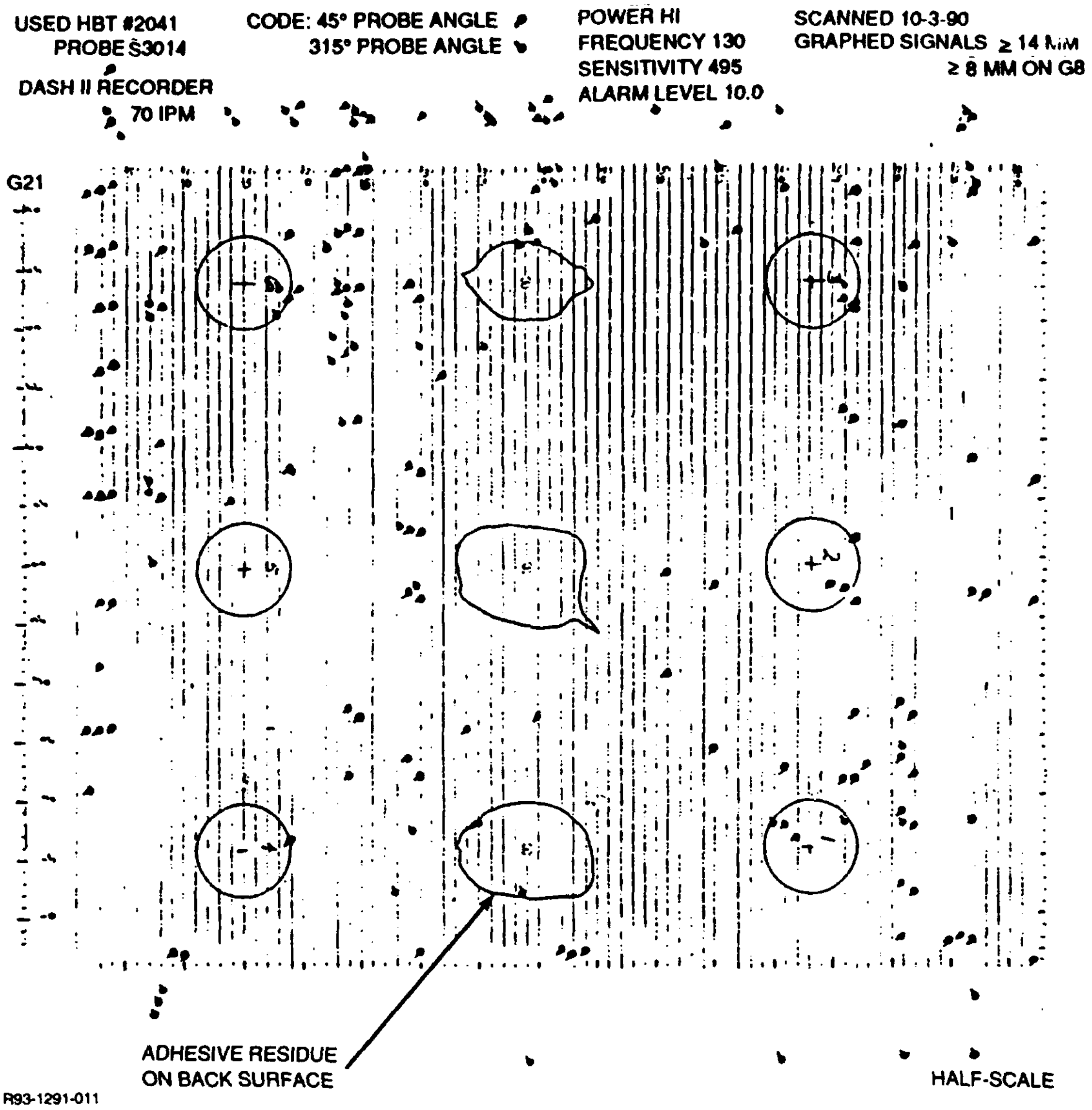

FIGURE 8. WEAK BOND INDICATIONS SENSED AND THEN GRAPHED ON A FACSIMILE OF SPECIMEN G21

Seven additional specimens were then tested using the alternative approach. The locations of the signals exceeding the threshold were denoted on a full-scale replica graph for each specimen. High concentrations of signals in the vicinity of the programmed defect locations were visually evident on the weak bond specimens while no obvious patterns were evident for G8. An objective way of distinguishing these differences was subsequently devised.

