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Damage Identification in Composite Materials Using Lamb Wave Propagation Parameters – As A Base of Structural Health Monitoring

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Abstract|:- Damage identification in composite materials is finding an important role in modern engineering. Conventional NDT methods, vibration based damage methods give ample flexibility to understand the extent of expected damages in the system. Measurement of vibration characteristics like natural frequencies and mode shapes, Fourier responses and transient responses can help in understanding the present status of the system either by comparing with their baseline equivalents.
The progression of SHM systems within composite structures has virtually paralleled that of metallic structures since these technologies have only recently begun to be implemented. The additional complexity introduced by composite materials is in the fact that the materials are not homogeneous or isotropic, so many of the analytical models previously produced are difficult to use. The frequency response methods for damage identification in composite structures, several analytical procedures are described that attempt to model the response of composite materials to damage in various frequency spectra. One particularly successful is the introduction of transmittance functions to correlate modal data with a database of finite element solutions for a composite structure. Boeing has been exploring the use of frequency response methods in SHM systems for composite helicopter blades.
Keywords:-Simple Harmonic Motion, Vibration, Composite Structure.

I. INTRODUCTION

Composite materials are gaining acceptance and demand in several commercial markets including sporting goods, construction and transportation. For many of these applications however, such as aircraft, without a reliable damage detection approach, the total cost of ownership may become a limiting factor for the structure's use. Several non-destructive evaluation techniques are compared on the basis of their strengths and weaknesses for in- service testing of composite materials. Damage identification in composite materials is finding an important role in modern engineering. Conventional NDT methods, vibration based damage methods give ample flexibility to understand the extent of expected damages in the system. Measurement of vibration characteristics like natural frequencies and mode shapes, Fourier responses and transient responses can help in understanding the present status of the system either by comparing with their baseline equivalents.

There are several inherent difficulties in detecting damage in composite materials as opposed to traditional engineering materials such as metals or plastics. One reason is due to its in homogeneity and anisotropy. Several techniques have been researched for detecting damage in composite materials; however Lamb wave methods have recently re-emerged as a reliable way to locate damage in these materials. There are generally five goals for damage detection, each of which is gained with increasing difficulty and complexity. The first is the determination of the presence of damage in a specimen. The second is to be able to calculate where the damage is located. The third goal is to be able to differentiate between different types of damage. The fourth is an estimation of the extent of severity of the damage. The final one is to estimate the dimensions of the damage. It appears that Lamb wave methods carry enough information potentially to meet all of these goals with a strategically placed array of sensors and suitable processing codes; however the current scope of this research focuses on the first two goals only.

Structural health monitoring essentially involves the embedding of an NDE system (or a set of NDE systems) into a structure to allow continuous remote monitoring for damage. There are several advantages to using a SHM system over traditional inspection cycles, which are presented in the following motivation section. A variety of SHM systems have been implemented in many industries, ranging from industrial machinery to spacecraft. Some of these systems are executed in-situ, such as with rotor bearings on gas turbine generators which are constantly monitored for changes in their characteristic frequencies, and others collect data for post-operation processing such as with black boxes on commercial airplanes. As companies strive to lower their operational costs, many of these SHM systems have been developed for use on particular systems. Several universities and research institutes have also attempted to devise strategies for generic SHM systems for a wide range of applications.

A procedure has been formulated for identifying and locating of damage in structures using Lamb wave propagation parameters as a base of the health monitoring of composite materials. The main focus was placed on ultrasonic based Lamb waves propagation method and combined finite element and modal Lamb waves propagation parameters method for finding various simulated damages in composite materials. The Ultrasonic based Lamb waves propagation method is totally a new approach for the problem of overlapping of the modes in the analysis of Lamb waves. In combined finite element and modal Lamb waves propagation parameters method, identification of change in natural frequencies and mode shapes of a freely vibrating damaged plate with respect to its undamaged state is worked out successfully.

II. LITERATURE REVIEW

Lamb waves are a form of elastic perturbation that can propagate in a solid plate with free boundaries [1, 2]. This type of wave phenomenon was first described in theory by Horace lamb in 1917, however he never attempted to produce them [3]. A comprehensive theory for such a wave was established by minding in 1950 [4], in parallel with experimental work conducted by schoch in 1952 and Frederick in 1962 [5].

