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Structures Technical Memorandum 370

EVALUATION OF A VIBRATION TECHNIQUE FOR DETECTION OF BARELY-VISIBLE IMPACT-DAMAGE IN COMPOSITES.

by

R. JONES and A. GOLDMAN

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EVALUATION OF A VIBRATION TECHNIQUE FOR DETECTION OF BARELY VISIBLE IMPACT DAMAGE IN COMPOSITES.

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SUMMARY

A vibration analysis technique has been used for non-destructive evaluation of the integrity of fibre composite components which contain barely-visual impact-damage. A description of the method and the associated problems is presented together with the results of laboratory tests.

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CONTENTS

1. INTRODUCTION

In recent years a vibration technqiue has been suggested for the non-destructive evaluation, and damage location, of fibre-composite structures. (Ref. 1 & 2) This technique involves the measurement of changes in the natural frequencies due to damage.

The aim of the present paper is to investigate the application of this method to laminates containing low-energy impact-damage which is non-visual, and to bonded fibre-composite repair schemes which have delaminated in the vicinity of the crack, in the metallic wing skin, which has been repaired. No attempt has been made to compute the changes in the natural frequencies due to the impact damage, or consequently to locate the damage using the techniques mentioned in Ref. 2. This would have involved a full three-dimensional finite-element analysis of the specimen, with the delaminations located between the same plies as in the damaged structure. Such an analysis is prohibitively expensive, and when attempted on a VAX 11/780 computer exceeded the total virtual address space. As the authors are looking for an in-service test proceedure such considerations must be taken. Furthermore, although an ultrasonic C-scan provides information on the planar dimensions of the damage, it provides no information on the individual inter-laminar bonds.

2. EXPERIMENTAL WORK

Several specimens were cut, from a single sheet of 16 layer graphite-epoxy composite material, such that the direction of material lay-up was the same for each specimen. The dimensions were approximately 190 x 45 x 2 millimetres and the overall mass approximately 28 grammes.

Several methods of excitation and measurement were used including random noise, impulse, FFT spectrum analyser, and time averaging, but the one showing the most repeatability was sine-dwell excitation and frequency-response analysis. This is described below in some detail.

The specimens were supported in a clamp mounted on an electromagnetic shaker. Fig. 1 shows the general configuration of the test rig.

An accelerometer was mounted on the clamp and another on the specimen at a location approximately 40 millimetres from the free end and 10 millimetres from the side edge. This location was chosen as being likely to pick up information about all modes of vibration.

The earlier tests using random noise excitation had established that most of the resonant frequencies lay within the frequency range 1000 to 6000 hertz. This information was used to set up a frequency response analyser which provided a sinusoidal excitation source stepping in 1 hertz steps through the range. At each step the transfer function $(A_2-A_1)/A_1$ was calculated. A_2 is acceleration measured on the specimen, and A_1 is acceleration measured on the Clamp. This method corrects for variations in amplitude of the shaker-specimen system and provides an answer equivalent to a single degree-of-freedom system. The modulus of the transfer function was plotted on a digital plotter as the test progressed. The test was repeated to check the repeatability of the clamping, and of the accelerometer location.

The specimen was then ultrasonically scanned, to obtain a visual indication of any defects, prior to being subjected to several impacts from a steel ball of 550 grammes mass being dropped from a height of 500 millimetres. The specimen was again ultrasonically scanned and the vibration test repeated. The results of the vibration test after damage were plotted on the same axes as the results from tests on the undamaged specimen.

Figs. 2, 4 and 6 show the results of the ultrasonic scans on two specimens, and Figs. 3, 5 and 7 show the corresponding vibration test results.

An attempt was made to measure the mode shape at each resonant frequency. However, because the effective mass of the accelerometer plus adhesive and cable attachment was over 0.5 grammes, the mass distribution was being varied too much by the accelerometer to allow much sense to be made of the higher order modes which are most affected by local changes in stiffness and mass distribution.

On completion of the vibration tests, one of the damaged specimens was subjected to a compression test, along the major axis, and showed a 16 percent reduction in compressive strength compared with a similar undamaged specimen.

3. <u>TEST RESULTS</u>

For the first specimen, Figure 2 shows that a significant account of damage had been introduced close to the location of the accelerometer. In Figure 3 it can be seen that changes in frequency have occurred around 1800 hertz and 5000 hertz. Both changes are approximately 2 percent. reductions.

The second specimen was subjected to increasing amounts of damage. Figure 4 shows the two stages of damage and Figure 5 indicates that there were no detectable changes in frequency of any of the modes of vibration observed in the 1000 - 6000 hertz range. The changes in amplitude are believed to be due to slight changes in the position of the accelerometer.

Further damage was introduced to this second specimen, as indicated in Figure 6, which brought about significant changes in frequency at 2100, 3500, and in the 5000 - 6000 hertz range.

This second specimen was not subjected to a compressive strength test because of problems associated with the proximity of the damage to the edge of the specimen.

