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Quantitative Evaluation of Delamination in Composites Using Lamb Waves

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Abstract. Ultrasonic guided wave monitoring has become very popular in the area of structural health monitoring (SHM) of aerospace structures. Any possible type of damage must be reliably assessed. The paper deals with delamination length determination in DCB specimens using Lamb waves. An analytical equation based on the velocity dependence on variable thickness is utilized. The group velocity of the fundamental antisymmetric A0 mode rapidly changes in a particular range of the frequency-thickness product. Using the same actuation frequency the propagation velocity is different for delaminated structure. Lamb wave based delamination lengths were compared to the visually determined lengths. The method of the wave velocity determination proved to be essential. More accurate results were achieved by tracking the maximum amplitude of A0 mode than the first signal arrival. These findings are considered as the basis for the damage evaluation of complex structures.

1. Introduction

Increased use of composite materials in aerospace structures require reliable methods for assessment of different types of possible damages. Non-destructive testing (NDT) methods are considered as a standard practice [1, 2, 3, 4], however, to increase the aircraft safety and availability and to decrease the maintenance costs the structural health monitoring (SHM) approach has been implemented in the process of the structural design and testing. Some NDT and SHM methods use similar physical principles, but the different approach makes SHM on-line, condition-based and predictive monitoring with sensors permanently attached to the structure [5].

There are many SHM techniques under detailed research as Acoustic Emission (AE) [6] Fiber Bragg Grating sensors (FBG) [7, 8], Electrical Resistance Tomography (ERT) [9], Ultrasonic Guided Wave testing (UGW) [5, 10, 11] and others, of which FBG and UGW play an important role with probably the highest technical readiness level (TRL). Certification of such methods starts of course on the baseline of the building block approach and require not only the assessment of reliability of the methods themselves, but also the sensors, measuring devices, algorithms etc. FBG sensors are particularly intended for the stress/strain measurements and are considered as a good alternative to the strain gauges (SG) especially due to their immunity to the electromagnetic interferences. UGW testing showed more capabilities especially due to their ability to localize damage. Tomographic imaging algorithms became very popular particularly for the impact damage assessment [12, 13].

Aircrafts are operated in such conditions which naturally lead to susceptibility to damage – either the fatigue cracks in metals or delaminations in composites. Delamination is the most common damage in composites and occurs as a result of impact damages, compression, tension or bending loadings. The main purpose of DCB test is to determine the fracture toughness in Mode I (G_{IC}) and delamination lengths are needed for G_{IC} calculations. This paper deals with determination of delamination lengths using Lamb waves (UGW) measurements. The literature on this topic shows a variety of approaches, which correlate Lamb wave signal features with delamination propagation either experimentally or numerically. Proposed methods incorporated for evaluation different signal features as correlation coefficients, magnitude changes, velocity/time of flight (ToF) changes etc [14, 15]. Another work is based on the numerical assesment of the time of flight of direct and turning Lamb mode during crack propagation [16]. In presented paper delamination growth of double cantilever beam specimens (DCB) using Lamb waves is investigated from the point of the possibility of the precise calculation of delamination length. Precise delamination length is determined using change in the time of flight of A0 mode and group velocity in the original beam and in the beam of half thickness. The paper deals with the question of tracking either the peak with maximum amplitude of the wavefront or the first arrival time of the wave. Finally the both approaches of delamination lengths calculation using Lamb waves are compared to the visually based values.

2. Materials and methods

2.1. Mechanical testing

Specimens were made of carbon fiber plain weave fabric with epoxy resin using a sequence of lamination $[45/0]_{4S}$. A polymer foil with the length of approximately 25 mm was inserted into the midplane of the 16-ply laminated panels as an artificial initial delamination. Specimens with dimensions of 250x25 mm and thickness of 3 mm were cut from the panels. DCB tests were performed according to the ASTM D5528 standard. Determination of the fracture tougness in Mode I (G_{IC}) is the main purpose of this test. Delamination lengths are needed for the G_{IC} calculation and usually the lengths are measured approximately to half of the specimen length. Nevertheless, for the objective of Lamb wave measurements 5 DCB specimens were loaded until the final fracture – until the splitting the specimen into 2 parts.