A proper lamb mode for damage detection should feature (1) non-dispersion, (2) low attenuation, (3) high sensitivity, (4) easy excitability, (5) good detect ability and (6) toil less selectivity [6]. Based on these criteria, different modes with various frequencies in large thick and thin plates (aircraft skin) were examined [6], and it was found that a narrow bandwidth input signal is able to effectively prevent wave dispersal. For this reason, windowed toneburst, rather than pulse, is frequently adopted as the diagnostic lamb signal. Alternatively, the most suitable cycle number and frequency for a lamb mode can also be determined by the minimum resolvable distance (mrd) approach [7].

Lamb wave-based damage identification is essentially subject to interpretation of the captured wave signals. However, the extraction of key features useful for damage identification from the collected lamb wave signal usually involves a number of confounding problems, such as contamination from diverse noise, interference from natural structural vibration, confusion of multiple modes and bulkiness of sampled data. Accordingly, various signal processing and identification techniques have been introduced, in particular time-series analysis, frequency analysis and integrated time– frequency analysis.

Chattopadhyay et al. [8] present a refined finite element model based on higher order theory to model the dynamic response of delaminated composite beams instrumented with sensors and actuators. The authors note that their model accurately accounts for through-thickness transverse shear deformations as well as nonlinear strains induced by applied electric fields from piezoelectric actuators. The model is verified with experiments performed on graphite/epoxy laminates. It is noted that the presence of delimitation obstructs the damping capacity of the actuators and the nonlinear actuation effects are more significant for lower stiffness's. Although the particular finite element method is developed for control applications of composites, the modeling techniques can also be useful for characterizing the behavior of damaged composites with finite element updating procedures.

Ruotolo, sorohan, and surace [9] create three finite element models of a three-dimensional, eight-bay truss and use experimental data from the truss structure to update the models. The first finite element model consists of simple truss elements, the second consists of euler-bernoulli beam elements, and the third consists of three beam elements per actual individual truss element. Three beam elements per an actual truss member are used to accurately model the effects of the connectors. Although the researchers do not introduce damage into the truss structure in this work, they note that an accurate numerical model of the structure in its undamaged state is essential for damage detection. The authors use the eigenvalue sensitivity method for model updating. The authors compare natural frequencies of the three updated models with the experimental frequencies and demonstrate that the third model performed the best, giving a frequency error of approximately 0.85%. The first and second models give errors of 3.5% and 2.1%, respectively. These results are verified by applying the modal assurance criterion and cross-orthogonality relations between the experimental and numerically calculated mode shapes.

The progression of shm systems within composite structures has virtually paralleled that of metallic structures since these technologies have only recently begun to be implemented. The additional complexity introduced by composite materials is in the fact that the materials are not homogeneous or isotropic, so many of the analytical models previously produced are difficult to use. In zou's review of frequency response methods for damage identification in composite structures, several analytical procedures are described that attempt to model the response of composite materials to damage in various frequency spectra [10]. One particularly successful method used by zhang is the introduction of transmittance functions to correlate modal data with a database of finite element solutions for a composite structure [10]. Recently, Boeing has been exploring the use of frequency response methods in shm systems for composite helicopter blades [10]. Their system, which is called active damage interrogation (adi), uses piezoelectric actuators and sensors in various patterns to produce transfer functions in components that are compared to baseline "healthy" transfer functions to detect damage.

While this system is incapable of locating specific areas of damage, it has been proven effective for monitoring the development of progressive damage in small composite components.

The use of lamb waves for shm of composites has been proposed in many papers in the literature. These methods are at a much less mature stage than frequency response methods in terms of real life applications, however in recent years attention has been given to key factors of their implementation. A few researchers have pursued analytical methods for the evaluation of the data received by lamb wave techniques, most of which have focused on wavelet decomposition or time of flight comparison using finite element techniques [11-13]. Other important preliminary experimentation has been performed by onera to evaluate the effects of testing composite sandwich structures; however their results published to date have proven inclusive [14]. Lastly, much work has been done by soutis's group at imperial college to investigate the effects of finite width on lamb wave propagation experimentally, and attempt to use these techniques to calculate the size, depth and location of delaminations [15, 16].