Although the discussion so far has been limited to two specimens, three specimens with similar damage were subjected to compressive strength tests with similar results.

The earlier experiments, carried out using random-noise excitation and impulse inputs, showed up the following problems which should be considered when developing an in-service test method:

a) The changes in frequency are generally in the order of 1 to 2 percent, which means that high resolution measuring devices are required.

b) Non-linearity of most structures is such that variations in input levels may introduce shifts in frequencies of 1 to 2 percent. Therefore the input force level must be accurately reproduced for comparison testing.

c) The location of the accelerometer is critical, expecially in the higher order modes of vibration, where there are many nodal lines. Two or more accelerometer locations should be considered to reduce the risk of missing a critical mode.

d) The method described is time consuming, taking 2 hours for a sweep of 5000 hertz in 1 hertz steps. This would be doubled for 2 accelerometer locations.

The inability of the method to detect the damage shown in Figure 4 may be due to the damage being of insignificant level, or that the accelerometer was placed too far from the damage, or on a nodal line of the significant mode. Further work is necessary to answer these questions.

4. MATHEMATICAL ANALYSIS

The ability to detect the presence of delamination damage in graphite-epoxy laminate specimens led to the investigation of whether the same method could be used to detect delaminations in bonded boron-fibre repairs to cracked metallic wing skins. This repair scheme has been pioneered by the Aeronautical Research Laboratories, Australia, and is now widely used to repair cracks in aircraft in service with the RAAF. Examples include skin cracks in the lower wing surface of Mirage III aircraft, stress corrosion cracking in Hercules wing planks, and cracks in the console truss in F-111. A detailed discussion of the current state of crack-patching technology is given in Ref. 3 and 4. In this scheme, cracked metallic components are repaired by bonding uni-directional boron-epoxy laminate over the crack with the fibres lying perpendicular to the crack. A typical repair to a cracked aluminium panel can be seen in Figure 8.

The panel, of dimensions 320 x 150 x 3 millimetres, contains a crack, 25 millimetres long, starting half way along one edge. The patch is a semi-circular unidirectional boron-epoxy laminate of radius 80 millimetres, and is bonded to the panel with an epoxy nitrile adhesive 0.1016 millimetres thick. The adhesive is type AF 126 and was widely used by the USAF.

For these repair schemes the adhesive bond playes a central role and is usually very highly stressed. If the adhesive delaminates, due to the accumulation of fatigue damage, over the crack, then the effectiveness of the patch will be seriously decreased. Hence the need to develop non-destructive evaluation methods to assess patch integrity.

A detailed three dimensional finite element model of the panel shown in Figure 8 was developed by the author as part of a joint Australian/U.S./Canadian co-operative program on repair technology.

This model was found to agree, for static testing, with all of the measured strain guage data and crack opening displacements, to within 5 percent.

Various amounts of delamination damage were simulated numerically. The delamination area was elliptical in plan view and constituted approximately

a) 5 percent of the total adhesive bond.

b) 10 percent of the total adhesive bond.

c) 15 percent of the total adhesive bond.

The effect that these various delamination sizes had on the computed natural frequencies is shown in Table 1. Only the frequencies over 100 hertz are shown since there were negligible changes at lower frequencies. From the table, it may be seen that, as for the impact damage specimens, significant changes are observed in the higher frequencies when delamination of 10 and 15 percent are simulated.

5. CONCLUSIONS

The work described above demonstrates that the vibration techniques developed in recent years are able to detect delamination damage in laboratory tests, and that the major changes occur in the higher order vibration modes.

Further work is required to establish this method as a reliable in-service test procedure, especially as applied to an aircraft with variations in fuel levels, tightness of bolted fairings, climatic conditions, etc.

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3. R. Jones, M. Davis, R. J. Callinan and G. D. Mallinson. Crack Patching: Analysis and Design, J. Struct. Mech., 10 (2), 177-190 (1982)

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TABLE 1 COMPARISON OF NATURAL FREQUENCIES

Frequency (Hz) undamaged	% change due to delamination size of 5%	10%	15%
113.052	-0.795	-0.795	-0.795
124.72	-0.010	-0.612	-3.499
134.776	-0.159	-0.195	-1.054
180.862	-0.079	-0.150	-1.054
198.66	-0.146	-0.191	-0.250
232.547	-0.637	-0.326	-2.250
252.357	-0.048	-1.029	-7.883
270.471	-0.236	-0.455	-0.951
323.438	-0.085	-0.690	-2.603
354.953	-0.116	-0.184	-1.758
372.521	-0.652	-0.241	-0.341
428.507	-0.002	-1.618	-7.712
445.968	-1.253	-0.550	-1.335
469.504	-0.781	-1.018	-3.503
481.326	-0.116	-0.470	-0.402
548.571	-1.038	-1.367	-0.494
582.867	-1.425	-2.697	-6.575
599.040	-0.329	-0.537	-3.147
614.508	-1.205	-0.016	-2.165
641.698	-0.551	-0.931	-1.345
685.799	-1.778	-1.765	-2.141
689.208	-0.946	-2.743	-5.322
748.798	-2.657	-0.122	-4.842
770.849	-1.540	-1.618	-3.543
847.371	-0.430	-3.773	-9.410

