Lamb wave detection in prepreg composite materials with fibre Bragg grating sensors

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ABSTRACT

This paper demonstrates that existing Structural Health Monitoring (SHM) techniques have potential during the production phase in addition to their application for maintenance and for in-flight monitoring. Flaws occur during composite fabrication in industry, due to an imperfect process control and human errors. This decreases production efficiency and increases costs. In this paper, the monitoring of Lamb waves in unidirectional carbon fibre (UD-CFRP) prepreg material is demonstrated using both Fibre Bragg Gratings (FBG)s and piezolectric acoustic sensors, and that these SHM sensors may be used for flaw detection and production monitoring. The detection of Lamb waves in a one ply thick sheet of prepreg UD-CFRP material is demonstrated for an FBG sensor aligned with the carbon fibre orientation and bonded to the surface of the prepreg, Furthermore, the velocity of Lamb waves in prepreg UD-CFRP in different orientations is investigated. Finally the successful detection of a material crack in a prepreg UD-CFRP sheet using the Lamb wave detection method is demonstrated.

Keywords: FBG, composites, damage detection, Lamb waves

1. INTRODUCTION

Flaws occur during composite fabrication in industry, due to imperfect process control and human errors[1]. This decreases the level of efficiency and increases the costs for a production facility. This paper demonstrates the potential of Lamb wave detection using Fibre Bragg Gratings (FBGs) sensors to monitor the composite production phase to prevent flaws. Improving the current production process will control man hours, costs and lead time in the production of composites. This paper studies how existing Structural Health Monitoring (SHM) techniques can be used in the production phase.

This research investigates the possibility of monitoring the layup of composites with FBGs. The reason for this specific choice is the fact that sensors used for SHM could be used for flaw detection during the production phase[2]. During the fabrication process several techniques are used to ensure that the product meets the design specifications[1], such as laser projection or checklists during the production. In "Composite Materials for Aircraft Structures" [1] these common defects are listed:

- Delaminations; an area of separation between fabric layers in the laminate.
- Unbond; an area in which two adherends or prepreg layers failed to bond.

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- Porosity, voids; enclosures of air or gas.
- Crack; a fracture in the laminate.
- Foreign object, an inclusion of a foreign substance, such as unremoved foil.

This lists only direct flaws. Process control should also be performed to reduce material flaws. For example, an incorrect pressure cycle will cause unwanted effects, such as porosity.

Structural Health Monitoring aims to provide an insight into the state of the monitored structure or material in any stage of the production or use of the material[2]. The "health" of the structure should remain within the boundaries of the design specification, although normal aging due to use, environmental influence or accidental events can alter the health of the structure. SHM can provide a prognosis of the evolution of (detected) damage and remaining lifetime of the structure.

1.1 Research goal

The research goal is to prove that an existing SHM method of flaw detection is also applicable in the production phase of composite material. Lamb waves are an excellent method to detect and monitor flaws in composite material[3]. In this paper, the same method will be tested to detect flaws in prepreg unidirectional carbon fibre (UD-CFRP). To detect and measure these Lamb waves, FBG sensors will be investigated, because of their small size, immunity to electromagnetic interference (EMI) and multiplexing capabilities[2]. The major bottleneck is the totally different behavior of prepreg material compared to the cured material. Both materials are characterized using different sets of variables: prepreg by variables related to processing, viscosity and rheology, and cured laminates by mechanical properties. Therefore these materials are hard to compare from specifications. In parallel tests in this research, PZT sensors are used for verification measurements of Lamb waves. One challenge of measuring Lamb waves with FBG sensors is that the frequency of Lamb waves are ultrasonic[4] and that the interrogation of the FBG sensors must reach this speed. A second challenge in the Lamb wave detection with FBGs in prepreg material is the coupling of the sensor with the material. A good quality bond between the material and the sensor is essential for the reducing signal noise.

2. BACKGROUND

In this section, typical composite production control procedures will be described, along with the method of Lamb wave detection and the principles of FBG sensors and interrogators.

2.1 Quality management in composite production

The information in this section is based on sections of "Composite Materials for Aircraft Structures"[1] and the "Reinforced Plastics Handbook"[5]. Quality control starts with physical testing of the raw materials at the prepreg production facility and secondly at the composite production facility. Tensile tests can be performed on the fibres to check the longitudinal tensile strength. Chemical tests can be performed to verify the chemical composition of the fibres, e.g. using X-ray photoelectron spectroscopy. Resin manufacturers also perform physical, chemical and spectrographic tests to ensure the quality of their product. For example, the resin content is checked for selected samples at high temperature and pressure to measure the degree of resin flow. Tack and drape tests are other tests often performed.