III. EXPERIMENTAL ANALYSIS

Two panels of quasi-isotropic laminate of carbon fiber/epoxy (CFRP) and quasi-isotropic laminate of glass fiber/epoxy (GFRP) have been fabricated by the above said process and with damage already introduce in one of them while fabrication itself is shown in Fig. 3.1. The specimens are cut to 250 x 50 x 2 mm using a continuous diamond grit cutting wheel. Next, various types of damages are introduced to the specimen are shown in fig. 3.2. In first group, 8 mm diameter holes are drilled at 115 mm distance away from one end at the centre of width of each specimen using silicon – carbide core drill to minimize damage during the drilling process. The next group with a slot of 20 x 1.1 mm along the whole width of the specimen at 100 mm away from one of its end. The third group is made with a cut of 30 x 2 mm and at a distance 100 mm from one end of each specimen. The final group is made with a hole due to impact by a 8 mm diameter cylindrical rod at 110 mm from one end of each specimen and some miscellaneous specimens used for damage detection in next chapter is shown in Fig. 3.3. a) composite pipe 250 mm height, 50 mm outer diameter and 30 mm inner diameter with through hole of 8mm diameter at 125 mm from one of its end b) sandwich beam 150x75x70 mm with cut on surface at 75 mm from one of its end c) laminated pipe 400 mm height, 100 mm outer diameter and 90 mm inner diameter with cut on circumference at 200 mm from one of its end d) pipe cap height 60 mm height with glue defect at flange joint e) laminated panel 280x120x10 mm with impact delamination.

3.2 *various types of damage introduced to the specimen*
a) Through hole b) slot c) cut d) hole due to impact

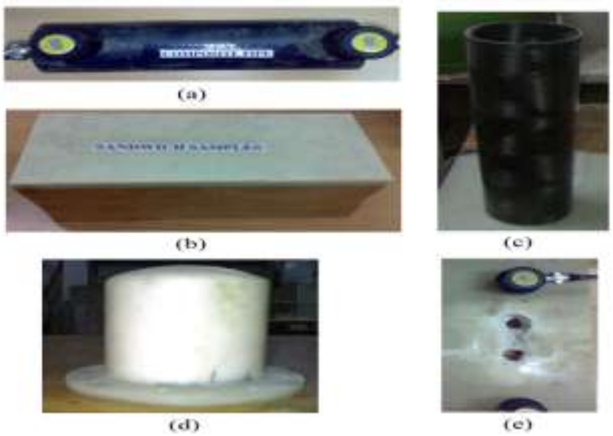

Fig. 3.3 a) composite pipe with through hole **b)** sandwich beam with cut
c) Laminated pipe with cut on circumference d) pipe cap with glue defect e) laminated panel with impact delimitation

IV. EXPERIMENTAL SETUP

The schematic diagram of the experimental setup is shown in fig. 3.4 the test specimen is clamped at one end on cantilever support fixed on basement and the transducers are placed on the test specimen 160mm distance from each other. A coupling fluid is used between transducers and the test specimen for getting good results. The pitch-catch rf test method has been used, which uses a dual-element, point-contact, ultrasonic transducer. One element transmits a burst of acoustic waves into the test part, and a separate element receives the sound propagated across the test piece between the transducer tips, as shown in fig. 3.5. Both the actuation and the data acquisition are performed using a portable panametrics-ndt™ epoch 4plus, and a desktop pc running scan view plus as a virtual controller.

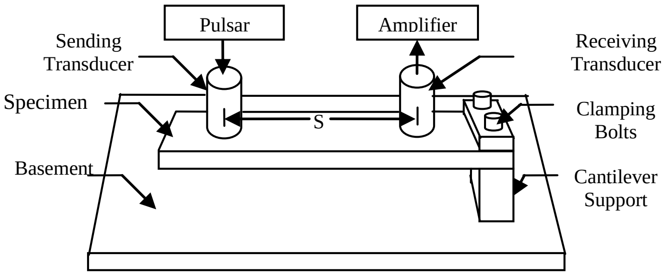

Fig. 3.4 Schematic representation of experimental setup

Fig. 3.6 represents a generalized block diagram of a modern microprocessor-controlled ultrasonic gauge. The pulser, under control of the microprocessor, provides a unidirectional broadband voltage impulse to a heavily damped broadband ultrasonic transducer. The broadband ultrasonic pulse generated by the transducer is coupled into the test piece, normally with the aid of a liquid coupling medium. Returning echoes are received by the transducer and converted back into electrical pulses, which in turn are fed to the receiver Automatic Gain Control (AGC) amplifier. The microprocessor-based control and timing logic circuits both synchronize the pulser and select the appropriate echo signals to be used for time interval measurement. If echoes are not detected during a given measurement period, the gauge will shut down to save power until a new measurement cycle is required. If echoes are detected, the timing circuit will precisely measure an interval appropriate for the selected measurement mode, and then repeat this process a number of times to obtain a stable, averaged reading. The microprocessor then uses this time interval measurement, along with the sound velocity and zero offset information stored in the Random Access Memory (RAM), to calculate distances. This measurement is then displayed on the Liquid Crystal Display (LCD) and updated at a selected rate.

