APPROACHES TO ULTRASONIC NON-DESTRUCTIVE EVALUATION OF COMPOSITES IN AIRCRAFT COMPONENTS

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Abstract

Non-Destructive Evaluation (NDE) has played a pivotal role in the course of development of composites in airframe structural components at the Advanced Composites Division (ACD) of National Aerospace Laboratories (NAL), through novel co-curing, co-bonding fabrication routes. An account of Ultrasonic NDE through C-scan technique on advanced composites is given here.

Introduction

NDE plays a crucial role in any composite component development programme. This is more so in our programmes as a number of innovative fabrication concepts have been developed in producing the co-cured assemblies [1].

There are many causes for occurrence of defects in a fabricated part : variations in the tool/mould, inadvertently embedded foreign material (inclusion) in between the layers and poor process parameters during curing. NDE inputs throw light on this and help the fabricator in fine tuning and arriving at a stabilized fabrication process. Even after formulating this, one cannot rule out occasional occurrence of defects in components. Delamination, foreign material inclusion, porosity etc. are the most commonly noticed defects. It is essential that the NDE procedures that are employed must be able to detect these defects. It is also important that the inspection techniques used have enough sensitivity when detecting these defects so that no defect would go un-detected.

For a variety of reasons, ultrasonic techniques have a distinct edge over other methods as far as NDE of advanced composites for aircraft applications are concerned [2, 3]. Automated ultrasonic C-scan systems have become almost a standard feature of composite shop engaged in airworthy product development tasks [4]. Now-a-days, these systems are computer controlled and not only detect defects such as porosity, delamination and inclusion but also produce a permanent image of the evaluated part. Additional features such as image analysis and enhancement capabilities of the computer system have made the state-of-the-art ultrasonic inspection systems among the most powerful NDE methods available for advanced composites. Pulse echo, through transmission or a combination of these techniques can be employed using C-scan systems [5]. Water is invariably the couplant used between the piezo-electric ultrasonic transducers and the component under inspection. This inspection could be carried out by moving the transducers across the component in a water tank or the water squirter method can be used. The present ultrasonic inspection employs a pair of water jets, known as water squirters, for realizing the requisite sonic coupling between the transducers and the component under evaluation. In the water squirter ultrasonic C-scan system, a nozzle with a uniform water column encircles the transducers. It is possible to sustain a turbulent-free water column, with careful choice of nozzle material and design. Squirter systems are more economical and highly flexible compared to immersion tank units. In our investigations we have used custom built computer controlled water squirter C-scan systems with a unique free standing design.

Typically aircraft structures comprise of parts like skin panels, spars, ribs etc. It is a common practice, whether with metals or composites, to build these structures through a multi-stage operation where in the individual parts are made separately and thereafter assembled using mechanical fasteners or adhesive bonding. However, such an approach fails to take advantage of many attributes of composites that could influence production cost and structural efficiency. Innovations in fabrication methodologies, like co-curing, have to be viewed against this background.

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Figure 1 shows schematically a Carbon Fibre Reinforced Plastic (CFRP) box type structure that has been fabricated through the co-curing method. This involves autoclave processing of CFRP prepregs with two half female moulds and inflatable rubber mandrills as internal pressure intensifiers. The outcome is an integral spar-rib-skin structure in a single step. There is no need for secondary fastening or bonding operation. There are, thus, significant reductions in fabrication and assembly costs. Absence of fasteners or adhesive bonding means savings in costs and weight, besides enhancing structural efficiency.

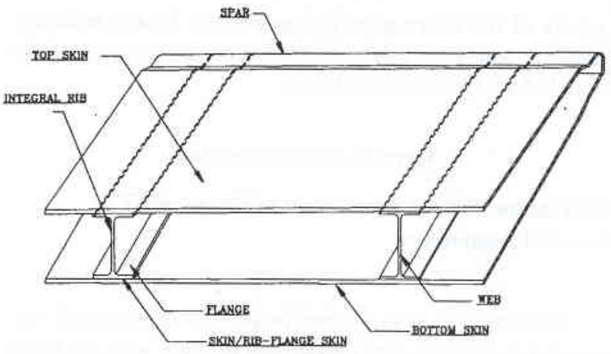


Fig. 1 Schematic of a typical cocured construrction with integral ribs

For the present case of NDE of composite co-cured assemblies, we have extensively employed ultrasonic techniques in effectively tackling the inspection requirements of fully co-cured co-bonded carbon fibre composite aircraft structural components. This involves the use of both portable and large computer controlled ultrasonic C-scan systems.