The 1 1/16 inch distance from the probe receiver (that was experimentally found to be the point at which an unbond exhibited a distinguishable amplitude increase) was the criterion used to predict the boundary of possible defect locations. Tinted 1 1/16 inch radius celluloid circles were cut out and used to represent the possible defect boundary locations by placing the circle center over the denoted signal location. High concentrations of signals would then be indicated by overlapping circles, with the tint density increasing as a function of the number of overlaps. Using this approach, G8 exhibited no areas with overlaps greater than six. Forty-eight of the sixty 1-inch-diameter programmed weak bonds exhibited areas with seven or more overlaps. In addition, eleven out of thirty bleed holes had more than six overlapping "signal" circles. Figure 9 shows a typical result using the seven minimum overlap criterion where 1-inch-radius "defect locator" circles were drawn, each centered over an area of seven or more overlapping "signal" circles.

This objective approach for determining defect locations was very tedious to implement in a manual mode but it could be readily executed under a computerized system.

A limited effort was made to determine the applicability of the harmonic frequency vibration prototype system to parts and other types of specimens. The only available part that was known to have weak bonds was a titanium skin, aluminum honeycomb core assembly that had been subjected to inadequate prebond surface preparation. Circular skin cuts and subsequent tension pull tests were performed at several locations on both sides. One side was verified to have varying degrees of weak bond, while the other side was verified to have adequate bond strength. The scanning bridge was removed from the specimen table and placed on the part surface where 2-inch-wide segments were scanned. The scanning system worked well but the signals displayed were extremely variable with no correlation to good versus bad side evident. An examination of the cutout locations revealed that pseudo edge effects were taking place throughout the part, rendering large amplitude variations. Any subtle changes due to weak bonds would be masked by these large signals.