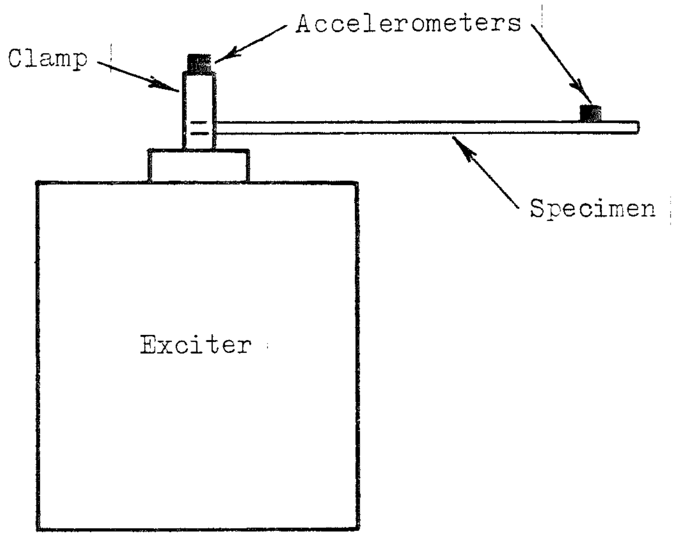
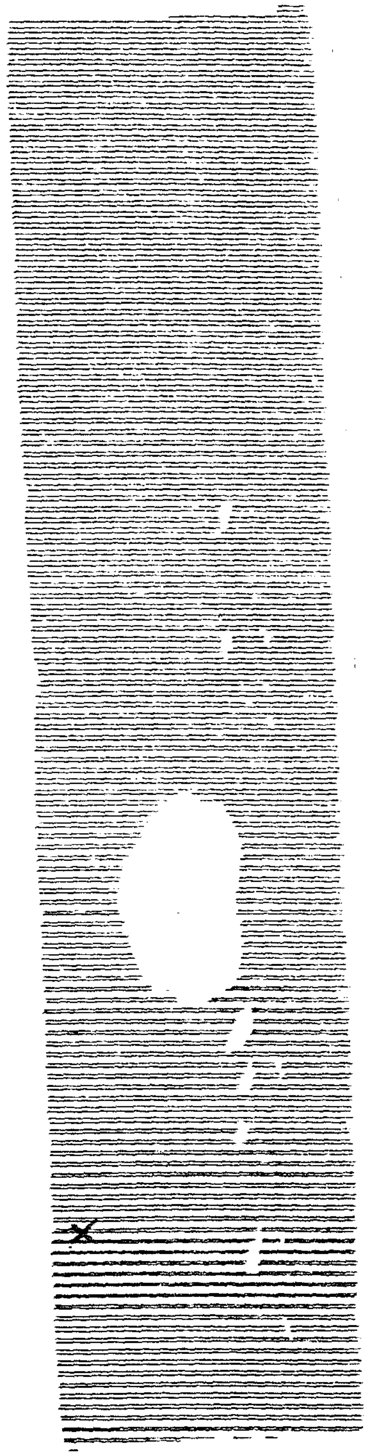