Ultrasonic C-scan systems

System 1 : In the beginning of the component development programme, during late 1980s, a custom built computer controlled ultrasonic through transmission water squirter system was set up to tackle the inspection requirements. This is a 3-axes system and has inspection envelope of 3M x 2M x 0.4M. The system is completely automated for through transmission inspection with limited facility for manual pulse echo inspection. The inspection frequencies range from 0.5-10MHz. The system would acquire and display the through transmitted amplitude data in the form of C-scan images. Further, the stored data can be processed through image enhancement for detailed analysis. The system is being extensively used to meet NDE requirements of a large number of composite components [5]. Fig.2 shows the system gantry of three axes C-scan system.

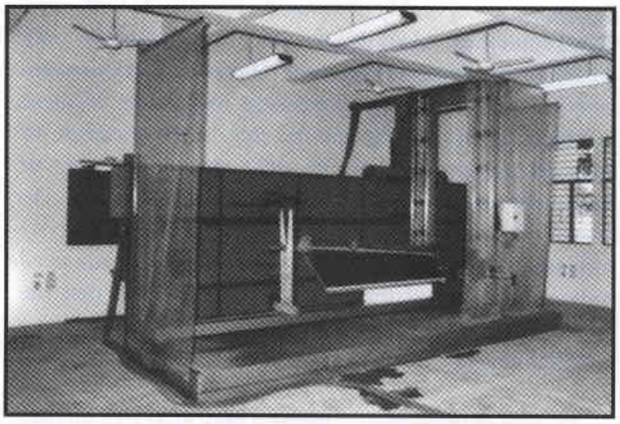


Fig. 2 Ultrasonic C-scan system - 1

System 2 : In the late 1990s, when ACU took up the responsibility of developing composite components of fuselage structures with very complex contours and geometry, the system 1 with three axes of probe manipulation was found to be inadequate. The inspection of such components are best done in a system having multi-axes probe manipulation facility. With this background, another custom built C-scan system with water squirters having 7 axes probe manipulation facility was set up. This system with drive-on and drive-off features has an inspection envelope of 5M x 4M x 1M. This system, with multi-axes probe manipulation facility, can follow the contours of a component during scanning while maintaining the beam normalcy. The component contour for inspection is taught to the computer through a teach and learn process so that probes would faithfully follow the component contour during inspection. The inspection frequency ranges from 0.5-20 MHz. It also has the capability to acquire and display, in real time, the ultrasonic through transmission amplitude, pulse echo amplitude and time-of-flight, either independently through separate scans or simultaneously in a single scan. Fig.3 shows the system

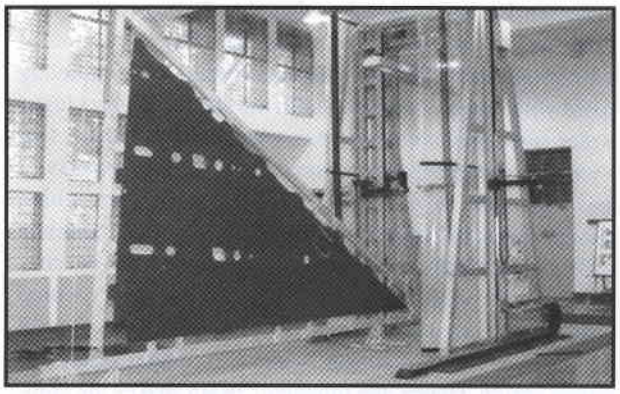


Fig. 3 Ultrasonic C-scan system - 2

gantry of the seven axes c-scan system. Image enhancement & analysis software packages are employed for detailed analysis of stored data.