Fig. 3.5 Experimental setup

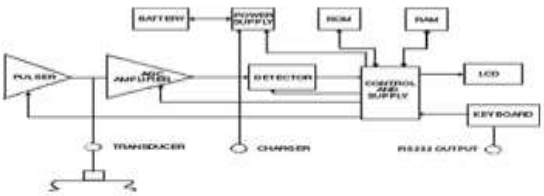

Fig. 3.6 block diagram of a modern microprocessor-controlled ultrasonic gauge

V. ULTRASONIC BASED LAMB WAVE PROPAGATION METHOD

Lamb waves can propagate in the structure and by way of mode conversion and reflection from the surfaces of the structure and can lead to interference patterns as a resulting wave vector propagates along the structure. In the analysis of Lamb wave signatures in experimental data, several different modes appear simultaneously in the signal and the modes overlap in both the frequency and time domains. In the present work the problem of overlapping of the modes is made ineffective in the analysis of Lamb waves by considering the ultrasonic sound velocity as input for finding dispersion curves and a method is proposed for SHM. An experimental setup discussed earlier is used for ultrasonic pulse generation and different materials with different damage introduced are tested in their undamaged and damaged conditions on the test setup.

The specimens with different type of damages induced are considered for this work. The Pitch-Catch RF Test Method has been used, Both the actuation and the data acquisition are performed using a portable Panametrics-NDT™ EPOCH 4PLUS, and a desktop PC running Scan view plus as a virtual controller. Fig.4.3 shows the time and frequency do mine waveform of the specimens both in damaged and undamaged condition which is recorded from the oscilloscope. The change in phase of waveform that occurs between undamaged plates and damaged plates can be seen from fig. 4.3. Therefore the velocity of the lamb wave also varies for undamaged plates and damaged plates. The velocities of the test specimens are calibrated experimentally and the values are tabulated in table 4.1.

The material properties considered in this work, Young's modulus (E) from table 4.1, density (ρ) 1800 kg/m^3 for GFRP, 1583 kg/m^3 for CFRP and Poisson's ratio (υ) 0.328. Table 4.2 shows the peak frequencies from oscilloscope, group velocities and TOF for specimens in undamaged and damaged condition.

The results from the experiments clearly show the presence of damage in all of the specimens. First of all, when the time traces of all of the control or undamaged specimens were overlaid, there was a high degree of visible correlation, especially for the first half of the voltage time trace. The slight variation in the second half of the data can be attributed to the reflected signals returning from the far end of the specimen and passing under the sensor again, which may encounter a slight cutting bias in the composite to cause a change in phase of the damaged specimens. The damaged specimen with through hole and slot, the time traces appear at the same phase and frequency, only having been delayed about 1 to 2 □ s due to the damage. For the other types of damage the frequency got changed and also a large reduction in amplitude and a large varying change