FIG.1 CONFIGURATION OF TEST RIG



x = Location of accelerometer

FIG.2 ULTRASONIC SCAN OF FIRST SPECIMEN - DAMAGED

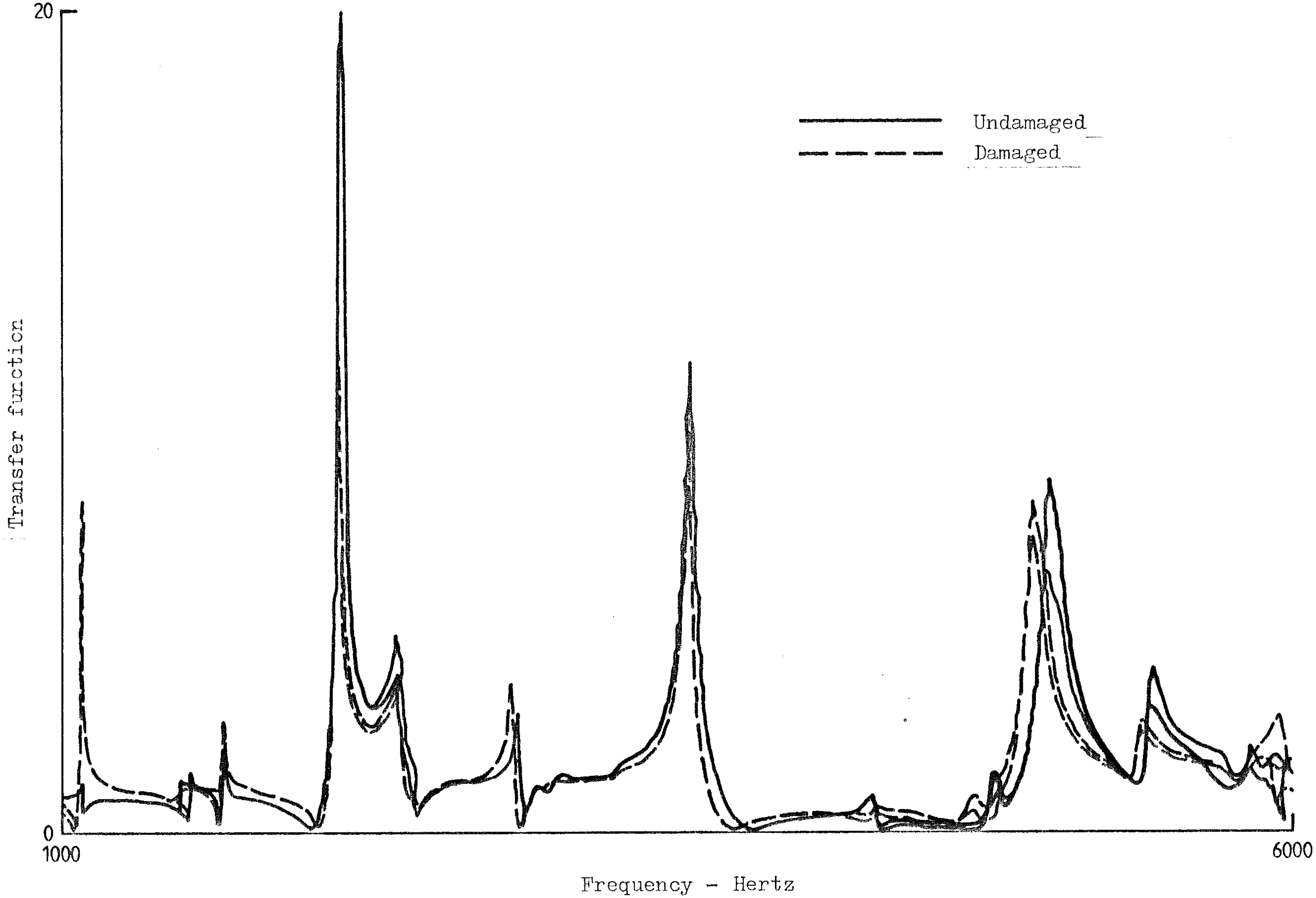
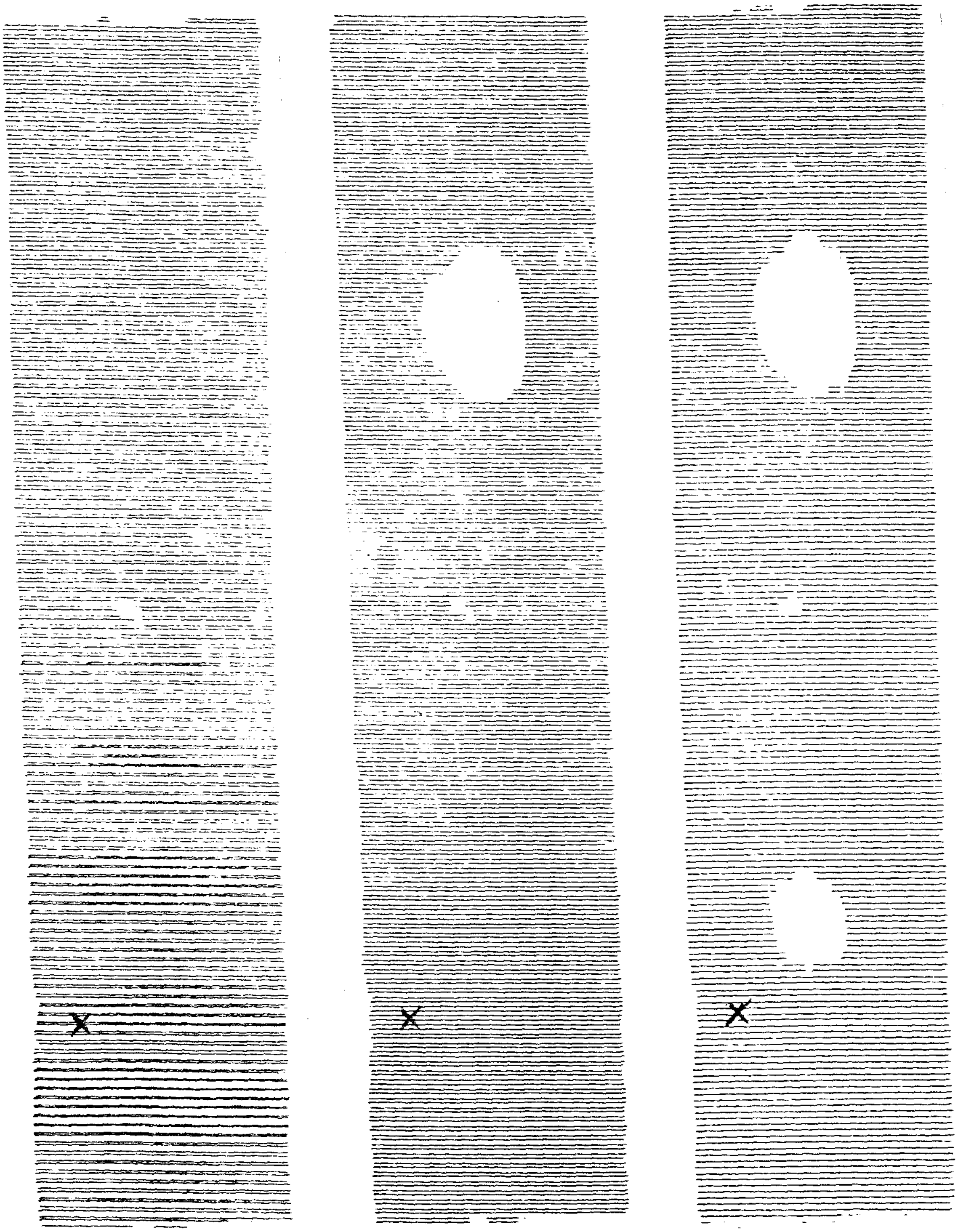