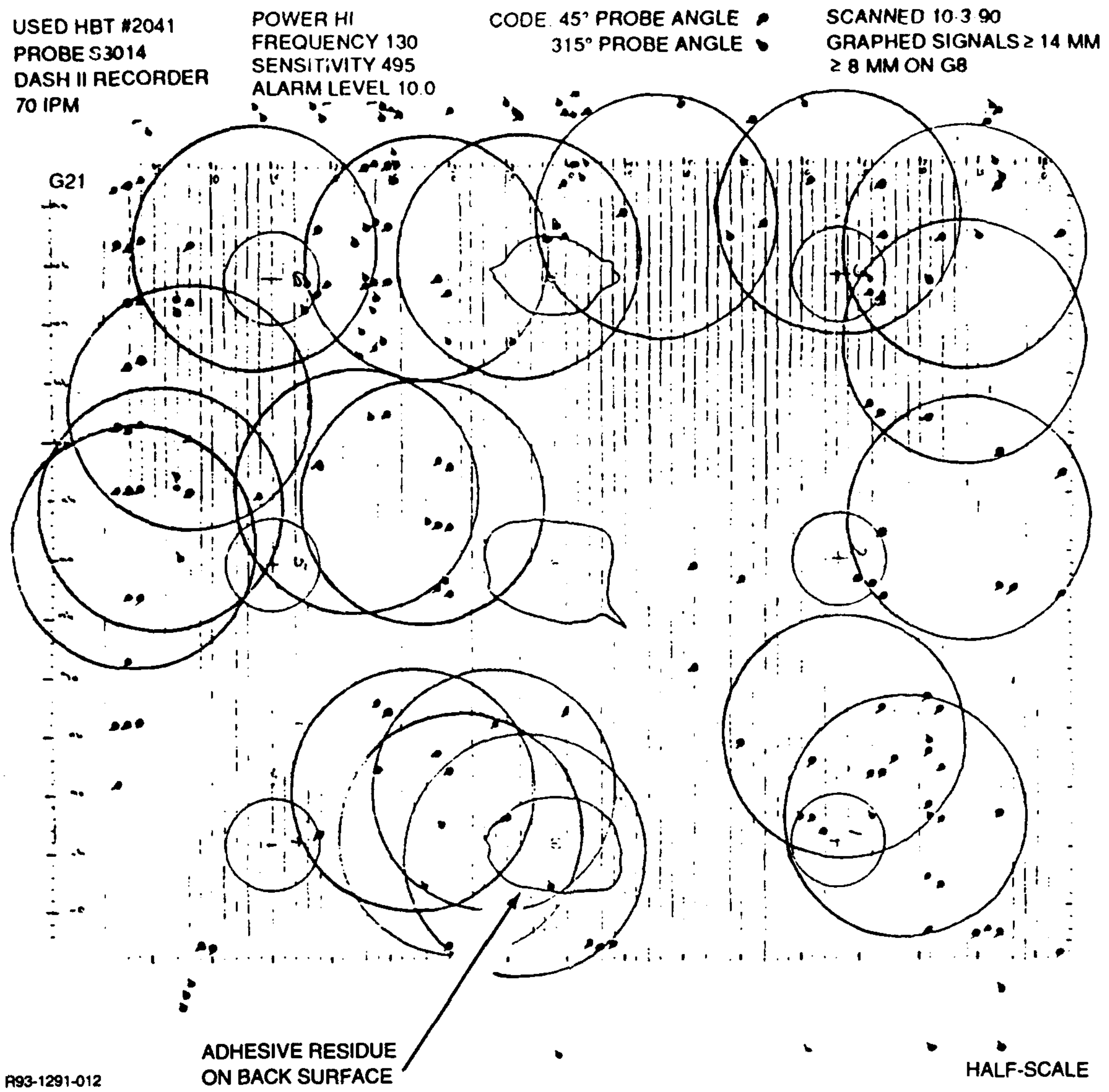

FIGURE 9. "DEFECT LOCATOR" CIRCLES CENTERED OVER A MINIMUM OF SEVEN OVERLAPPING "SIGNAL" CIRCLES (NOT SHOWN)

Preparation of Specification.

In accordance with the contract, a specification was established with three separate sections involving calibration, operation, and data recording and analysis. This specification incorporated the procedures developed during this phase using the improved prototype system. A complete copy of the specification was included as an appendix to the Phase II Interim Report.

CONCLUSIONS (PHASE II).

1. The prototype ultrasonic resonance system has demonstrated that 1-inch-diameter "weak bond areas" created by silica-based contaminated surfaces can be detected with a high degree of success (over 80 percent) in graphite/epoxy-to-graphite/epoxy bonded laminates

2. The prototype system revealed that this resonance test is significantly affected by edge and changing configuration conditions. The use of identically configured replicas of the part to be tested (with known bond conditions) is therefore required to set up the test technique

3. Not every weak bond area will be detected. Small areas (less than 1.0-inch diameter) and occasionally larger areas may not be detected if their locations coincide with places in which natural resonance peaks do not exist

4. The procedure utilizing this prototype system is very complex and time consuming (over 2 hr/ft^2), making it impractical for use on actual parts. Substantial additional development involving the use of multi-angle sensor heads to reduce scan times and built-in software to analyze the data would be required to make this technique suitable for real applications.

PHASE III

GENERAL DISCUSSION.

The need to conclusively demonstrate the bond strength detection capability of the prototype ultrasonic resonance technique and to quantify bond strength of contaminated areas led to destructive testing of the specimens containing the weak bonds. This phase also called for the evaluation of the prototype system on samples or parts submitted in response to an industry solicitation, but none were conducted due to a lack of industry response. Instead, a feasibility evaluation of a recently developed ultrasonic feature analysis/adaptive learning technique was conducted in response to initial favorable data involving this technique.

RESULTS AND DISCUSSION.

Destructive Testing of Specimens.

The flatwise tension test was identified as the most practical means of assessing the adhesive bond strength of the composite specimens. This procedure permitted the test area to be localized to small discrete areas and could be readily performed using available equipment.