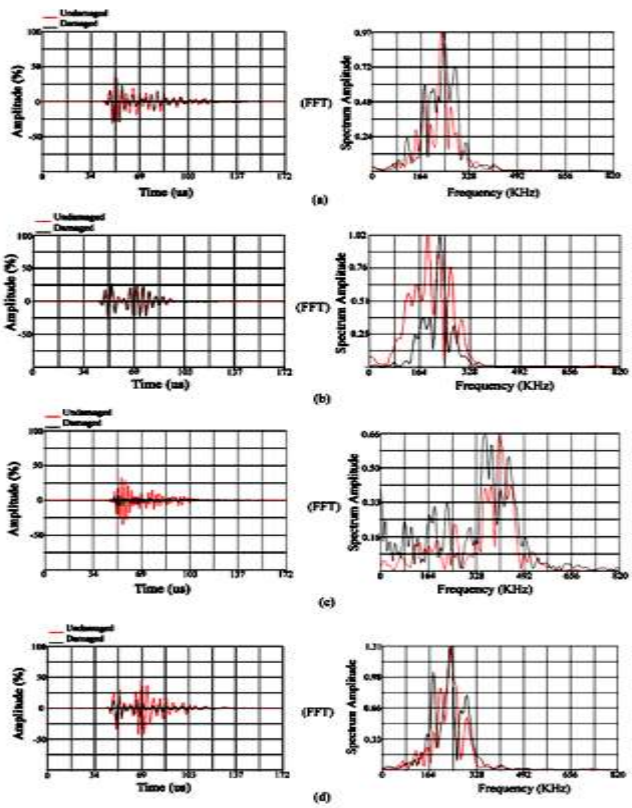

Fig. 4.3 the time and frequency domine waveform of the specimens (GFRP) both in damaged and undamaged condition a) through hole b) slot c) cut d) hole due to impact In phase.

Time traces were reproducible within a single specimen, although the results were not consistent across multiple specimens with identical forms of damage. This was due to the scatter and reflecting of the waves on the various damage features, which may not be identical specimen to specimen. This makes a "damage signature" difficult to define. The most distinctly altered signal was that of the cut and impact hole, which had the smallest sensed voltage amplitude of all the specimens. The control specimens retained over twice as much energy at the peak frequency as compared to all of the damaged specimens, and especially contained much more energy in the reflected waves. The loss of energy in the damaged specimens again is due to the dispersion caused by the micro-cracks within the laminate in the excitation of high-frequency local modes.

The sandwich beam results were more difficult to interpret, due to the damping nature of the cores, which significantly reduced the signal captured by the sensors. In the laminated panel and pipe, the Lamb waves were able to propagate across the stiffened region without much dispersion since they were well bonded and uniform across the specimen. By comparing the laminated panel with and without a delamination, a reproducible signal was transmitted across each of the intact portions of the composite stiffeners while it was obvious that the signal traveling through the delaminated region was propagating at a different speed. Finally, in the composite pipe, the through hole region caused severe dispersion of the traveling Lamb wave, which in turn attenuated the received signal at each sensor further down the tube.

Table 4.1 *Experimentally calibrated velocities and Young's modulus*

Specimen		Undamaged condition			Damaged condition			ΔTOF (us)
		Peak frequency (KHz)	C_{group} (m/s)	TOF (us)	Peak frequency (KHz)	C_{group} (m/s)	TOF (us)	
CFRP	Through hole	310	482	33.19	305	456	35.08	1.89
	Slot	296	472	33.8	284	438	36.52	2.72
	Cut	290	475	33.62	285	467	34.20	0.58
	Impact hole	287	475	33.6	279	463	34.5	0.9
GFRP	Through hole	245	458	34.9	246	431	37.12	2.22
	Slot	240	472	33.8	242	458	34.9	1.1
	Cut	410	467	34.22	365	445	35.93	1.71
	Impact hole	241	481	33.26	241	473	33.82	0.56
Miscellaneous	Composite pipe	360	491	32.58	351	455	35.16	2.58
	Sandwich beam	270	432	37.03	265	426	37.55	0.52
	Laminated pipe	306	471	33.9	301	453	35.32	1.42
	Pipe cap	288	438	36.52	271	421	38.00	1.48
	Laminated panel	272	443	36.11	265	426	37.55	1.44

Ultrasonic based Lamb waves propagation method for structural health monitoring. The proposed method is affective for finding dispersion curves even though if at all the Lamb wave signatures in experimental data with different modes appear simultaneously in the signal or the modes overlap in both the frequency and time domains. So the method presented in this work can be used successfully for structural health monitoring using the change in TOF in undamaged and damaged conditions.

VI. COMBINED FINITE ELEMENT AND MODEL PROPAGATION PARAMETERS METHOD

Modal analysis allows identifying the mode conversions induced by the defects. A simulation combining a finite element approach and Lamb wave propagation parameter for finding natural frequencies and mode shapes of the structures in undamaged and damaged condition is proposed and they are compared theoretically and with ANSYS model for validation. The lamb wave propagation parameters are calibrated using the ultrasonic pulse generator test setup and a methodology is presented for finding the stiffness matrix and consistent mass matrix for generating natural frequencies and mode shapes.

