Delamination Detection and Evaluation in Composite Laminates Using Guided Ultrasonic Waves

Gurdyal Singh, Anoop Aggarwal, Sunil Kumar, and Sushil Kalra

Abstract Demand from aircraft, automobile and manufacturing industries has generated the requirement of laminated composite materials with high strength, low weight, ease in manufacturing and desired control over properties. However, composite materials are susceptible to damages such as delamination and dis-bonding caused by abrupt loading or manufacturing defects. This study explored the utilization of ultrasonic waves for delamination detection and evaluation in glass-reinforced polymer composite laminates. Simulated delamination defects of varying extent and location in between layers of composite laminates were studied with the help of ultrasonic guided waves in terms of their effects on corresponding signal signature. Relative comparison of wave signatures in healthy and damaged composite laminates helped in the evaluation of delamination location and severity. Lamb wave through transmission signatures was mapped to determine the extent of delamination and pulse-echo signatures were used to determine the location of delamination by using 0.5 MHz transducers on laminated specimens submerged in water. Results indicated a marked decrease in signal amplitude with increase in delamination size. Also, it was revealed from experiment that ultrasonic can detect the delamination in between different layers at different depths by striking ultrasonic signal at particular angle to generate particular mode for detection. This study further established the ability of ultrasonic guided waves to detect the defects in composite laminated structures occurring due to manufacturing flaws or due to work loading or degradation, thus acting as effective tool for structural health monitoring.

Keywords Delamination · Ultrasonic · Lamb waves · GFRP · Multi-layered laminates

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1 Introduction

Composite materials are being widely used for numerous applications from most advanced structures for aircraft structures to basic household appliances and sports goods. Among the various composite materials, glass fibre-reinforced polymer (GFRP) composites laminates offered good replacement for steel and other metal structure due to relative advantages such as high strength-to-weight ratio, high stiffness, corrosion resistance and desired control over properties by controlling the manufacturing/laminates [1, 2]. However, GFRP composites may develop defects arising due to different loading conditions like delamination, fibre pull-out and cracks or may develop under working condition due to environmental degradation, exposure or it may be developed due to manufacturing flaws like missing fibre and air voids which could influence the functional integrity, load-bearing capability or may lead to complete structural failure [3, 4].

Delamination defect is one of the major cause of failures in composite laminated structures [5]. Delamination is de-bonding in between the adjusted layers due to the application of load or environmental degradation. In particular, laminated composites are particularly vulnerable to delamination damage due to their weak interlaminar shear strengths and transverse tensile [6]. It is not possible to detect the damages to the composite laminates by visual inspection. Non-destructive testing (NDT) offered the reliable techniques to estimate the structural health monitoring (SHM) of engineering structures. Among the various NDT techniques, guided ultrasonic waves have proven its ability to detect hidden delamination defects effectively and efficiently with good sensitivity while inspecting large area [7].

Different researchers over the period of times have proposed different techniques for damage detection in GFRP composites. Ultrasonic guided waves offer great potential for the detection of defects in composite structures [8]. Guo et al. [9] studied the influence of delamination's on lamb waves signature and showed that reflection amplitude of the S_0 mode of lamb wave strongly dependent on the delamination depth. Staszewski et al. [10] demonstrated the ability of lamb waves amplitude profiles to capture severity and location of delamination in a composite plate by using three-dimensional (3D) laser vibrometry. Petculescu et al. [11] used ultrasonic waves to detect and determine the size, location of delaminations in unidirectional and cross-ply composites by using a group delay measurement technique and found that the delamination affects the travelling time of waves. Purekar et al. [12] showed the detection of damage caused by delamination in a composite laminate by using piezoelectric phased sensor arrays. Michaels et al. [13] studied the guided wave interactions with defects in composite materials by using guided wavefield images and frequency–wavenumber domain analysis. Yeum et al. [14] demonstrated the use of dual piezoelectric transducer network for delamination detection and concluded that interaction of anti-symmetric A_0 mode with delamination slow down their speed while it had no effect on symmetric S_0 mode. Pudipeddi et al. [15] studied the scattering and mode conversion of lamb wave during interaction with delamination using three-dimensional (3D) finite element (FE) model. However, research in this area is never enough due to tremendous potential offered by ultrasonic testing as NDT technique for health monitoring and damage detection in composite laminates.

