Influence of Location and Thickness Variations on Guided Waves in Defective Carbon/Epoxy Plate

Noorfaten Asyikin Ibrahim, Bibi Intan Suraya Murat

Abstract**: *This paper addresses the effects of plate thickness and defect location on guided wave propagation in carbon/epoxy plates. A three-dimensional (3D) finite element model (FEM) of the plate was developed using MATLAB program codes, and simulated in Abaqus/Explicit. Referring to experimental ultrasonic C-scan images, the complex impact damage was modelled with irregular-shaped delamination and through-thickness matrix cracks. The simulated results show that a slower arrival time signal and amplitude drop of guided wave captured behind the defective region can be used as an indicator of the impact damage. A largOer scattering occurred when delamination was located closer to the plate surface. The extent of scattering gets larger, especially in the direction of 345^{o} from the excitation point. It is also observed that the impact damage can still be detected through a line scan method across the impact damage, although the wave attenuation is greater in a thicker composite plate. By investigating these factors independently, the trends of the scattered guided ultrasonic waves can be classified and perhaps will revolutionize a smart non-destructive method for composite structure in the future.***

Keywords**: *3D finite element, composite plate, guided ultrasonic waves, impact damage.***

I. INTRODUCTION

Guided ultrasonic waves (GUW) is an effective non-destructive testing (NDT) method for composite structural health monitoring [1], [2]. From a single sensor location, guided waves can propagate over a large composite structure with limited energy loss, which helps to reduce the inspection time and cost [3]. The reflection of the guided waves at defects enables the rapid detection of defects in large structures. However, the behaviour of the guided waves in composite structures is somewhat more complicated due to the inhomogeneous properties of composites. The propagation of GUW depends on many factors such as the excitation frequency, geometry of the structure, material properties, direction of propagation, and interlaminar conditions [2], [4]. A study in [5] has shown that an increase in elastic properties will increase the speed of the guided waves and an increase in material density would have the opposite effect. Results show in [6] describe that GUW attenuation is strongly related to the material properties, where greater inhomogeneity leads to a larger attenuation. These are some of the variations in the wave properties that could complicate the structural diagnosis of composite materials. The accuracy of these wave parameters is vital for sizing and localizing defects.

There have been several studies to investigate and understand the propagation behavior of GUW in composites, experimentally and numerically. By using numerical FEM, the prediction of GUW behaviour can be obtained quickly. Many researchers prefer 2D FEM as the model and simulation are less complex and easy to do [7], [8]. Limited publications were found for the analysis using 3D FEM models due to the large computational demand. However, several FE simulation tools have been used in a previous study and found that all of the tools are adequate to simulate the guided waves in composite laminate through 3D FEM [9]. Studies in [10], [11] show that 3D simulations can accurately predict the scattering characteristics of guided waves by using simple rectangular-shaped defects, where both FE and experimental results show comparable results. Using numerical simulations, it was found that the amplitudes around circular-shaped delamination showed a large forward scattered wave relative to the reflected pulse [12], [13]. Ng and Veidt [14] conducted an FE and experimental study of through-thickness delamination in the composite plate. The results show that the location of the delamination at different composite laminate presents a complicated scattering directivity pattern. Yang *et al.* [1] explained that the guided waves propagate higher at fiber direction. Thus, the accuracy of defect detection is higher when it is located in the fiber direction. After all, the listed studies were employing a single type of defect only. A complex damage mechanism for representing realistic impact damage makes accurate modelling employing full 3D analysis more challenging. In a recent study [15], it has been demonstrated that a 3D FE model with combined delamination and material degradation is the best model to represent the impact damage in composite plates. In order to model a good FE representation of composite plates with impact damage, microscopic images or experimental data such as length, width, and depth of the defects are needed. By using an X-ray microfocus computed tomography (microCT) machine, Leckey, Rogge and Raymond Parker [16]

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show that the real impact damage consists of multi-mode damages such as delamination and matrix cracks, and the damages seem to have occurred in each laminate but at different positions. Similarly, Tan, Falzon, Chiu and Price [17] presented the contour images of the low-velocity impact that shows matrix damage and delamination presence at each layup. Using X-ray imaging and ultrasonic immersion C-scan [18], the size and shape of delamination in a cross-ply carbon fiber plate with low-velocity impact damage has been approximately estimated.