Concurrently runs the process verification, where the material and the production process are controlled. Prepreg material is perishable and must be controlled throughout the complete production process. The prepreg material must be used within its allowable storage life and outside a controlled area, such as a freezer, it will perish faster. Also, the production process must be controlled to ensure the correct number, position and orientation of layers. For example, a laser projection system can ensure the correct sequence and orientation of the prepreg layers. Currently, some manufacturers use testing of reference or witness test specimens which were processed with the product.

Monitoring the cure cycle of prepreg material can be performed by electrical measurements, acoustic methods and/or optical methods. For example, thermocouples monitor the temperature locally to ensure the correct temperature cycle, so placing the sensors is critical. Dielectrometry depends on the mobility of the prepreg molecules in an alternating electric field, whereas electrical conductivity depends of the degree of crosslinking between the molecules. During the cure these parameters change and can therefore be monitored.

In the non-destructive testing (NDT) phase, composite materials are checked for deviations from the initial design specifications. NDT has specified threshold values; flaws below this threshold are regarded as non-existent, unless specified otherwise (e.g. porosity). Flaw detection in NDT can be done by several techniques. The down side of this situation is that the flaw is already irreversibly present at the time the inspection is performed. Current NDT techniques, such as ultrasonic or x-ray methods, can detect the flaws, but are cumbersome or dangerous to operate during a manual hand layup of the composite material, so cannot be used during the production phase. Therefore new monitoring techniques need to be investigated for the production phase.

2.2 Lamb waves

Lamb waves propagate in thin solid media and these waves have already been used successfully for damage detection in structures, such as metal or composite plates[4]. A Lamb wave is made up of a superposition of longitudinal and transverse modes. Plates support these two infinite sets of Lamb wave modes, whose velocities depend on the relationship between wavelength and plate thickness.

A Lamb wave mode can be either a symmetric or an antisymmetric mode (see Figure 1). The 0-order modes are built up from all frequencies which are generated by the transducer; higher-order modes have cut-off frequencies.

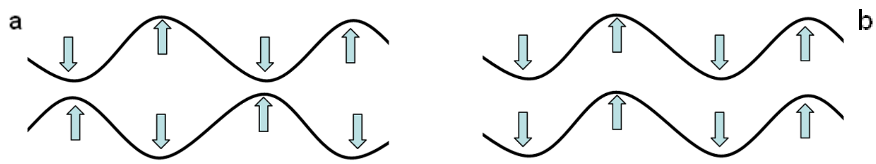

Figure 1 Configuration a represents the zero-mode symmetrical wave (S_0). In configuration b the antisymmetrical wave (A_0) is shown.

Equations (1) and (2) give the phase velocity dispersion curves for symmetric and antisymmetric modes, respectively[6].

$$\frac{\tan(qh)}{\tan(ph)} = \frac{4k^2qp}{(k^2-q^2)^2} \tag{1}$$

$$\frac{\tan(qh)}{\tan(ph)} = \frac{(k^2-q^2)^2}{4k^2qp} \tag{2}$$

where,

$$p^2 = \frac{\omega^2}{c_L^2} - k^2, \quad q^2 = \frac{\omega^2}{c_T^2} - k^2, \quad k = \frac{\omega}{c_p} \tag{3}$$

and $\omega, h, k, c_L, c_T, c_p$ are the circular wave frequency, thickness of the (plate) material, wavenumber, velocities of the longitudinal and transverse modes and phase velocity, respectively. In an N-layered composite the Lamb wave can be modeled by using its displacement field u using Navier`s displacement equations within each layer:

$$\mu^n \nabla^2 u^n + (\lambda^n + \mu^n)\nabla(\nabla \cdot u^n) = \rho^n \frac{\partial^2 u^2}{\partial t^2} \qquad (n = 1, 2, ..., N) \tag{4}$$

Where $\rho^i, \lambda^i, \mu^i, u$ and t are respectively density, the first and second Lamé parameters for the i^{th} layer, displacement field and time. These parameters are directly linked to Young`s modulus, E, by:

$$E^i = \frac{\mu^i(3\lambda^i + 2\mu^i)}{\lambda^i + \mu^i} \tag{5}$$

Equations (1) and (2) show that the speed of Lamb waves is frequency dependent and therefore dispersive[6]. These equations can be solved for multiple modes, which are denoted S_0, S_1, S_2, etc. for symmetric modes and A_0, A_1, A_2, etc. for antisymmetric modes. An example of these solutions is shown in Figure 2, where the equations are solved for a 1mm thick aluminium plate. These dispersion curves show the relationship between velocity and frequency.