The specific procedure was based on cutting localized test specimens from selected areas of the test panels, which were then bonded to aluminum loading blocks using a high strength adhesive. The loading blocks were then connected to the upper and lower jaws of the tensile machine and pulled to failure at room temperature. The failure load was divided by the square-inch area of the test specimen to provide tensile strength values in pounds per square inch (psi). The larger the area being tested, the more reliable the test procedure, since it is easier to align the test specimen perpendicular to the loading direction. Any misalignments would result in partial peeling loads that would erroneously provide lower failure load values.

The first flatwise tension tests were conducted on specimens G5 and G31 during Phase II, utilizing a 1-inch-diameter loading block with the specimens cut out using a hole saw. The results were encouraging, with a close correlation to the NDT results evident. However, two of the six treated areas on specimen G31 could not be tested because they unbonded during the hole-cutting operation. It was therefore decided to increase the size of the specimen on the next tests to avoid cutting through the 1-inch-diameter treated areas. It was also decided to use 2- by 2-inch-rectangular loading blocks, which would permit the use of a band saw to cut out the specimens.

A total of eight panels with specimens taken out of the six treated areas were flatwise-tension-tested using the 2- by 2-inch-rectangular loading blocks. The test results were considered indecisive since no correlation with the nondestructive test results was evident; this was contrary to the earlier results on G5 and G31. An analysis of the conflicting test results led to the conclusion that the 1-inch-diameter loading block procedure was more valid, since the treated area in the 2- by 2-inch specimen only represented 20 percent of the total area assumed to be weakly bonded.

The subsequent five panels were therefore tested using the 1-inch-diameter loading block procedure. Panel numbers G3, G4, G7, and G29 were all tested with specimens taken out of the six treated areas. Panel G8, which did not have treated areas, was also tested to serve as a control. Table 4 lists the results of all the 1-inch-diameter loading block flatwise tension results, along with the prototype ultrasonic resonance nondestructive test results.

TABLE 4. LISTING OF FLATWISE TENSION (FWT)/NDT RESULTS

PANEL NO.	"DEFECT" LOCATION					
	1	2	3	4	5	6
G3						
NDT	YES	YES	YES	YES	YES	YES
FWT	2420	3694	1783	2522	1452	1694
G4						
NDT	NO	NO	YES	YES	NO	NO
FWT	1376	4464	2127	2076	3873	2739
G5						
NDT	YES	NO	YES	YES	NO	YES
FWT	1680	3950	1300	2158	2674	1617
G7						
NDT	YES	NO	YES	YES	YES	YES
FWT	2115	3006	2968	2930	3057	3694
G8	CONTROL PANEL: NO PROGRAMMED DEFECTS,					
NDT	(NO DEFECTS DETECTED BY NDT)					
FWT	2318	3121	3274	2191	2268	2306
G29						
NDT	YES	YES	YES	YES	YES	YES
FWT	1197	1975	892	1274	2166	1758
G29						
NDT	YES	NO	YES	YES	YES	YES
FWT	–	4690	866	–	1400	344

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A review of table 4 shows fairly good correlation between the results when using the average flatwise tension value for the control panel (2580 psi). In all but one case (location 1 on panel G4), all areas exhibiting flatwise tension strengths below the control panel average strength (2580 psi) were detected nondestructively (as indicated by a Yes in table 4). In the eight other cases where the programmed defect areas (treated areas) were not detected, the flatwise tension results indicate that the bonds in these areas were not actually weak. However, the high bond strengths indicated for nondestructively detected treated areas G3-2 and G7-3, 4, 5, and 6 suggest that either the NDT technique is subject to making false reject calls, and/or there are scatter errors involving the flatwise tension test. Figure 10 shows these data in a plotted format with the assumed good bond/weak bond threshold displayed.