Results and Discussion

Ultrasonic C-scan Inspection of Co-cured, Co-bonded Assemblies

Ultrasonic C-scan system inspection of co-cured, co-bonded assemblies was carried out initially with the three axes c-scan system. This system does not have the facility for multi axes probe manipulation for effectively tackling the inspection of highly contoured components with complex geometries. Also, this system is automated for only through transmission inspection. This posed certain problems for the through transmission inspection of these co-cured, co-bonded assemblies due to the presence of large air path in between the outer skins. A number of inspection methods were tried and many of these failed to meet the requirements in terms of repeatability, sensitivity and inspection time. These factors are important and need to be considered at the development stage so that the methods are attractive and can be used effectively during production inspection.

In view of these requirements a very effective inspection method based on ultrasonic through transmission principle has been developed and is being extensively used. In this inspection procedure the hollow portion of the component in between the outer skins was completely filled with water to the brim with the sides suitably closed water tight and investigations were carried out on this water filled component to assess the suitability, sensitivity and reliability of this novel practical procedure which allows the use of standardized 5MHz inspection frequency and novel transducer assembly. Due to the aerofoil construction, the outer skins and the spars of the co-cured construction are tapering at different angles from about 3 degree over the skin region to about 10 degrees over the crown region. Hence, the ultrasonic beam strikes the component surface at an angle making an oblique incidence. Due to this oblique incidence of the transmitted beam, complex mode conversions take place at the interface. The effect of this oblique incidence and mode conversions was carefully studied on representative test segments and the ultrasonic beam path from transmitter to receiver was traced. Due to the large acoustic path offered by the web region of the integral stiffeners, the inspection of this web was extremely difficult and was tackled separately. This was accomplished with a specially designed attachment with a long hollow tube with the transducer mounted at one end. This attachment included facility for movement over guides and enabled access to inside portion of the ribs.

This approach of through transmission inspection of co-cured assemblies was quite effective and met all the inspection requirements in terms of sensitivity and resolution. The inspection of the component was carried out in two stages. In stage one, the automated C-scan inspection would provide information on both the skins and also on the junctions of rib-flange and skin. In stage two, the inspection of the web portion of the stiffeners and other regions which could not be inspected in the automated c-scan system was inspected manually using ultrasonic contact pulse echo technique.

Eventhough the through transmission ultrasonic inspection of co-cured assemblies was very fast, repeatable, met all the requirements in terms of sensitivity, resolution and very attractive for production inspection, there was an uncertainty while analyzing and evaluating the c-scan results over the junctions of the rib-flange and skin. This would arise when there are delaminations existing at these junctions. When we fill the hollow portion of the co-cured construction with water, there are possibilities that water would fill these delaminations and allow the ultrasonic beam to effectively pass through this water filled delaminations. This might go undetected which is a very serious issue. In view of this situation, another mandatory inspection stage was introduced after subjecting the component to automated ultrasonic c-scan inspection. This procedure calls for removal of any water entrapped in the delamination at the rib-flange skin junctions and subjecting all these junctions for a thorough manual ultrasonic contact pulse echo inspection. Such a procedure resulted in additional inspection time and laborious manual inspection. Alternative approaches have to be considered to overcome this uncertainty in detecting the delamination at the junctions. One such approach was to resort to inspection procedure where the presence of water in the hollow portion of the co-cured assembly may not be required. This calls for an automated inspection from one side of the component using the presence of air between the outer skins effectively as a reflecting medium. This is best done in pulse echo inspection from one side. Hence, the component needs independent inspection of the two skins with integral stiffeners. The regions that are not amenable for automated C-scan inspection were inspected manually.

Figure 4 shows the through transmission amplitude C-scan plot, over a small region of a co-cured construction, showing the delaminations at the rib-flange and skin junctions at three rib locations. Fig.5 pertains to the same but obtained with pulse echo time-of-flight (calibrated to read thickness) inspection methodology. In Fig 4 the delaminations are seen as high attenuation (above 40 dB) patches. However, in Fig 5, the same delaminations are signified by the indication of only skin thickness where the total skin rib-flange thickness should have been revealed. It can thus be noticed that a clearer definition of the delamination is obtained through the pulse echo time-of-flight scan when compared with through transmission scan. One can clearly see the uncertainty in the through transmitted amplitude plot in the detection of delamination and also its size due to water filling the delaminated region thereby masking the actual delamination detection and its size. However, in pulse echo time-of-flight scan one can