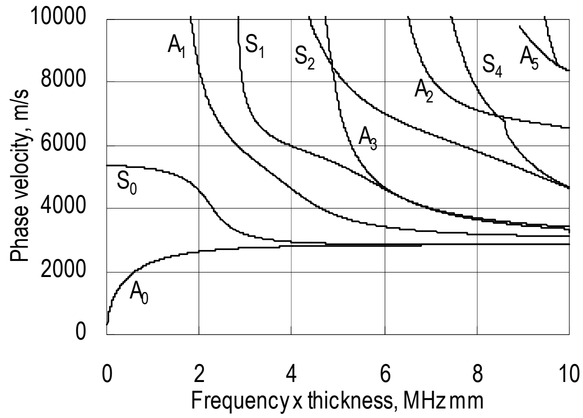

Figure 2 The dispersion curve of an 1mm thick aluminium plate. The antisymmetric (A) and the symmetric (S) waves are plotted, including the higher modes.

For inspections the S_0 and A_0 modes are used[7], as these are the only modes that exist over the full frequency range. Secondly, these modes carry more energy than the higher-order modes. This paper presents a simplified description of Lamb waveves which excludes the visco-elastic behavior of the prepreg sheet. Additional terms could be included in a detailed future analysis.

Several characteristics of the Lamb wave method can be used in production monitoring or flaw detection[4]:

- A deviation from the dispersion curve will indicate a flaw;
- Time for the wave to arrive, i.e. the fastest frequency. Note this is coupled to the previous statement, but requires a simpler analysis method,
- A disturbed wave form indicates also a flaw.

In this research the latter two methods of detection are used.

2.3 Fibre Bragg gratings

An FBG is a passive optic component in a fibre, which exhibits basic reflection and filtering[8]. These FBGs are relatively simple to fabricate and have several advantages compared to electrical sensors, such as small size and good immunity to EMI[2].

The FBG sensor acts as a bandpass filter in reflection (reflecting the Bragg wavelength) and a bandstop filter in transmission, see Figure 3.

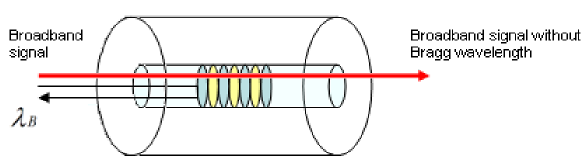

Figure 3 Fibre Bragg Grating concept.

An FBG is a longitudinal periodic variation in the index of refraction of the core in an optical fibre. The spacing of the variation determines the reflected Bragg wavelength. When the environmental conditions vary, e.g. strain or temperature, the index of refraction slightly changes and so the reflected wavelength shifts. This property makes it possible to use the fibre as a sensor. The Bragg condition can be expressed as:

$$\lambda_B = 2 n_{eff} \Lambda \tag{6}$$

λ_B is the reflected Bragg wavelength, n_{eff} is the effective refractive index of the grating in the fibre core and Λ is the grating period. This optical sensor has been subject of research in the field of SHM for its useful characteristics[2]. Strain changes applied to the sensor will alter both the n_{eff} , through the electro-optic effect (Kerr effect), and Λ by physically increasing the grating period. Temperature changes will also alter n_{eff} through the thermo-optic effect, and Λ by thermal expansion or contraction. This can be expressed as[8]:

$$\Delta\lambda_B = \lambda_B((1-\rho_\varepsilon)\varepsilon + (\alpha_\Lambda + \alpha_n)\Delta T) \tag{7}$$

$\Delta\lambda_B$ is the shift in the Bragg wavelength, ρ_ε the electro-optic coefficient, ε the applied strain, α_Λ the thermal expansion coefficient, α_n the thermo-optic coefficient and ΔT is the environmental temperature change.

Fibre Bragg grating interrogators typically use wavelengths-division or time-division multiplexing[9] to interrogate a series of FBGs. Alternatively, vibrations can be monitored can be made by tracking the spectral response of the FBG reflection using an arrayed bandpass filter[10,] or edge filter[11] combined with higher speed data aquisition.