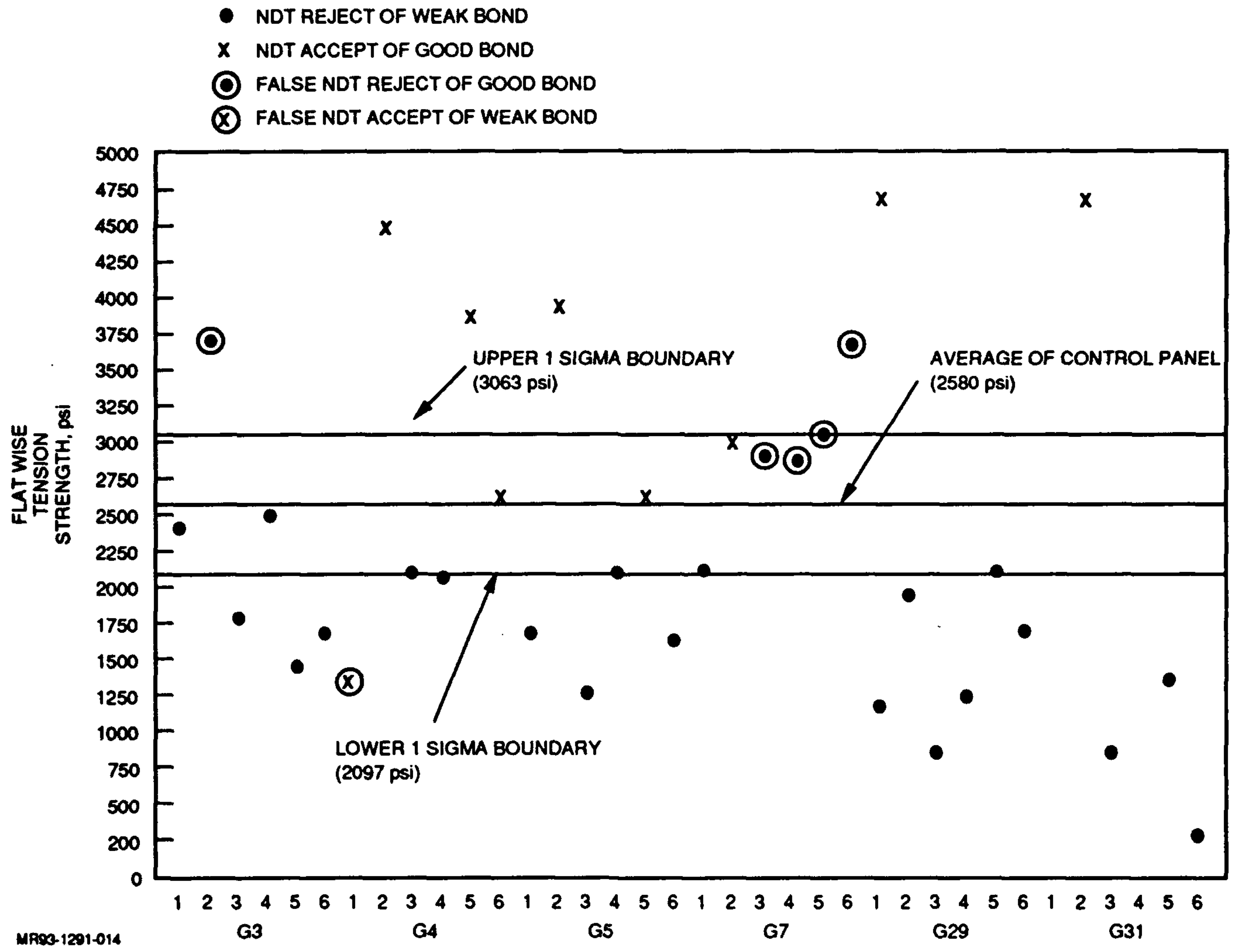

FIGURE 10. PLOT OF FLATWISE TENSION/NDT RESULTS

A more conservative analysis of these data, assuming a 1 sigma variation from the control panel average strength, would indicate significantly less correlation between the NDI and destructive results but a definite trend would still be evident. Six additional points (G3-1, G3-4, G4-3, G5-4, G7-1, and G29-5) could be interpreted as false reject calls which would then expand the possible false reject error to 31 percent. The 1 sigma bands are shown on figure 10 to illustrate this possibility.

The 1 sigma bands in figure 10 also illustrate the wide variation of test results encountered using the singular flatwise tension approach. The use of other destructive test techniques such as peel or lap shear were discussed at the on-site end of Phase II technical review and it was concluded that these alternative tests would be subject to the same variation as the flatwise tension test. The flatwise tension test was therefore selected based on its significance to design properties. The singular test per area was necessitated by the limited size (1 inch in diameter) of the programmed weak bond area. This prevented using the standard destructive testing approach of averaging the results of three or more tests, which certainly would have reduced the variation.