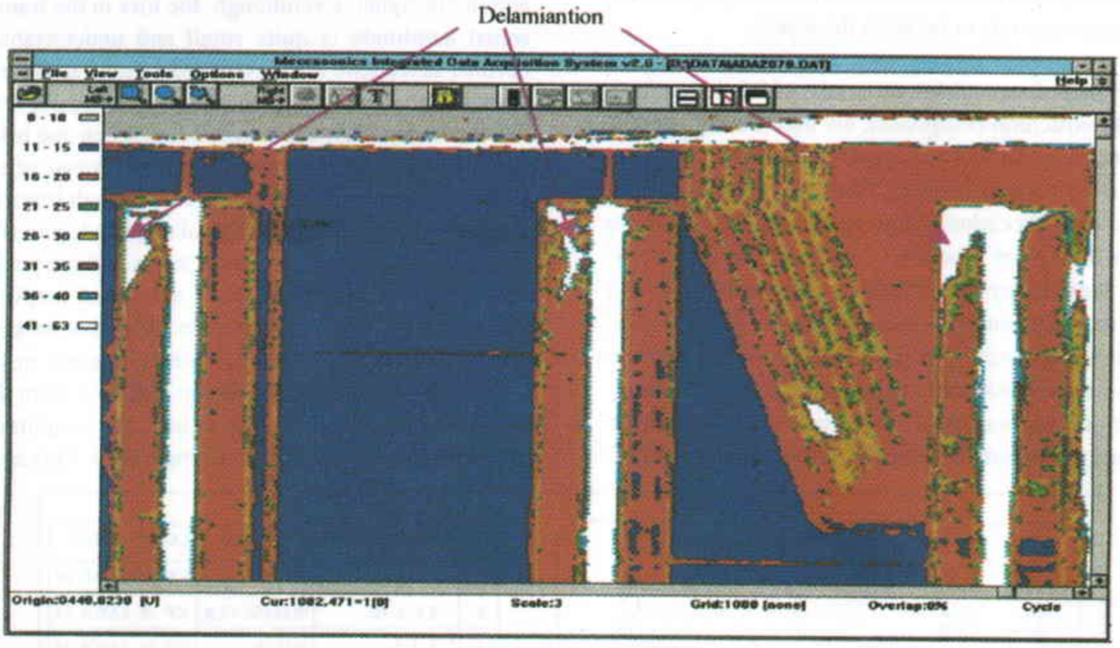


Fig. 4 Through transmission amplitude scan

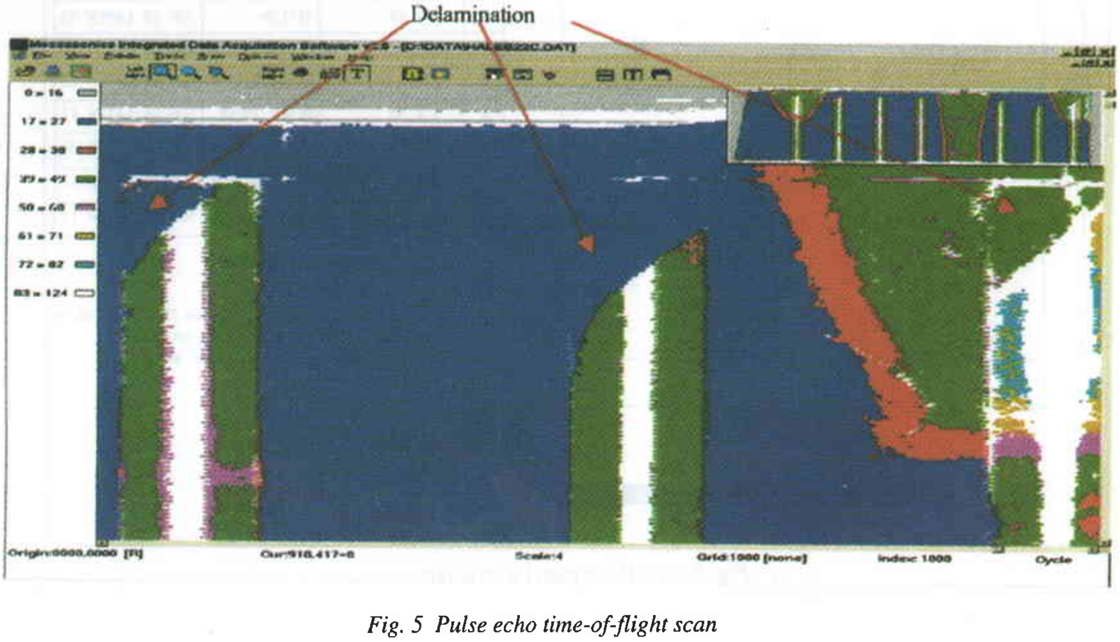


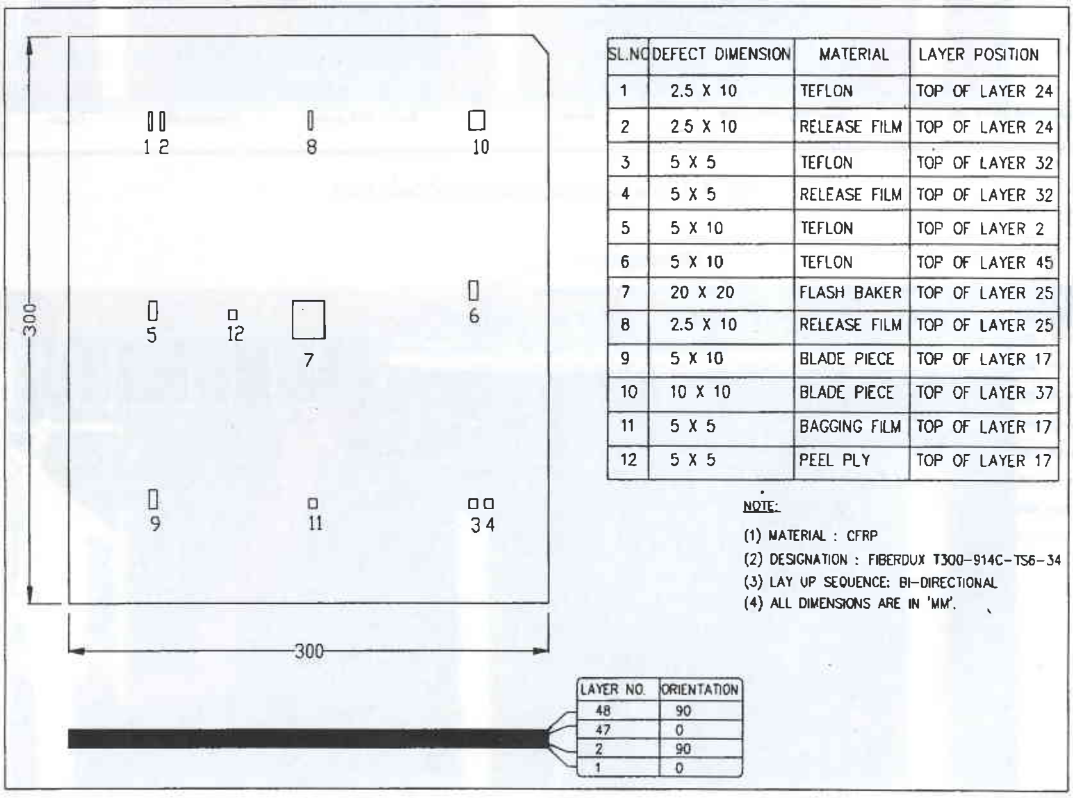
Fig. 5 Pulse echo time-of-flight scan

see that there is no uncertainty in detecting the delamination and its size can be evaluated more precisely. Again the inspection was carried out at 5MHz with normal transducer assembly.

Detection of foreign material inclusions

Also, there was another problem that was noticed in the through transmission inspection of composite components with regard to the detection of inadvertently embedded foreign materials in between the layers.