2.2. Lamb wave propagation

Lamb waves belong to the group of ultrasonic guided waves and propagate with very low attenuation in structures with comparable or greater wavelength than the structure thickness. In general, these are plate-like structures or shells acting as a waveguide. Unlike bulk waves guided waves show multimodal and dispersive character which may be considered either as an advantage or a disadvantage. Dependency of phase and group velocities on the frequency-thickness product is described by dispersion curves (Figure 1). Two fundamental modes symmetric S0 and anti-symmetric A0 exist within the whole frequency-thickness spectra. Above the cut-off frequency (or the cut-off frequency – thickness product) increases the number of propagating modes.

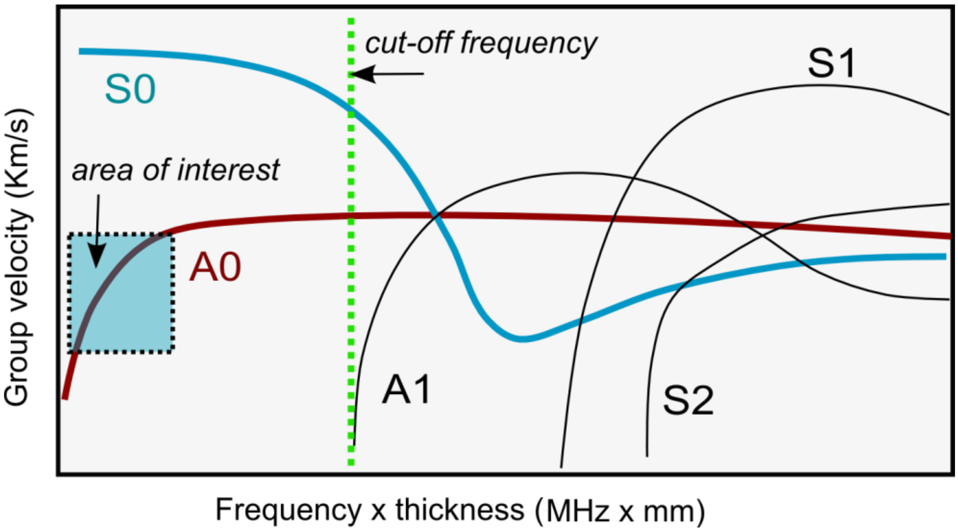

Figure 1 Example of group velocity dispersion curves.

As previously mentioned dispersion curves describe the relationship between the group velocity of different modes and the product of the actuation frequency and thickness of the structure. In the low values of the frequency-thickness product the velocity of A0 mode rapidly increases with the thickness change as is highlighted in the Figure 1. For the purpose of DCB measurements it is useful to choose the actuation frequency within this range. With delamination growth the part of the specimen with half thickness extends which results in time delays of signal arrivals compared to the baseline measurement.

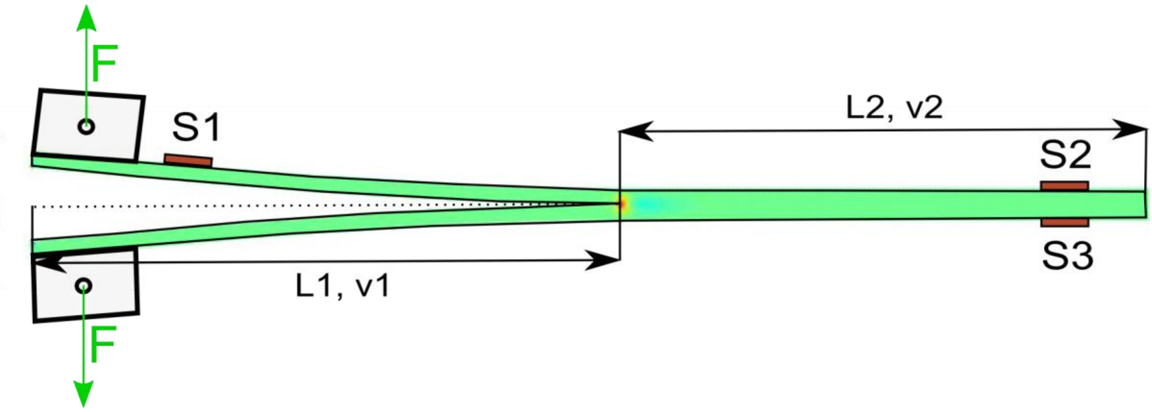

Figure 2 Sensor arrangement on the DCB specimen.