This paper provides the further exploration for the utilization of ultrasonic guided waves for delamination detection in GFRP laminates under water-coupling mode. In this study, delaminations of varying extent were provided in between the layer of composite laminated specimen. Basic aim of this study is to map ultrasonic lamb wave signatures of specimens with seeded delamination defects of varying extent and studying the change in signal signature with delamination extent.

2 Experimental Details

2.1 Materials

Material was procured from BASF construction chemicals (India) private limited. E-Glass 900 GSM unidirectional glass fibre was used as fibrous material. MBrace base and hardener were used to prepare epoxy for composite laminates. Epoxy was prepared by mixing base and hardener in 10:4 (by weight).

2.2 Methods

Fabrication of specimens laminates, insertion of simulated delamination, experimental set-up details, measurement settings were described in the following paragraphs.

Specimens Fabrication. Glass fibre sheet of required size was cut from roll of GFRP sheet. The sheets were initially cut 50 mm more than actual sample length. The reason for overcutting was that after laminated specimen has been fabricated and cured, extra edges were trimmed in order to remove flaws after layup operation. Epoxy was prepared by mixing base and hardener in 10:4 (by weight). Approximately, 300gms of epoxy was needed to apply to both sides of the sheet of given one layer of specimen. The epoxy was applied on sheet using a steel scrapper by hand layup operation by carefully spreading it evenly on all sides of sheet. Care was taken to avoid air bubbles inclusion in epoxy while layup process. After that step another sheet was placed in the same direction (0° orientation), and once again epoxy coating was applied to create a laminated sheet. Finally, the prepared laminate specimen consists of three epoxy layers and two glass fibre sheets in between them. Then laminate sheets were left for curing under ambient conditions for seven days. Once the specimens were fully cured, they were cut to actual specimen size by using the circular saw machine.

Insertion of Simulated Delamination. Two types of delamination were put into specimens to study delamination effects. One was of varying extent and other was

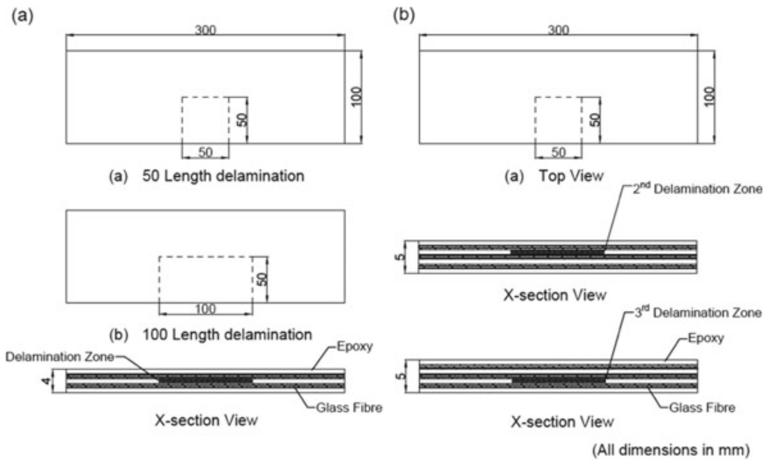

Fig. 1 Specimen with simulated delamination damage **a** varying extent, **b** varying depth

by varying depth, i.e. in between different layers. For varying extent delamination, two-layer (glass fibre) laminate was fabricated at 0° orientation and different size of delamination was created by inserting steel strips of 50 × 50 mm and 100 × 50 mm as shown in Fig. 1a. To simulate delamination at different depths, three-layer (glass fibre) unidirectional laminate was fabricated. For this, two delaminations of same size (50 × 50 mm) were created in three-layer laminated specimens at different depth locations. One delamination, called second-level delamination, was inserted in between first and second fibre layer, whereas third-level delamination of same size was induced in between second and third layers of glass fibre laminate specimens as shown in Fig. 1b.