A number of expendable materials, which do not form part of the structural component, are used during component fabrication. These are materials like release film, peel ply, back-up papers, bagging films etc. Through strict quality control procedures, care is taken to see that these materials do not get inside the component lay-up. Occasionally, these materials get inadvertently embedded, as a foreign material, during layer deposition process. The presence of such foreign material (inclusion) can become a potential failure initiation region, which may get debonded during the service life of the component and is a matter of concern for structural integrity. When a cured component is subjected to ultrasonic inspection, majority of the foreign materials are detectable in through transmission inspection because these materials are highly attenuative or may not bond well with the neighbouring layers. However, some of these materials adhere well to epoxy matrix in the composite and may be difficult to detect in through transmission inspection. The reason for this is the presence of tightly bonded foreign material (inclusion) does not cause enough insertion loss in the through transmitted amplitude signal. Eventhough, the loss in the transmitted signal amplitude is quite small and undetectable, they become detectable if the reflected echoes are monitored. Eventhough, the foreign material may be a poor reflector, the sensitivity is expected to be better when one is looking for the change from a zero base line instead of a small change on a large background. The through transmission inspection would provide a signal amplitude plot showing the variations in the attenuation levels and the pulse echo inspection would provide both the signal amplitude as well as time-of-flight information. With this background, it is best to carry out an automated ultrasonic inspection in a system that would acquire, in real time, both through transmission amplitude and pulse echo amplitude and time-of-flight information in a single scan. This approach



SL.NO	DEFECT DIMENSION	MATERIAL	LAYER POSITION
1	2.5 X 10	TEFLON	TOP OF LAYER 24
2	2 5 X 10	RELEASE FILM	TOP OF LAYER 24
3	5 X 5	TEFLON	TOP OF LAYER 32
4	5 X 5	RELEASE FILM	TOP OF LAYER 32
5	5 X 10	TEFLON	TOP OF LAYER 2
6	5 X 10	TEFLON	TOP OF LAYER 45
7	20 X 20	FLASH BAKER	TOP OF LAYER 25
8	2.5 X 10	RELEASE FILM	TOP OF LAYER 25
9	5 X 10	BLADE PIECE	TOP OF LAYER 17
10	10 X 10	BLADE PIECE	TOP OF LAYER 37
11	5 X 5	BAGGING FILM	TOP OF LAYER 17
12	5 X 5	PEEL PLY	TOP OF LAYER 17

NOTE:

(1) MATERIAL : CFRP
(2) DESIGNATION : FIBERDUX T300-914C-TS6-34
(3) LAY UP SEQUENCE: BI-DIRECTIONAL
(4) ALL DIMENSIONS ARE IN 'MM'.