FIG.3 FREQUENCY RESPONSE OF SPECIMEN No.1



Undamaged

1st Stage damage

2nd Stage damage

FIG.4 ULTRASONIC SCAN OF SECOND SPECIMEN - UNDAMAGED & DAMAGED

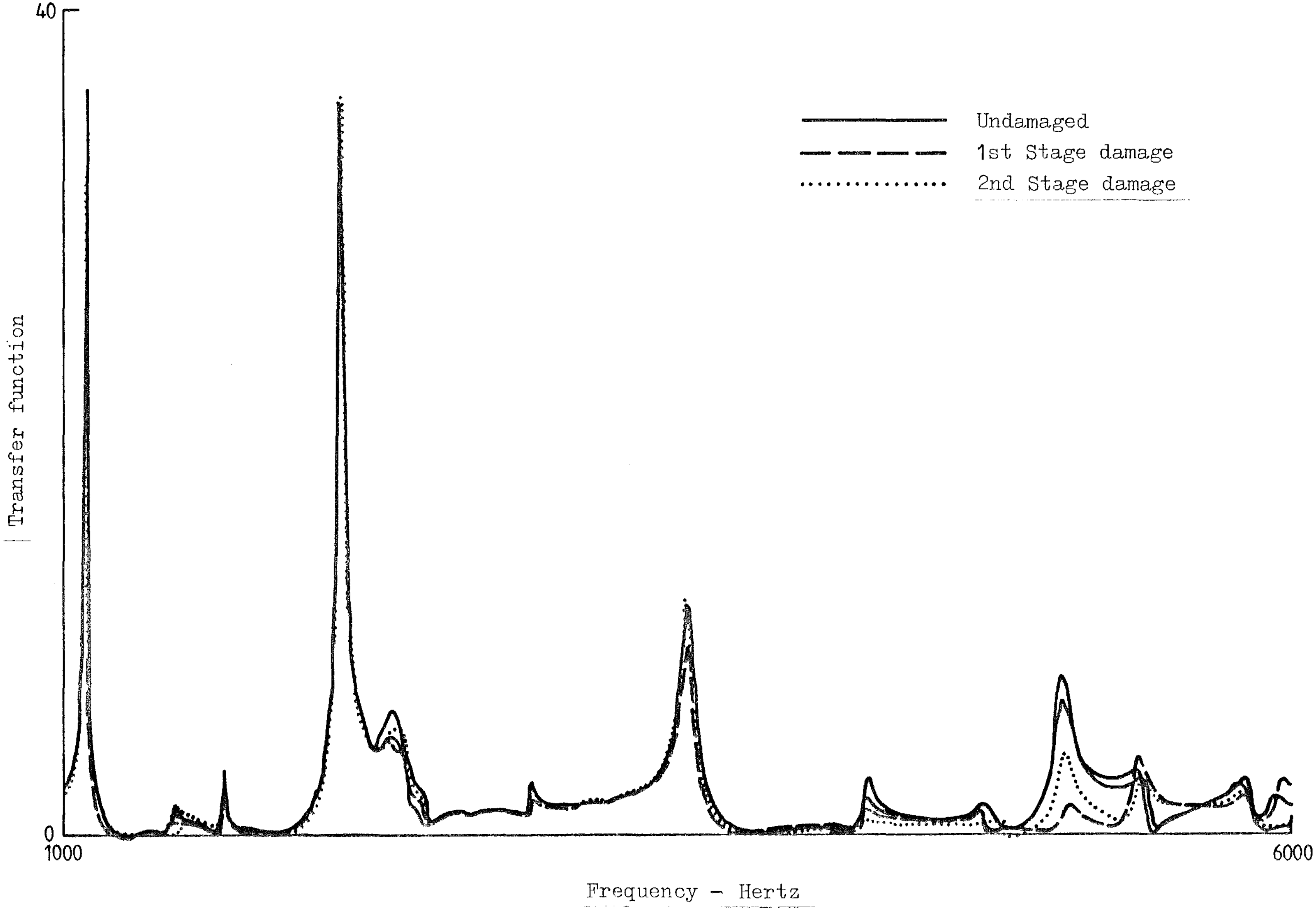
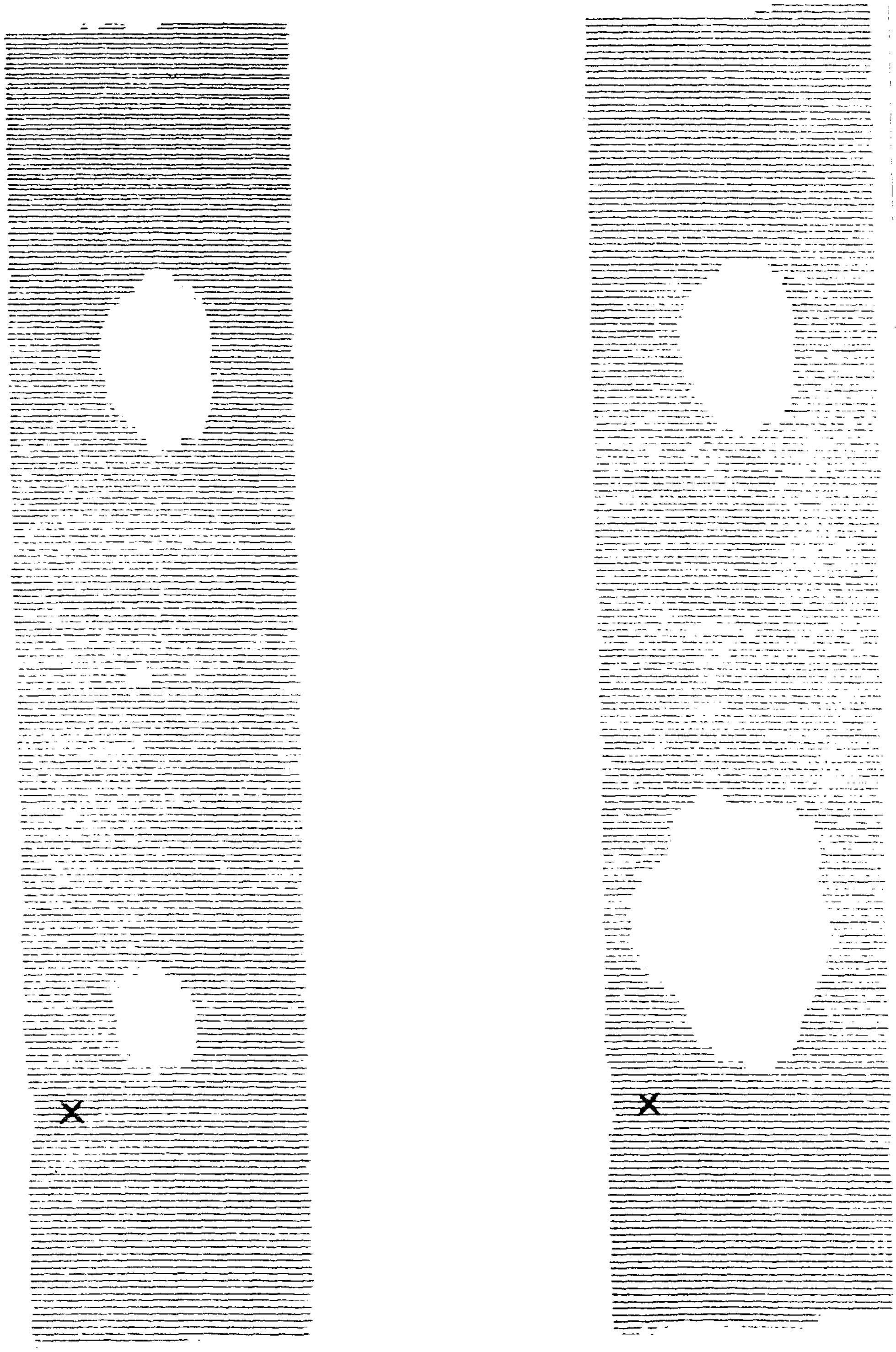