Experimental Set-up for Measurements. The experimental set-up consists of pulser/receiver system which generates the negative spike pulse with pulse duration ranging from 10 to 70 ns. This pulse is sent to the transducer which converts the pulse to mechanical wave. Transmitting transducer is kept in contact with the composite plate using the couplant (water), and at the other end, the receiving transducer is arranged in the same way. The receiving transducer is connected with pulser/receiver system which in turn sends the received signal to computer through digitizer card. JSR Ultrasonics DPR 300 pulser/receiver system with Olympus Panametrics standard transducer of 0.5 MHz (1″ diameter) and 1 MHz (0.5″ diameter) were used. Figure 2 shows schematic representation of set-up (Fig. 2a) and actual experimental set-up (Fig. 2b). Testing was done in water as compared to air because water acts as good couplant [16]. Transducers with central frequencies of 0.5 MHz and 1 MHz were used for the experiments. As dispersion characteristics vary as function of frequency and wave mode, higher frequencies were avoided because at higher frequency, multiple wave modes exist and energy of the transducer is distributed among various modes. Multiple modes and frequencies are not considered ideal for damage detection [13]. It is also particularly difficult to excite a particular mode. Also, higher-frequency

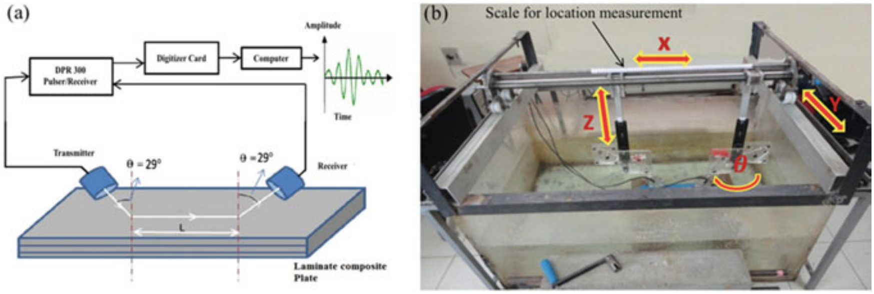

Fig. 2 **a** Schematic representation of set-up and **b** Actual experimental set-up

wave propagation has high attenuation and generally avoided for damage detection [17].

Here, we adopted the approach of finding the particular mode of lamb wave which was helpful for detecting the particular type of damage like delamination, by testing the laminate plate at various angles [18]. The angle which was particularly suitable to find particular damage more appreciably was then selected. This process was done at both frequencies, i.e. 0.5 and 1 MHz. Then angle was fixed for that damage, and signal scanning was done over laminate plates to check the delamination or health of specimens. First through transmission scanning was taken over healthy region or healthy specimen, and then compared with that of defected region or specimen with simulated delamination. Loss in amplitude had helped in determining the severity and location of delamination [8].

3 Results and Discussions

Measurement of delamination extent was done by generating particular mode of lamb waves. Further, exact location of delamination boundary was ascertained by using pulse-echo method. Secondly, the determination of delamination depth in between different layers was presented.