The basic arrangement is shown in Figure 2. Sensors S2 and S3 are mounted symmetrically on different sides of the specimens. If the sensor S1 is an actuator this arrangement enables to determine the specific propagating mode. Symmetrical mode reaches the sensors S2 and S3 with the maximum wave deflection at the same time so that the wave for the 2 sensors propagates in phase whereas asymmetrical mode would look out of phase. The asymmetrical mode A0 actuated by the sensor S1 and measured by the sensors S2 and S3 is shown in Figure 3 for the baseline measurement and for delamination of 74.5 mm.

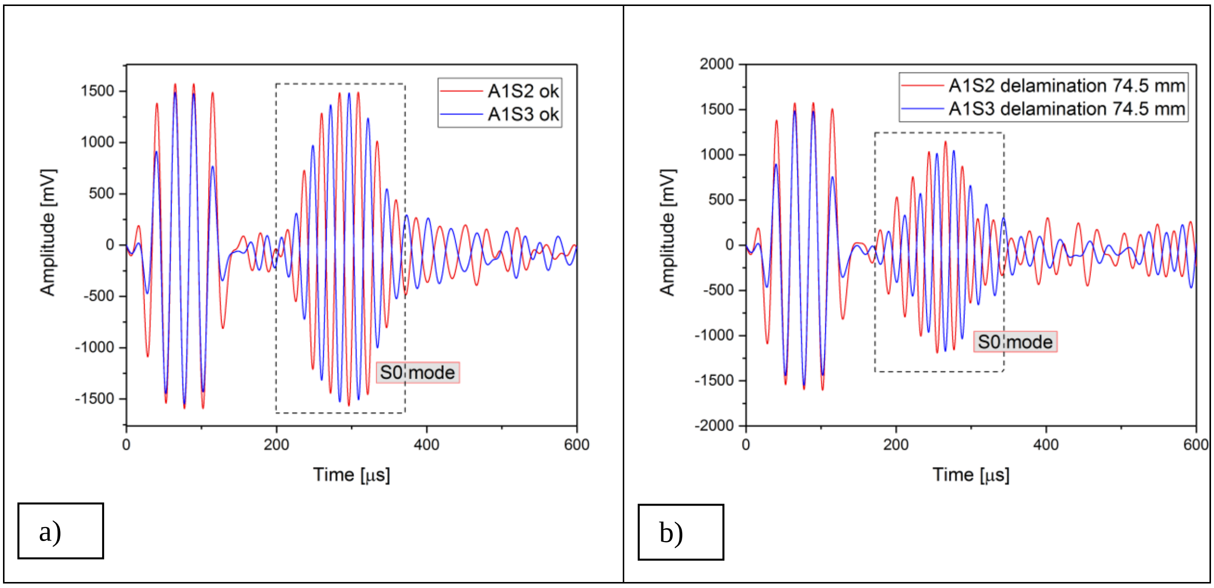

Figure 3 Actuated symmetrical mode A0 propagating in undamaged and delaminated specimen.

3. Results

An equation based on the known velocities for the both thicknesses and time of flight delays during the test was analytically derived as follows:

$$a_n = \frac{v_1 v_2 dt_n}{v_2 - v_1} \tag{1}$$

where v_1, v_2 are group velocities for the half thickness and the original thickness respectively, dt_n denotes difference in the time of flight compared to the baseline measurement and a_n represents delamination length.

Using the equation (1) delamination lengths were calculated by two different approaches. The first technique uses group velocities and time differences by tracking the maximum amplitude peak of the wave and the second uses the first arrival of the wave. Figure 4 gives an example of determination the time delays by means of these two approaches. Due to the dispersion character tracking the first arrival peak or the maximum amplitude peak show different time delays as shown in Figure 4 – 4.82 µs or 6.76 µs, respectively. In general tracking any peak would cause different delays.

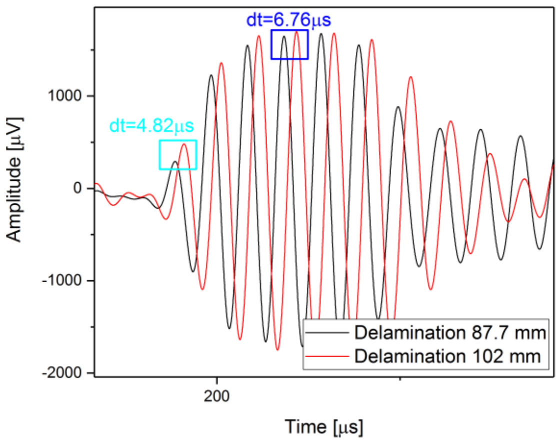

Figure 4 Example of time delays of the corresponding peaks for 2 delamination lenghs.