FIG.5 FREQUENCY RESPONSE OF SPECIMEN No.2 (Fig.4)



Original

Further damaged

FIG.6 ULTRASONIC SCAN OF SECOND SPECIMEN - FURTHER DAMAGED

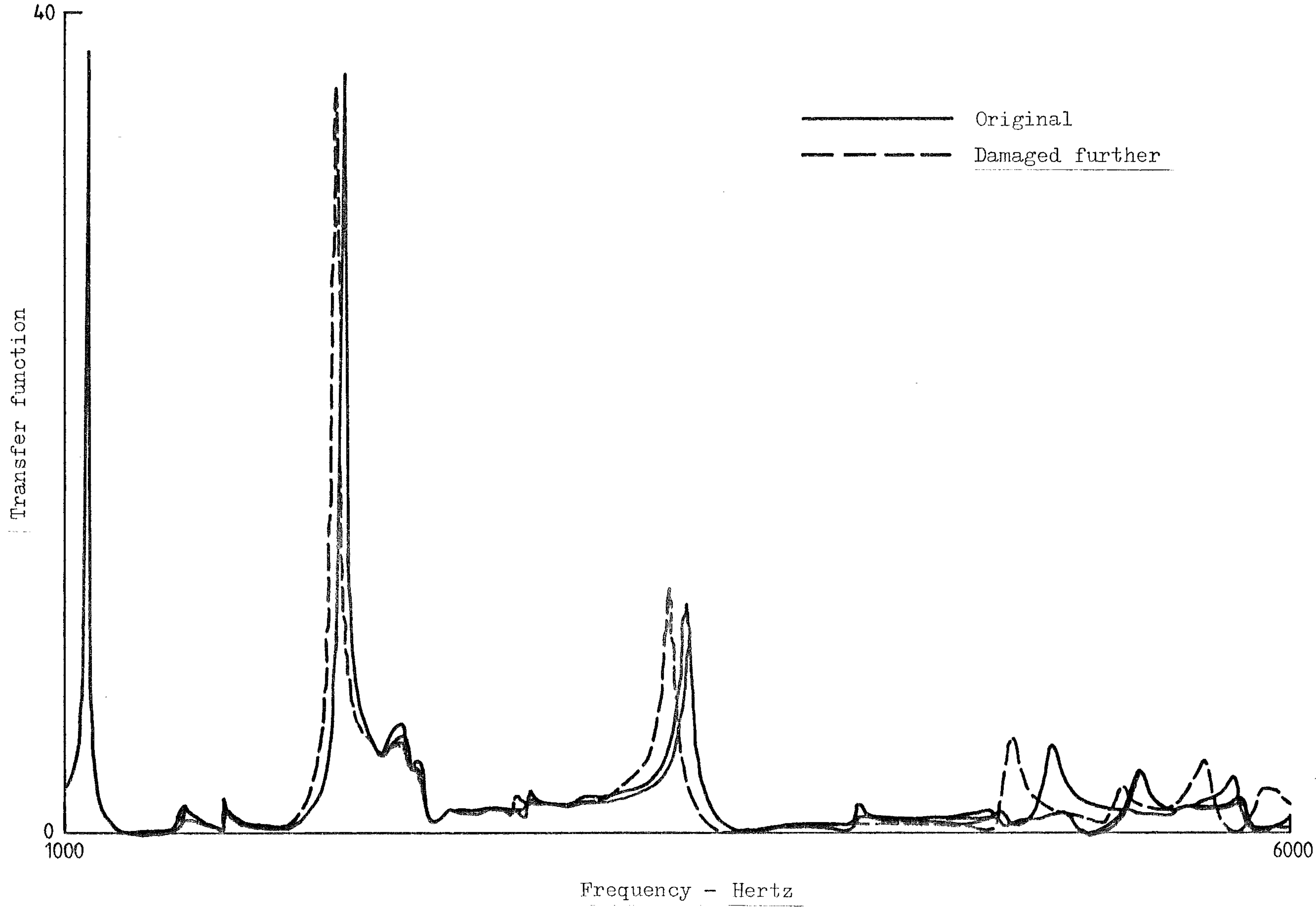


FIG.7 FREQUENCY RESPONSE OF SPECIMEN No.2 (Fig.6)