3. EXPERIMENTAL SETUP

To measure Lamb waves in prepreg UD-CRFP, experiments were conducted using both FBGs and piezoelectric sensors. Both systems are described below.

Figure 4a shows the experimental setup used for the FBG measurements[12]. A super luminescent diode (Frankfurt Laser Company, 20 mW, 1520-1580 nm wavelength range at FWHM) was used as the light source. Reflection spectra from the FBG sensors were directed via an optical coupler to a scanning Fabry-Perot interferometer (Micron Optics, Model FFP-TF2) and detector (Micron Optics FFP-C). The FFP-T2 was used initially in scanning mode to detect the FBG reflection, subsequently the scanning voltage was decreased until the interferometer acts as an edge filter. This edge filter monitors the shift in the slope of the FBG reflection. The signal was digitized by an A/D converter (PICO Technology Model 3224). The interrogation speed is therefore only limited by the A/D converter. Digitized data is fed to the computer and analyzed by software developed using LabVIEW (National Instruments). The FBG sensor (FOS&S, Bragg wavelength 1530 nm) was attached to the sheet of prepreg UD-CFRP specimen (200mm × 300mm) using ultrasonic gel (Sonotrace, Sonotech). The attachment was without adhesive, as this would not be suitable to use in the production phase. To generate Lamb waves, an impact source of a weight dropped from a height of 35mm was used.

Figure 4b right shows the experimental setup for the validation measurements with PZT sensors (Physical Acoustics corporation PICO-HF1.2). An in-house developed MOS-FET based pulser was used to excite a conventional transducer (Honda Electronics HEC-301002 at 102 kHz). The signal from the PZT sensors was amplified using a low-noise wide band amplifier (NF electronic instruments 9913). The same experimental setup is used for the FBG measurements, except that the drop weight is replaced by a transducer and the FBG sensor was replaced by two PZT sensors placed 30mm and 50mm along a line from the transducer.

The results from the Lamb wave measurements are presented in section 4.

The algorithm to determine the arrival time of the first wave at the measurement point was developed according to the Akaike Information Criterion (AIC)[13].

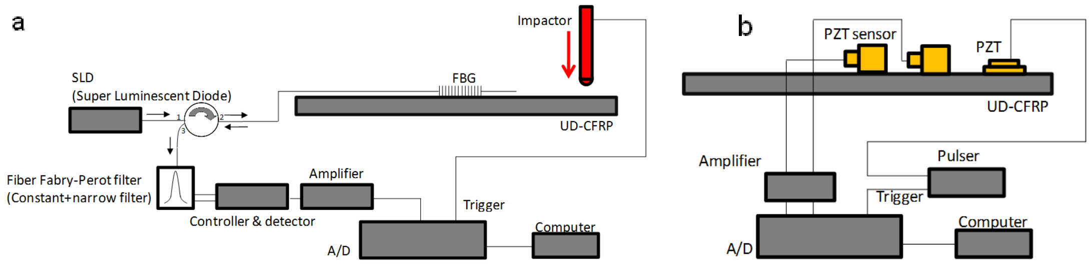

Figure 4 Schematic over view of the experimental setups. (a) shows the FBG setup and (b) the setup for the verification measurements with PZT sensors.

4. RESULTS

The type of UD-CFRP is the DT120 matrix system with toughened thermosetting epoxy from Delta-Preg Spa. This UD-CFRP is used in the experiments as a representative prepreg sheet.

4.1 Damage detection of Lamb wave in prepreg UD-CFRP using PZT sensors

In these validation experiments the PZT sensors at 30mm and 50mm were used to determine the velocity of the Lamb wave in a prepreg UD-CFRP sheet. This experiment aims to show the potential of Lamb wave velocity measurements as a qualitative tool in the production process of composite materials. After determining the velocity in a healthy sheet of UD-CFRP prepreg, cracks (10mm) were introduced at 40mm (between the PZT sensors) from the transducer perpendicular to the Lamb wave propagation. The transducer was aligned with the PZT sensors using a mould. Two perpendicular orientations were investigated to determine the velocity, because of the dependency of the velocity with respect to the fibre orientation, as shown in Figure 5.