The specimen considered are two carbon reinforced plastic (CFRP) plates (plate A and plate B), with the dimensions 250x50x2 mm in undamaged state and the same plates, one with a 8mm dia through hole at a distance 110mm away from free end and other with a cut (30x2x2mm) at a distance 120mm away from free end in damaged state shown in fig. 5.3. The Pitch-Catch RF Test Method has been used, both the actuation and the data acquisition are performed using a portable Panametrics-NDT™ EPOCH 4PLUS, and a desktop PC running Scanview plus as a virtual controller.

Fig. 5.4 shows the time amplitude waveform of the plate A and plate B both in damaged and undamaged condition. From fig. 5.4 it can be seen that the change in phase of wave form occurs between undamaged plates and damaged plates. Therefore the velocity of the lamb wave also varies for undamaged plates and damaged plates. The velocities of the test specimens are calibrated experimentally and the values are tabulated in table 5.1.

The material properties considered in the present work, Young's modulus (E_1 and E_2) from table 5.1, density (ρ) 1599.92 kg/m^3, Poisson's ratio (υ) and Shear modulus (G) from [19]. In ANSYS model, the Young's modulus of the undamaged plates from table 1 respectively is used for both the damaged plate and undamaged plate analysis.

Table 5.2 shows the natural frequencies of the first four mode shapes for plate A and corresponding mode shapes of the plate in damaged case is shown in fig. 5.5. Similarly table 3 shows the natural frequencies of the first four mode shapes for plate B and corresponding mode shapes of the plate in damaged case is shown in fig. 5.6.

The difference between the natural frequencies of plate B in damaged condition and undamaged condition is very small when compared the same with plate A. Therefore the stiffness of a structure is less affected by a central hole than a cut on the edge.

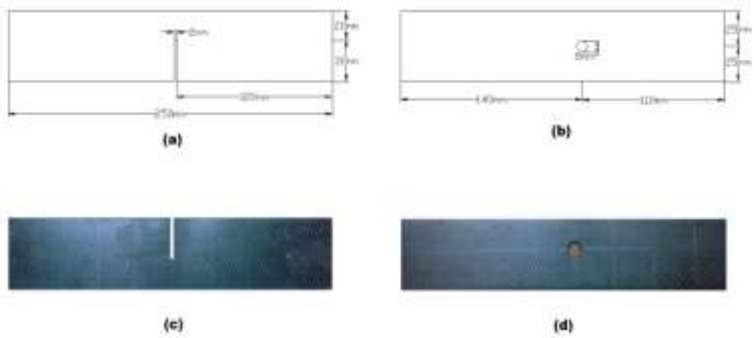

Fig. 5.3 a) schematics diagram of damaged plate having a cut b) schematics diagram of damaged plate having a hole c) test specimen having a cut d) test specimen having a hole

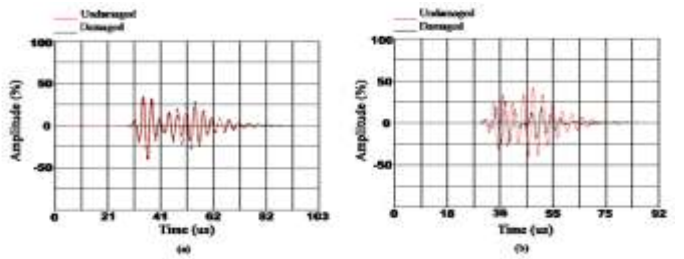

Fig. 5.4 a) Time amplitude signal of undamaged and damaged plate having a cut **b)** Time amplitude signal of undamaged and damaged plate having a hole

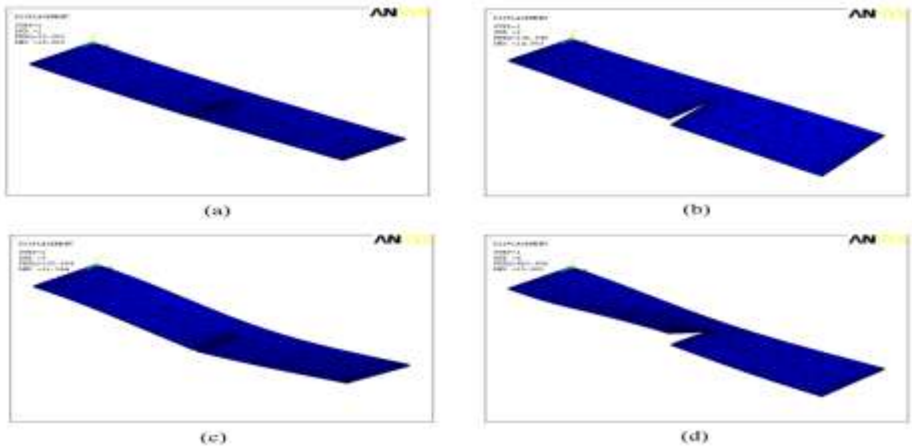

Fig. 5.5 a) 1st Bending mode at 38.08 Hz b) 1st Torsion at 136.55 Hz c) 2snd Bending at 195.90 Hz d) 2nd Torsion at 463.44 Hz