3.1 Delamination of Varying Extent (Length)

Delamination extent was evaluated on specimen having different length delamination in two-layer composite laminates. Transducer of 0.5 MHz frequency has been used at various angle settings to identify which angle was best suitable to excite particular mode of lamb wave that can detect delamination and its extent. After careful examination of through transmission signature at various angles, angle of 23° was found to be best suitable to find delamination in between layers of laminate. Through

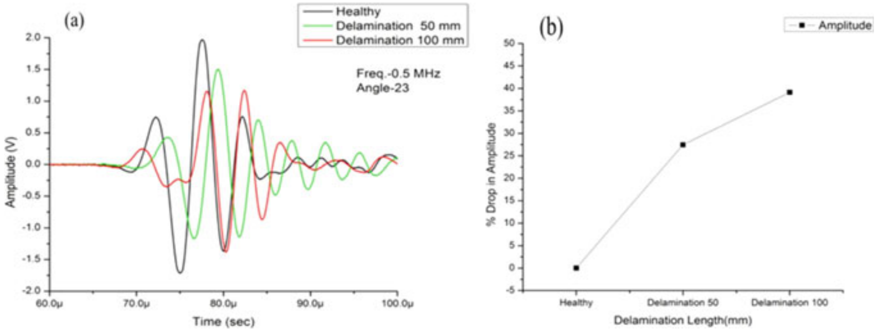

Fig. 3 **a** Through transmission signature and **b** Percentage drop of specimens having varying delamination extent

transmission signature over healthy region was taken and then compared with the signature taken over delamination region of different lengths with same angle setting and probe–probe distance as presented in Fig. 3a.

The percentage drop through signal amplitude at different delamination extent is shown in Fig. 3b. It was observed from results that with the use of right frequency-angle combination, it is possible to detect the delamination extent in laminate composite layers [19]. There was a drop of 27% in through transmission signature over delamination region having length of 50 mm as compared to signature over healthy region. When delamination length was increased to 100 mm, then percentage drop in through transmission signature was increased to 39%. This clearly indicates that with increase in delamination extent, there was drop in lamb wave signal amplitude. The region behind drop in signal amplitude may be due to the presence of multiple interfaces in delamination region [20]. This acts as hindrance in wave propagation, which results in dispersion and loss of ultrasonic signal [21]. Further, localization of delamination defect to determine its boundary was done by using pulse-echo signatures at different locations.

It is quite evident from Fig. 4 that pulse-echo signature over delamination region showed greater amplitude as compared to healthy region. This may be due to reason that incident wave was reflected back from the delamination interface instead of passing throughout thickness and getting dispersed from thickness boundary of the specimen [22]. Regions or boundaries with delamination defect were indicated by fall in amplitude of pulse transmission testing, probed by using pulse-echo technique, and exact location of defect was ascertained by reading location from the scanning set-up scale.

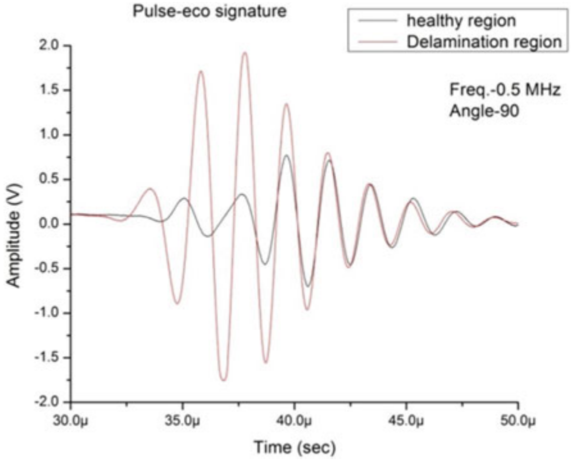

Fig. 4 Pulse-echo signature at healthy and delamination region

3.2 Delamination Defects at Different Depths

Lamb waves with frequency 0.5 MHz were used at different angle setting to determine the delamination at different depths of laminated specimens by generating different lamb wave modes at different angles settings for particular frequency–thickness combination. As different modes detect defects in different layers of composites, so to detect defect in particular layer that particular mode needs to be excited for defect evaluation [23]. For detection of delamination at second level, various angles were tested and it was found that angle setting of 16° generates particular mode which can detect the delamination at second level (Fig. 5a). Similarly, for detection of delamination at third level, number of angles were tested and then angle of 29° was found to be most suitable to detect the delamination at third level (Fig. 5b).