In view of the above explanation, the composite plate models constructed in this study was developed with a combination of irregular-shaped delamination and through-thickness matrix cracks, by referring to the information obtained from these references [16]–[19]. An improvised damage model may provide an understanding of the GUW signal patterns more accurately, which ultimately may enable advances in the 3D modelling of complex impact damage in composites. Furthermore, this paper seeks to evaluate the detection sensitivity and the influence of plate thickness and defect locations in a defective cross-ply carbon /epoxy plate.

II. 3D FE MODELLING

The 3D carbon epoxy plate is created using the MATLAB program code. Then the simulation of GUW in carbon epoxy plate is run using ABAQUS/Explicit software. The size of the carbon epoxy is set to 500 mm x 500 mm x 2 mm, with an 8-layer arrangement of $[0/90]_{2s}$. The material properties is applied with unidirectional properties obtained from [20]. The excitation frequency of the A_0 wave mode is 100 kHz, which consists of 5 cycles sinusoidal tone burst modulated by Hanning window. An 8-node linear brick with reduced integration (C3D8R) is chosen with 1 mm^2 of the element size. Two types of monitoring points located at the mid-plane are used to capture the GUW signals: 200 mm line scan and 30 mm radius circular scan. In this study, the defective area was modeled based on the experimental works obtained from a previous study [18]. Referring to the frontal image of ultrasonic C-scan, as in Fig. 1, the defective region was approximated to look like a flipped T-shaped area, with a coverage area of 20 mm width and 40 mm in height. This one-layer delamination was positioned at the middle of the plate thickness.

Fig. 2 shows the illustration of the carbon/epoxy plate with the flipped T-shaped delamination. The location of excitation and monitoring points also shown in the figure. For a more realistic representation of impact damage, the combination of both delamination and matrix cracks are modeled together. The matrix cracks were introduced by applying a 75% reduction in stiffness properties at the defective area, through-thickness depth, as can be seen in Fig. 3.

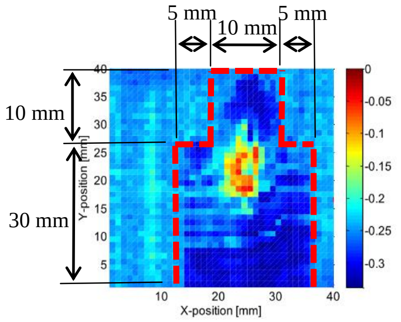

Fig. 1. Frontal image of ultrasonic C-scan; the approximation of the flipped T-shaped delamination represents by dotted red line [18].

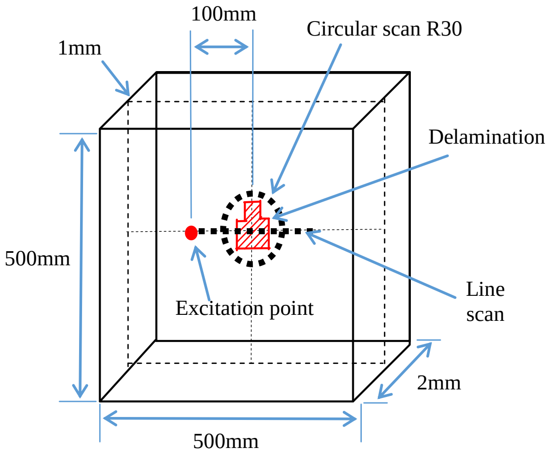

Fig. 2. Illustration of carbon/epoxy plate with flipped T-shaped delamination; excitation point located 100 mm from the center; 200 mm length of line scan; 30 mm radius of circular scan; all located at the mid-plane.