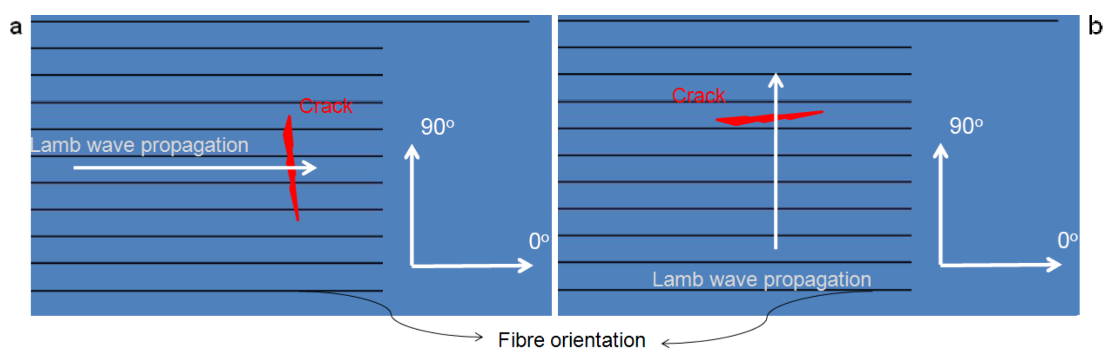

Figure 5 (a) The Lamb wave propagates parallel with the fibres in the 0˚ orientation with the crack at 90˚ to the wave propagation. (b) The Lamb wave propagates perpendicular to the fibres in the 90˚ orientation with the crack at 0˚ to the wave propagation

The results for the 0˚ configuration are shown in Figure 6. The original velocity of the first frequency is $7.1{\cdot}10^3$ m/s. After introducing a flaw at 40mm the velocity of the Lamb wave decreases drastically to an average velocity of $2.0{\cdot}10^3$ m/s. The error in the measurements is in the worst case 17% of the average velocity.

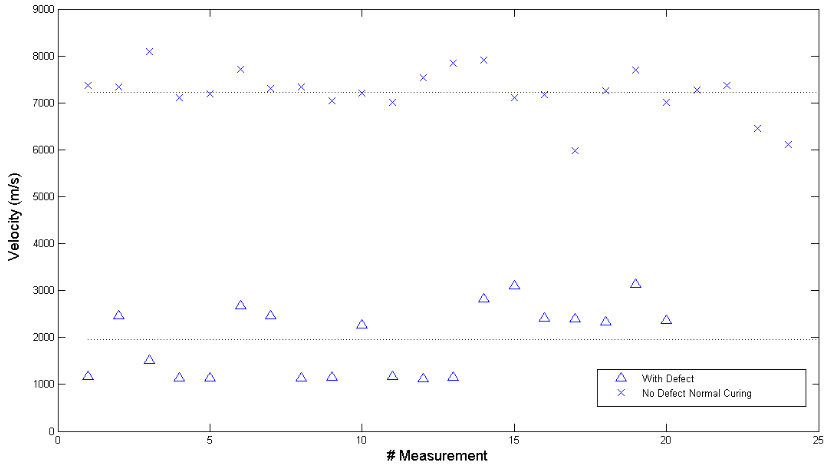

Figure 6 PZT measurements for configuration (a) in a single prepreg UD-CFRP sheet. The x-axis shows the number of measurement samples. The dotted lines show the mean values for the dataset.

To decrease the error in the measurements an amplifier was used to increase the signal from the PZT. The error in the measurements has decreased as the AIC software could now determine the time of arrival with more precision. After introducing a flaw at 40mm from the transducer in the 90˚ configuration, the velocity of the Lamb wave decreased drastically from $2.4\cdot10^3$ m/s to $0.9\cdot10^3$ m/s. This is shown in Figure 7. The error in the measurement is now less than 1%.