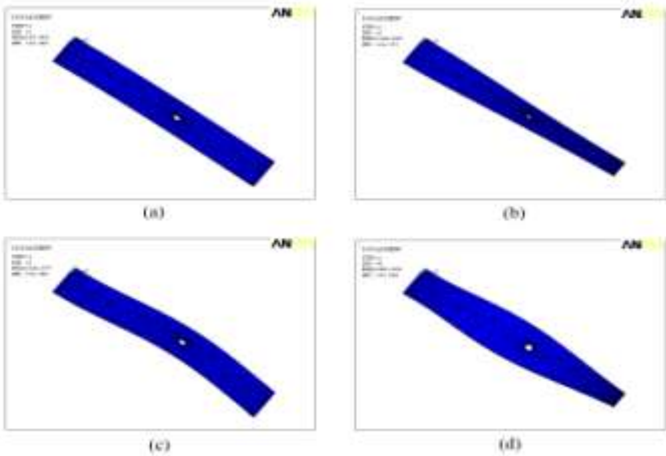

Fig. 5.6 a) 1st Bending mode at 38.70 Hz b) 1st Torsion at 145.00 Hz
c) 2nd Bending mode at 242.88 Hz d) 2nd Torsion at 485.67 Hz

Table 5.1 Eexperimentally calibrated velocities and Young's modulus

Specimen	Undamaged condition				Damaged condition			
	V_L (m/s)	V_T (m/s)	E_1 (Gpa)	E_2 (Gpa)	V_L (m/s)	V_T (m/s)	E_1 (Gpa)	E_2 (Gpa)
Plate (A)	9321	2347	70.11	4.44	9078	2218	66.5	3.97
Plate (B)	9286	2185	69.58	3.85	9050	2041	66.09	3.36

Table 5.2 Natural frequencies of first four mode shapes of plate (a)

Mode (Hz)	Undamaged condition			Damaged condition		
	Theoretical	Present work	ANSYS	Theoretical	Present work	ANSYS
1st Bending	36.23	38.68	38.77	-	38.66	35.08
2nd Bending	164.14	166.24	167.86	-	135.27	136.55
1st Torsion	240.26	242.79	243.40	-	195.83	195.90
3rd Bending	557.03	558.02	560.95	-	462.20	463.44

Table 5.3 Natural frequencies of first four mode shapes of plate (b)

Mode (Hz)	Undamaged condition			Damaged condition		
	Theoretical	Present work	ANSYS	Theoretical	Present work	ANSYS
1st Bending	36.23	38..22	38.61	-	38.25	39.00
2nd Bending	164.14	166.89	167.38	-	144.94	145.00
1st Torsion	240.26	241.65	242.35	-	242.86	242.88
3rd Bending	557.03	557.17	558.13	-	484.94	485.67

Combining a finite element approach and Lamb wave propagation parameter for finding natural frequencies and mode shapes of cantilever plates in undamaged and damaged condition and they are compared theoretically and with ANSYS model. A very good correlation is found between the proposed method and the other methods used in this work for validation purpose.

So the method presented in this work can be used successfully for structural health monitoring using the change in natural frequencies in undamaged and damaged condition in composite materials.

VII. CONCLUSIONS

A procedure has been formulated for identifying and locating of damage in structures using Lamb wave propagation parameters as a base of the health monitoring of composite materials. The main focus was placed on ultrasonic based Lamb wave's propagation method and combined finite element and modal Lamb wave's propagation parameters method for finding various simulated damages in composite materials. The Ultrasonic based Lamb waves propagation method is totally a new approach for the problem of overlapping of the modes in the analysis of Lamb waves. In combined finite element and modal Lamb waves propagation parameters method, identification of change in natural frequencies and mode shapes of a freely vibrating damaged plate with respect to its undamaged state is worked out successfully.

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