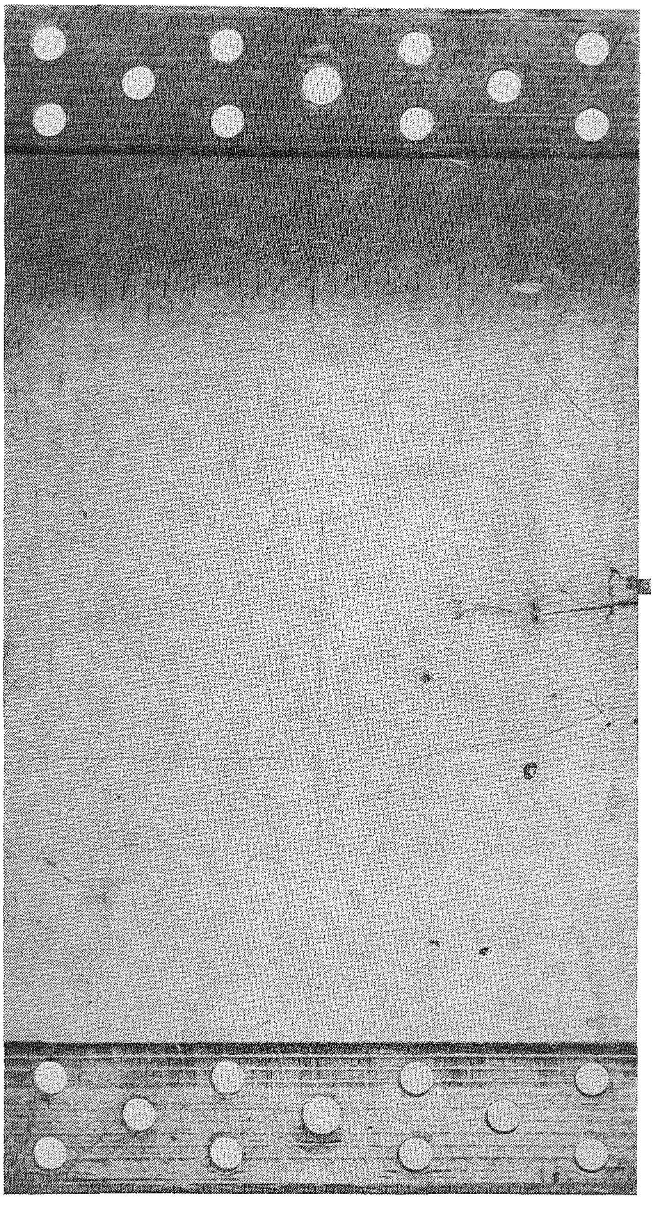


FIG.8a ALUMINIUM ALLOY PANEL WITH CRACK

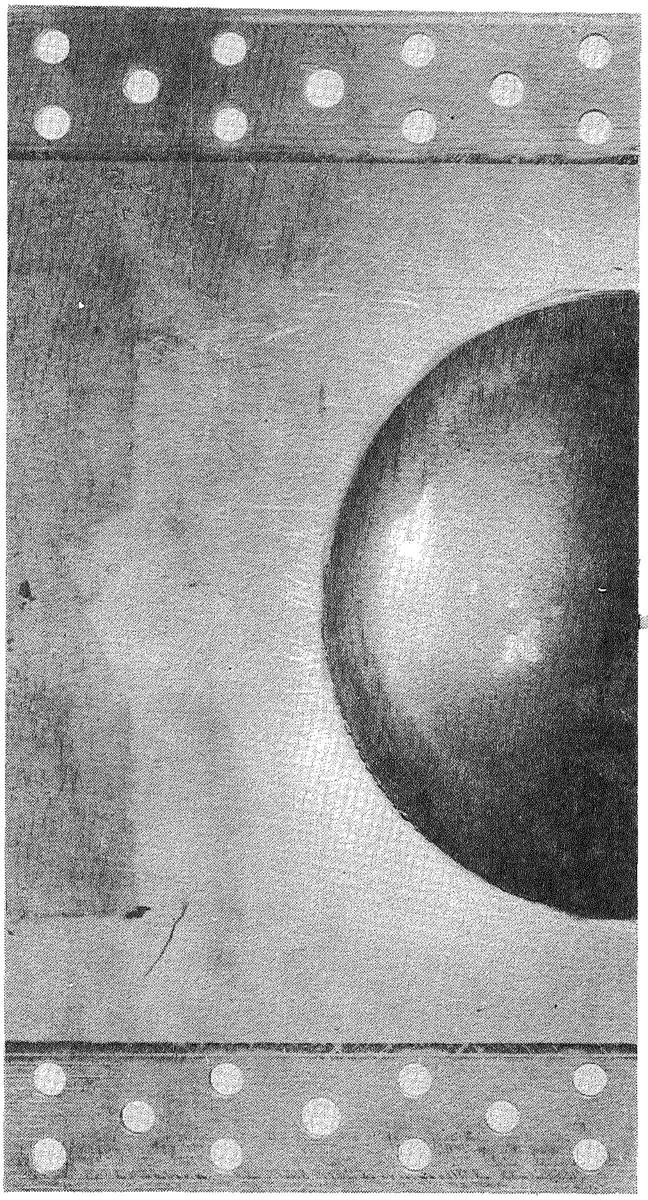


FIG.8b PANEL WITH PATCH APPLIED

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16. Abstract

A vibration analysis technique has been used for non-destructive evaluation of the integrity of fiber composite components which contain barely-visual impact-damage. A description of the method and the associated problems is presented together with the results of laboratory tests.