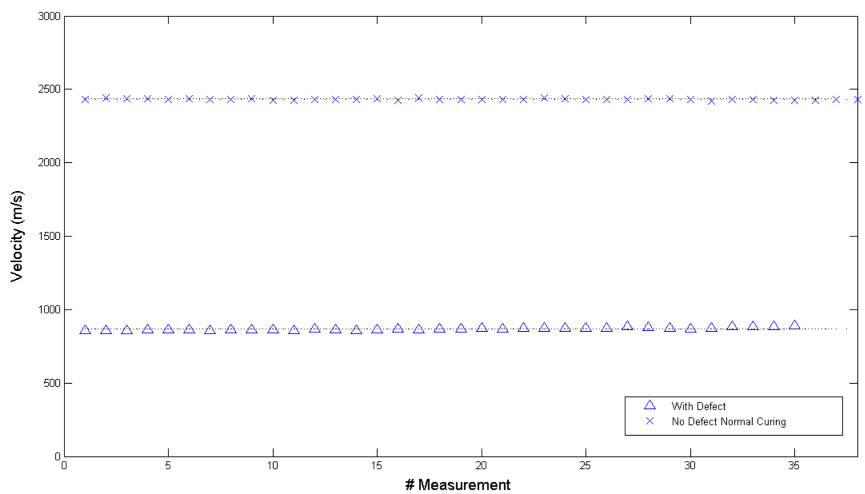

Figure 7 PZT measurements in configuration (b) in a single prepreg UD-CFRP sheet. The x-axis shows the number of measurement samples. The dotted lines show the mean values for the dataset.

Not only is the velocity of the Lamb wave of value in the production process, the wave form itself can contain information on the "health" of the material. As shown by Zhang et al. for cured composite material, a hole (i.e. a flaw) in the material reflects the Lamb wave and an extra wave group appears compared to the non-flaw situation[3]. In this research the same phenomenon is detected in prepreg UD-CFRP, which is shown in Figure 8. Before a flaw is introduced the PZT sensor at 30mm measures three separate wave packets. After introducing a crack of 10mm at 15mm from the source a reflection wave packets are measured after approximately 1.5 msec.

The reflection wave packets are not the only effect on the crack in the prepreg material, as all wave groups arrive earlier than in the non-flawed sample setup.

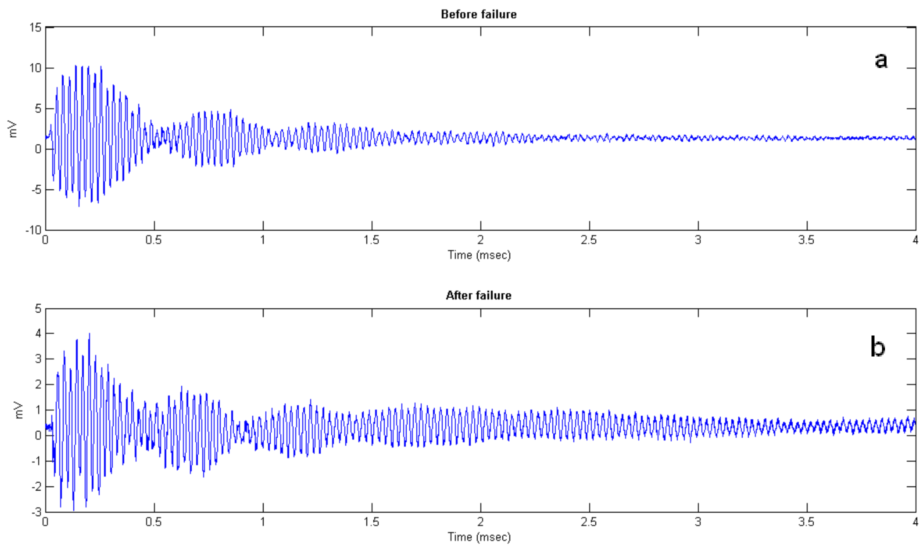

Figure 8 Wave measurements before (a) and after (b) flaw situation in a single prepreg UD-CFRP sheet are shown for the 0˚ configuration. The crack produces a reflection of the source signal, which is shown in the bottom graph.

4.2 Lamb wave detection with FBG sensors in prepreg UD-CFRP

An impactor was used to generate a lower frequency signal with the higher amplitude required, for the measurements using the FBGs. The results are shown in figures 9 and 10. To provide reference measurements, two PZT sensors were used, with PZT 1 was on the same side on the sheet as the FBG sensor and PZT 2 was on the opposite side.