Dispersion and mode conversion on the crack tip may cause the change in the maximum amplitude peak and increased number of peaks compared to the baseline measurements. After the final failure the last measurement was conducted for the half thickness specimen. The same energy was actuated as into the specimen of the original thickness, so that the wavepacket contained more peaks. Therefore, tracking the corresponding peaks is essential. Example of all measurements is shown in Figure 5. With increase of the split part of the specimen the maximum amplitude peaks overflows to the earlier peaks and the content of other modes (converted or backwalled) is included into the wave packet.

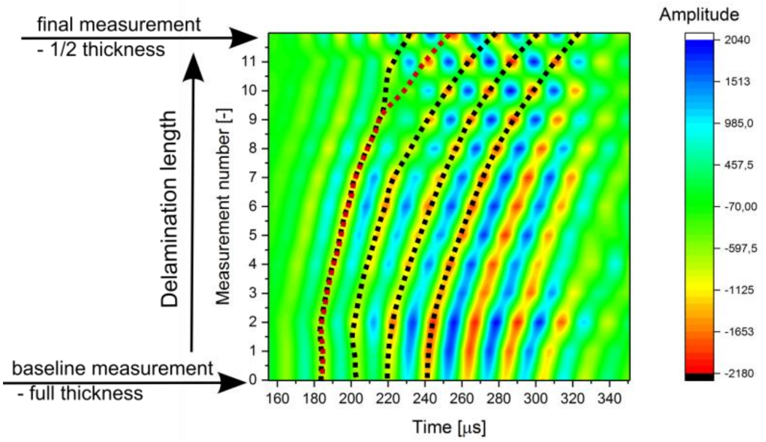

Figure 5 Time delays of different peaks of the wave for all measurements.

The comparison of delamination length using visually based tracking and Lamb wave measurements is shown in Figure 6 for 2 specimens. Calculating the mean absolute percentage error (MAPE) the approach of tracking the maximum peak amplitude shows the average error (average for all specimens) only 7.9 % while the approach using first peak arrival 13.7 %. As can be seen from Figure 6 b crack lengths determined visually might be underestimated.

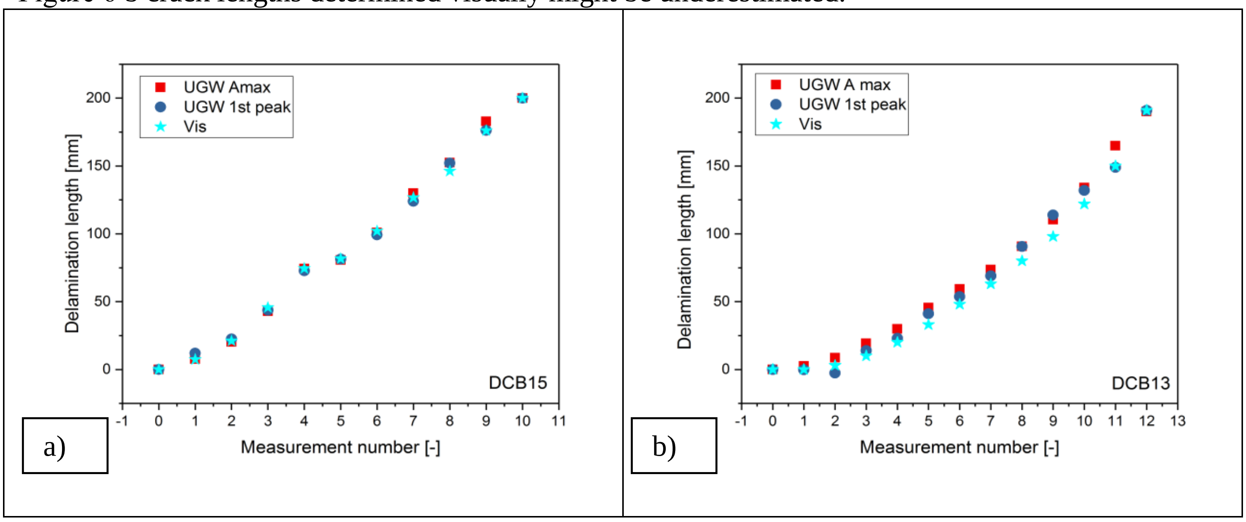

Figure 6 A comparison of visually based and UGW based delamination lengths for two specimens.