It was observed from result graphs that right frequency-angle combination is helpful in determining the delamination in between different layers of laminated composite structures by exciting particular mode of lamb wave. Here, it was observed from Fig. 6a that with 0.5 MHz probe setting at 16° angle, there was significant change

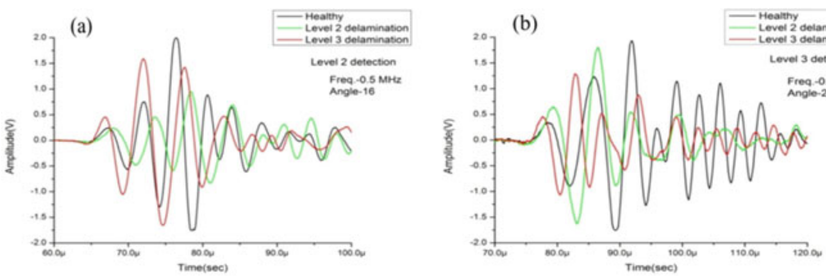

Fig. 5 Through transmission signature for **a** second-level detection, **b** third-level detection

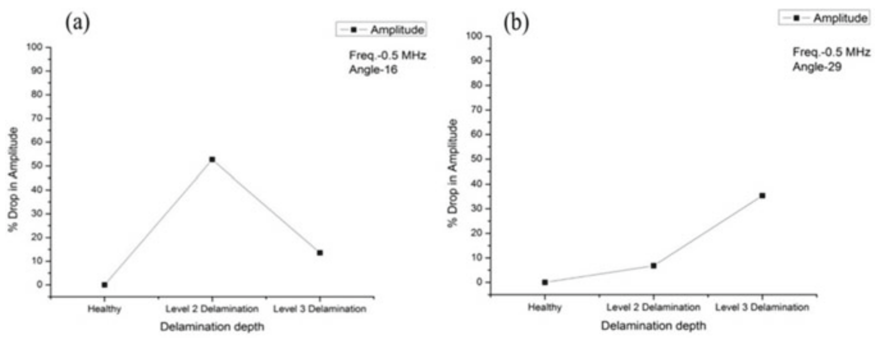

Fig. 6 Comparison of through transmission signatures for simulated delamination defects at different depths at angle **a** 16° and **b** 29°

in peak–peak amplitude wave signature between healthy zone and defective zone for specimen seeded with delamination defect at second level as compared to region having similar defect at third level. Similarly, when probe was set at angle of 29° as shown in Fig. 6b, significant change in peak–peak amplitude in lamb wave signature was observed between healthy zone and defective zone for specimen seeded with delamination defect at third level as compared to defective region with similar defect at second level. The main reason behind that as established by different researchers was different amount of energy is injected by probe into different layers of laminate at different angle setting. Maximum energy flows into particular layer at particular angle by exciting particular lamb mode. This energy of ultrasonic waves helps to determine the defect in that particular layer of composite.

4 Conclusions

Delamination study done on GFRP composite by using ultrasonic guided waves ascertain their ability to evaluate delamination severity and location in between the layers of laminated composite. From the experimentation, it was depicted that there was drop in through transmission signal (27%) over delamination length of 50 mm as compared to healthy region. Further, this drop increases to 39% with increase in delamination length to 100 mm. Also, boundary of this delamination was localized by capturing the change in pulse-echo signature. Further, lamb waves ability was successfully tested to determine the delamination in between different layers of laminated composite at different depths. By setting different angles, different lamb modes were generated which detected defects in between different layers of composite laminate. Delamination in between first and second layers of three-layered laminated specimen was detected at angle of 16° with drop of 53% in signal amplitude over delamination region as compared to healthy region. Secondly at angle 29°, delamination in between second and third layers was detected by comparing loss in amplitude (35%) over delamination region as compared to healthy region. This study further established the ability of ultrasonic guided waves to monitor the health of composite laminated structures by determining delamination defects severity and location before catastrophic failure.

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