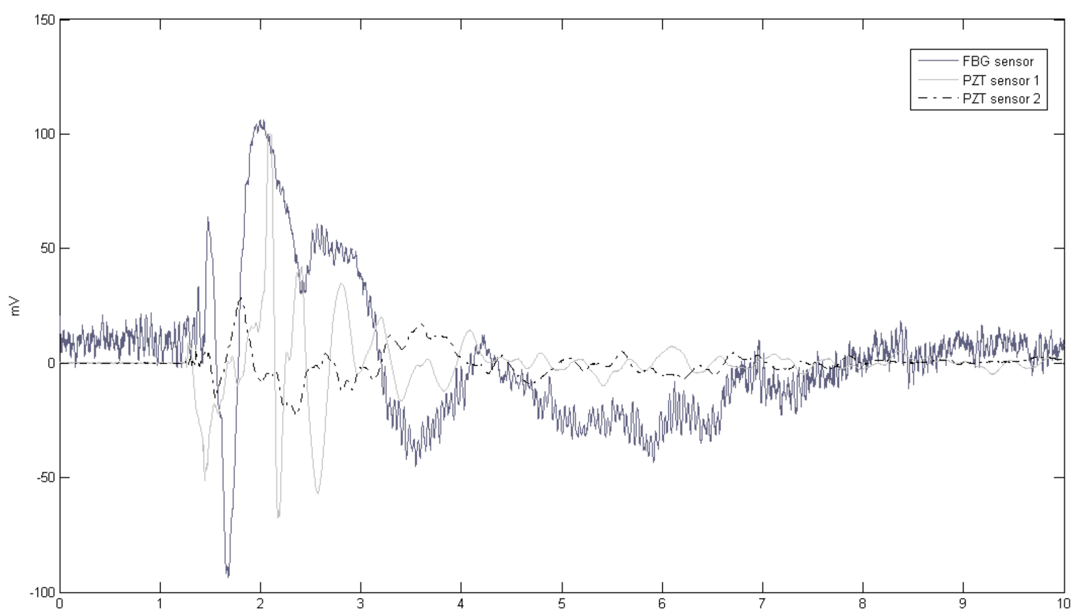

Figure 9 FBG measurements in the 0˚ orientation in a single prepreg UD-CFRP sheet.

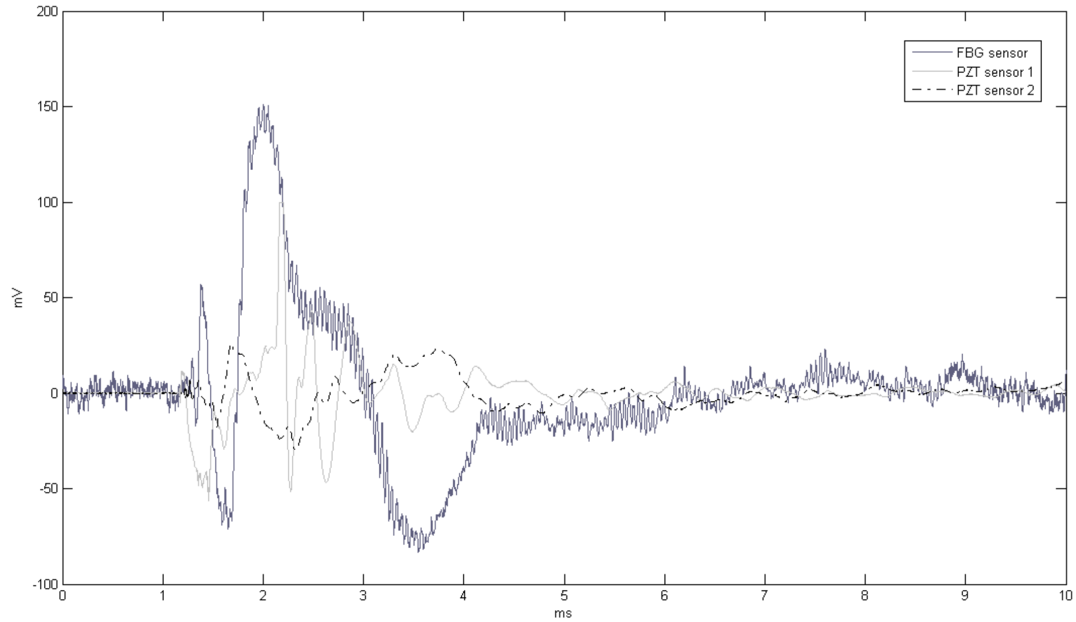

Figure 10 FBG measurements at 0˚ orientation in a single prepreg UD-CFRP sheet

In Figure 9, since the phase of the Lamb waves detected by the PZT sensors are opposite, the dominant Lamb waves are in A_0-mode. The frequency of Lamb waves detected by FBG sensor is low compared to that by PZT sensors. The FBG and PZT sensors were interrogated at 312.5 kHz. Comparable results from duplicate measurements are seen in Figure 10.