4. Discussion

The main concern of this paper was to exploit delayed Lamb wave time of flights during DCB test and calculate exact delamination lengths. Particular attention is paid to the suitable peak tracking. The following findings based on the experimental results can be stated.

- The suitable central frequency to actuate the A0 mode in the 3 mm thick specimen lies in the range of 40 - 60 kHz. Faster S0 mode is "hidden" in the crosstalk and A0 is therefore very well distinguished.

- The A0 mode propagates slower in the split part of the specimen and therefore time delays are recorded.
- If the crack tip approaches the sensor S2 (the split part of the specimen increases) probably another converted mode content amplifies and/or the same amount of actuated energy propagating in the longer part of the half thickness specimen (compared to the longer full thickness part) cause propagation of more peaks. In order to find out the exact reason numerical simulation would be useful to understand the propagation in this exact test.
- Based on the absolute mean percentage error of visually based and Lamb wave based measurements tracking the maximum amplitude peak showed better agreement. However, visual determination of delamination length might be underestimated. More accurate delamination lengths might lead to better agreement.

5. Conclusion

Based on the results it can be concluded that presented equation using time of flight and group velocity of Lamb wave A0 mode with the central frequency of 48 kHz can be used for determination of delamination length for DCB specimens. However, for the future study numerical methods would be beneficial and might help with the suitable frequency selection with respect to the peak tracking.

References

[1] Military handbook 1999 *USA, Handbook on Nondestructive evaluation system*
[2] Military Handbook 2012 *USA Composite Materials Handbook* Volume 3 Polymer Matrix Composites Materials Usage, Design, and Analysis
[3] Gholizadeh S 2016 A review of non-destructive testing methods of composite materials *Procedia Structural Integrity* 1 pp 50–57
[4] Kadlec M, Růžek R 2011 A Comparison of Laser Shearography and C-Scan for Assessing a Glass/Epoxy Laminate Impact Damage *Applied Composite Materials* 19(3-4) pp 393–407
[5] Rose J L 2014 *Ultrasonic guided waves in solid media* (New York: Cambridge Univ. Press)
[6] Michalcová L Růžek R 2016 Fatigue test of an integrally stiffened panel: Prediction and crack growth monitoring using acoustic emission. *Procedia Structural Integrity* 2 pp 3049–3056
[7] García I et al. 2015 Optical Fiber Sensors for Aircraft Structural Health Monitoring *Sensors* 15(7) pp 15494–15519
[8] Ruzek R et al. 2014 Strain and damage monitoring in CFRP fuselage panels using fiber Bragg grating sensors Part II: Mechanical testing and validation *Comp. Structures* 107 pp 737–744
[9] Cagáň J 2016 Hardware implementation of electrical resistance tomography for damage detection of carbon fibre–reinforced polymer composites *Structural Health Monitoring: An International Journal* 16(2) pp 129–141
[10] Giurgiutiu V 2016 *Structural health monitoring of aerospace composites* (London: Elsevier)
[11] Su Z Ye L & Lu Y 2006 Guided Lamb waves for identification of damage in composite structures: A review *Journal of Sound and Vibration* 295(3-5) pp 753–780
[12] Bonet M et al. 2015 Identification of Barely Visible Impact Damages on a Stiffened Composite Panel with a Probability-based Approach. *Structural Health Monitoring 2015*
[13] Salmanpour M S, Sharif Khodaei and Z Aliabadi M H 2017 Instantaneous Baseline Damage Localization Using Sensor Mapping *IEEE Sensors Journal* 17(2) pp 295–301
[14] Wang D et al. 2012 Monitoring of delamination onset and growth during Mode I and Mode II interlaminar fracture tests using guided waves *Composite Science and Tech.* 72pp 145–151
[15] Karpenko O Y et al. 2013 Lamb Wave Based Monitoring of Delamination Growth in Mode I and Mode II Fracture Tests. *Conf. Proceed. of the Society for Exper. Mech. Series* pp 33–43
[16] Ramadas C et al. 2012 Ultrasonic Lamb Wave Based Crack Growth Prediction for Estimation of Strain Energy Release Rate *Advanced Materials Research* 585 pp 24–28