LAYER NO.	ORIENTATION
48	90
47	0
2	90
1	0

Fig. 6 CFRP test panel with inserts

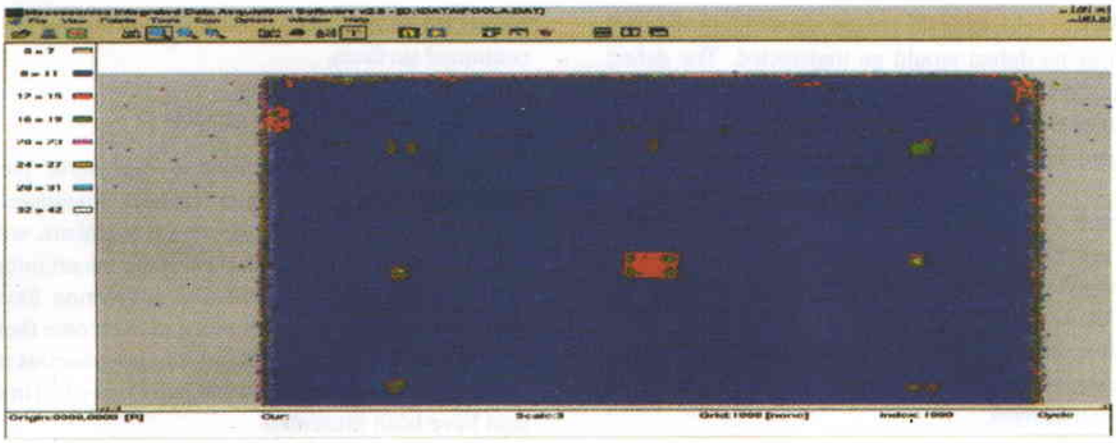


Fig. 7a Through transmitted amplitude scan

Fig. 7b Pulse echo amplitude scan

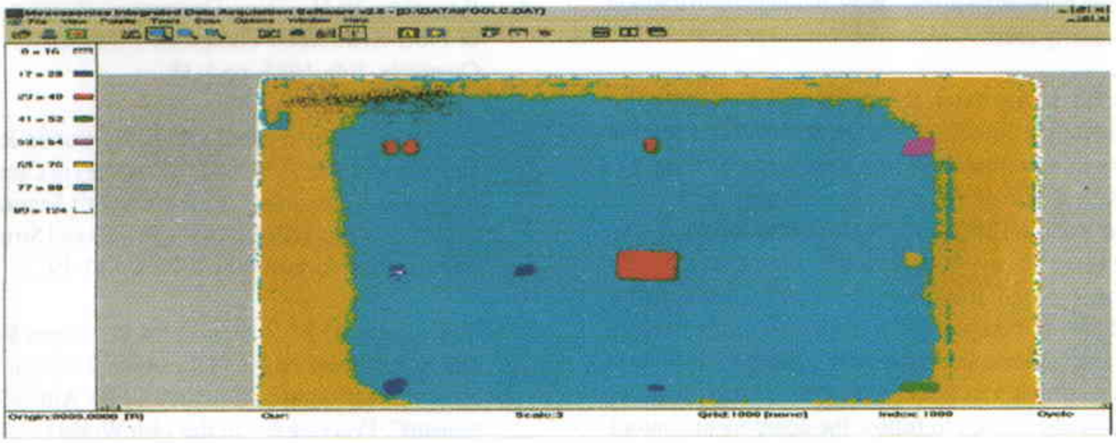


Fig. 7c Pulse echo time-of-flight scan

would result in enhancing the present capabilities of defect detection as no defect would go undetected. The defect missed in one technique would be detected in another technique when one resorts to simultaneous through transmission and pulse echo inspection modes.

Figure 6 shows a Carbon Fibre Reinforced Plastic (CFRP) sensitivity test panel specifically fabricated by introducing the expendable materials as foreign materials that are likely to get embedded in between the layers during fabrication. These materials are embedded at different locations through the thickness of the laminate and are of different sizes.

Figure 7 shows the ultrasonic C-scan inspection results obtained from the multi axes C-scan system on this sensitivity test panel. Fig.7a, 7b and 7c show the through transmission amplitude, pulse echo time-of-flight (calibrated for thickness) and pulse echo amplitude plots respectively obtained for the sensitivity test panel in a single scan. From the above C-scan plots, one can clearly see the defects, numbered 11 with bagging film as an insert and 12 having peel ply as an insert, are not detected in through transmission amplitude scan. However, Figures b & c show the presence of both these defects 11 and12 which are clearly detected in both pulse echo amplitude and time of flight (thickness) scans.

Except for the defects 11 and 12, all the other defects are seen in both the through transmission as well as in pulse echo scans. From the above results, the limitations of through transmission inspection alone and the advantages of simultaneous acquisition of both through transmission and pulse echo information obtained from a single scan are clearly seen.

With this background, to overcome the uncertainties and the limitations in using only the through transmission inspection, as mentioned above, a large multi-axes C-scan system with a pair of water squirters having seven axes probe manipulation has been recently added to the existing NDE facilities. This system is capable of inspecting components in through transmission or pulse echo modes independently or can perform a combined through transmission and pulse echo inspection simultaneously in a single scan. The seven axes probe manipulation features would allow the probes to follow the component contour to maintain beam normalcy during an automated inspection. This system has been installed and is in use for the inspection of large structural components having flat or contoured surfaces.

Conclusion

An effective non-destructive inspection procedure based on ultrasonic principles has been developed for the inspection of co-cured, co-bonded components with integral stiffeners. The limitations and the uncertainties arising out of through transmission inspection have been addressed and the measures taken to overcome these have been discussed. The advantages of simultaneous acquisition of through transmission and pulse echo data in a single scan have been presented.

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