Industry Samples.

The original plan for this program called for the solicitation of weak bond specimens or parts during Phase III to permit further evaluation of the prototype NDT system. This activity was considered important since it would provide an opportunity to evaluate weak bonds that were generated by other mechanisms. The programmed weak bond areas evaluated during the earlier phases of this program closely simulated one type of weak bond involving a thin layer of contamination, but there are other mechanisms that can also cause weak bonds such as improper surface preparation, nonoptimum tooling, and nonoptimum processing parameters. Unfortunately, there was no response to the letter requesting such samples. This letter was sent to all the major U.S. and European aerospace companies.

Preliminary Feasibility Evaluation of Ultrasonic Feature Analysis/Adaptive Learning.

A small Independent Research and Development (IR&D) study conducted at Grumman, involving the evaluation of an ultrasonic feature analysis/adaptive learning system on titanium skin to aluminum honeycomb core bonds, indicated that this technique might be applicable to weak bonds. These early studies demonstrated the ability of the technique to distinguish between good bonds with proper surface preparation and weak bonds with poor surface preparation (too smooth). The commercially available system employed identified up to 68 different waveform features of signals reflected from the back surface of the titanium skin. Several reflections from known good bond areas and known bad bond areas were used to train the system, which ultimately identified several features that made the reflections distinguishable. The "trained" system was then used to evaluate other known good bond and bad bond areas, with over 90 percent demonstrated success. Based on these results, the technique was considered very promising for weak bond detection applications.

The Phase III study involving this technique was initially performed in-house using the same commercially available system. Several graphite-to-graphite bonded panels were evaluated with this system using the programmed defect areas and known good areas for training. The results were very inconclusive, with no demonstrated ability to distinguish between good bond and weak bond areas. Following these results, the feature analysis/adaptive learning system supplier was contacted and they indicated that a more advanced system is now available that might have better success.

Graphite panel G29 was forwarded to the instrument supplier for study using their latest system. Several signals reflected from the back surface of the panel in "good" and "bad" bond areas were used to train the system. The system was then used to evaluate 12 random signals from programmed defect areas and another random 12 signals from good bond areas. Of the first 12 signals taken from the programmed defect area, 10 were classified as bad. Of the 12 signals collected from the good areas, 10 were classified correctly. Specimen G29 was then sent back to Grumman, where it was destructively tested using the flatwise tension 1-inch-diameter loading block procedure. Each of the programmed defect areas were confirmed to be weakly bonded (table 4). In 2 of the 3 specimens taken from good areas, the data confirmed them to be good (3,057 psi and 2,624 psi), while the other good area appeared to be marginally weak (2,331 psi). The random nature of collecting signals did not permit specific correlations of NDT data to flatwise tension data. The results from this brief study were encouraging, with a probable success rate of 83 percent for detecting weak bonds demonstrated. The supplier recommends further study on additional samples.

CONCLUSIONS (PHASE III).

1. The capability of the prototype ultrasonic resonance system to detect weak bonds was demonstrated. It successfully detected 97 percent of known weak bond areas evaluated while experiencing a false reject rate of 14 to 31 percent (depending on whether or not the 1 sigma variation of destructive test results are considered).

2. The singular flatwise tension destructive testing approach is subject to substantial variation which causes some uncertainty to exist regarding the degree of effectiveness of the ultrasonic resonance technique.

3. The capability of the prototype system to effectively detect weak bond conditions caused by mechanisms other than thin layer contamination was not determined due to the unavailability of other test specimens.

4. The preliminary feasibility of the ultrasonic feature analysis/adaptive learning technique to detect weak bonds was demonstrated. The instrumentation for this technique is commercially available and, therefore, would require little or no further development. Additional studies on several more specimens representing weak bonds caused by several different mechanisms would be required to further evaluate the feasibility of this technique.

RECOMMENDATIONS.

A further study should be conducted to evaluate the ultrasonic resonance and ultrasonic feature analysis techniques using specimens representing several weak bond mechanisms in addition to contaminated interfaces. The specimens should have large programmed weak bond areas to accommodate multiple destructive test correlations.

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