5. DISCUSSION

The velocity of the Lamb waves were first measured in the verification measurements with PZT sensors. It was demonstrated that Lamb waves can detect a crack in prepreg UD-CFRP in both 0° and 90° angles of propagation. In the verification measurements a high scatter was seen in Figure 6, but the use of an amplifier decreased the error under 1% in the next measurements. The amplifier increased the signal and the AIC algorithm was able to detect the time of arrival with higher accuracy.

The transducer, which was used in the verification experiments, introduced low amplitude Lamb waves. The combination of the FBG sensors and the bond between the sensors and the prepreg sheet needed higher amplitude Lamb waves. The FBG sensors could not detect the low amplitude Lamb waves and therefore an impact source of a weight was used. This generated high amplitude Lamb waves, and these were successfully detected by the FBG sensors. Ideally the measurement should be easier to perform, as manually tuning an edge filter was time-consuming. This will be addressed in a new FBG interrogation system currently under construction at TU Delft. How the sensor is bonded to the prepreg is also important. The bond of the FBG sensor to the single sheet of prepreg was insufficient to transfer the energy from the Lamb waves in the prepreg material to the sensor. A single sheet prepreg configuration is not representative in the industry; instead multiple sheets will be stacked. The FBG sensor could therefore be embedded between two layers of prepreg and the bond between the sensor and the prepreg will be enhanced.

More complex configurations need to be investigated. In this research a crack was introduced in a single layer of prepreg. There must also be a better understanding of the behavior of prepreg composite material. The material properties change over time as the material is subjected to room temperatures. Future research must include multiple prepreg layers and a range of typical flaws which occur during the layup production phase. Furthermore the detection of a flaw is the first step. Locating and identifying the flaw is a more difficult task. As stated in section 2.2 the visco-elastic properties of the prepreg sheet are neglected. In this paper are models not used to compare the experimental results to simulations, but in the future these must be taken into account. In this research the goal was to demonstrate the feasibility of Lamb wave detection.

The FBG sensor measures at a lower interrogation speed the same Lamb wave as the PZT sensor on the same side of the prepreg sheet. The FBG sensor is sensitive to the negative and the positive strain induced by the Lamb wave. The higher frequencies are detected before the lower frequencies arrive, as the theory for antisymmetrical waves describes. The results presented in this paper demonstrate that the FBG sensors can measure Lamb waves, but have some technical difficulties to overcome. Although PZT sensors are currently more sensitive than FBG sensors, the benefits of using FBG sensors for SHM remain. Demonstrating the potential of Lamb waves for the layup phase in composite production, increases the need to improve the FBG sensors for SHM. The benefits of small size, immunity to EMI and multiplexing capabilities makes the FBG sensors suitable to embed these in these composite structures and to use as production monitoring sensors in the layup phase.

6. CONCLUSIONS

This paper presents these novel aspects:

- The measurement of Lamb waves with an FBG sensor in prepreg UD-CFRP, where the Lamb waves were generated by an impactor.
- The velocity of Lamb waves in prepreg UD-CFRP was determined for the 0˚ and 90˚ carbon fibre orientations. The velocity of the Lamb wave propagating in 0˚ is much higher, compared to the velocity of the Lamb wave propagating in 90˚ to the carbon fibres.
- Damage detection in prepreg UD-CFRP using Lamb waves is possible by measuring the Lamb wave velocity or by monitoring the wave form. The velocity drops drastically if a crack is present between the transducer and the receiver. This effect is demonstrated in two perpendicular propagation directions. The Lamb wave is also deformed by the crack, which causes reflection of the original signal.

The initial goal was to prove that an existing SHM method of flaw detection is also applicable in the production phase of composite material. The first Lamb waves exited in prepreg UD-CFRP and successfully detected with FBG sensors was demonstrated. The velocity of these Lamb waves can be used to determine if a prepreg sheet has a crack, because the velocity drops drastically if a crack is present. This effect was investigated in two perpendicular wave propagations. So the velocity of the Lamb waves and also the waveform of the Lamb wave can be used to detect a crack in the prepreg. The original wave form is deformed by a crack, which reflects the original signal and adds wave packets to the signal.

This paper demonstrates that existing SHM techniques have potential in another phase besides the in-use phase of the composite material, such as the layup phase. If the sensors are placed in the production phase, these sensors could prove their value immediately by using them for layup monitoring. In the near future the above described challenges will be addressed to improve the quality of this method.

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