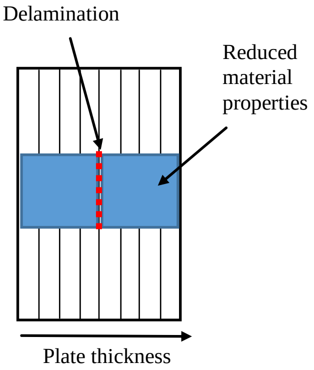

Fig. 3. Illustration of carbon/epoxy plate with through-thickness multi-mode defects.

III. DEFECT DETECTION FROM DIFFERENT MONITORING POINTS

In order to prevent any signal interferences, the monitoring points (MP) are all located 150 mm away from the boundary of the plate (Fig. 4). GUW signals measured at four MPs are shown in Fig. 5. At MP1, the incident wave pulse can be seen to match the prescribed excitation signal as a 5 cycle sinusoidal wave packet.

Comparing all four monitoring points, it can be observed that only MP1 has the highest incident waves, which is 90% higher than the incident waves arrived at MP2, MP3, and MP4. This amplitude reduction is due to the distribution of impact damage, which scatters GUW into many directions and causes higher energy loss. There are not many differences can be seen between signals from baseline and defective plates captured at all monitoring locations except at MP2. The incident wave at MP2 seems to arrive later than the baseline signal and this corresponds to a reduction in the wave velocity. This is consistent with the effect of reduction in material properties, where the material properties is directly proportional to the wave velocity. From an NDT view, the chosen monitoring points will have a big influence on the received signals and the defect will be detected if the monitoring points are placed before and after the defective area aligned in the same direction as the excitation point. It also demonstrates that the defect location based on the amplitude reduction and arrival time cannot be easily estimated.

IV. EFFECT OF DEPTH VARIATIONS

In this section, the influence of delamination depth is investigated. The location of the delamination through-thickness is varied from 1 mm, 0.75 mm, 0.50 mm to 0.25 mm. Three distinctive regions can be seen in Fig. 6, but no significant influence can be seen in the region before delamination. The amplitude on the delamination can be seen consistently higher at the exit of the defective region, approximately 50-60% higher than the baseline amplitudes. It is obvious that the delamination located at 0.25 mm depth has the highest impact on the GUW signal amplitudes, which contradict to what has been reported in [18] that the highest amplitude fluctuation is coming from singular rectangular-shaped delamination located in mid-plane. This finding could be attributed to the combined defects, where the irregular-shaped through-thickness defects have a bigger influence on the GUW scattering. Meanwhile, the amplitudes past the defective region for all case studies started to show different patterns and have a much bigger discrepancy compared to the baseline data. This is due to the local changes in the sub-plate thicknesses, which affects the GUW propagation to split and travel into two sub-plates above and below the delamination layer with different velocities. After travelling 40 mm behind the defective region, all GUW amplitudes started to behave exponentially as the baseline attenuated wave pattern, except for the GUW with delamination located at 0.50 mm. In NDT point of view, the detection of defect might not be successful if the signal amplitudes are used as the marker and the monitoring points were placed behind the defective regions. However, comparing to signals captured at MP2 (Fig. 5b), it is obvious that the arrival time of the signal from the defective plate is slower than the baseline signal. This is an important finding in NDT field, where these two results (Fig. 6 and Fig. 5) demonstrate that amplitude is not significant, but the arrival time is more capable in providing information about the presence of impact damage inside the composite plate.

Fig. 7 presents the angular pattern of the wave scattering around various delamination depths. One notable effect can be seen here: the forward amplitudes inclined to the direction between 30° and 330° counter-clockwise. This could be related to a larger geometry of the lower part of the defective region (30 mm bottom vs 10 mm top) that a causes higher number of transmitted waves out from this region. The scattering around delamination located at all depths shows very similar behaviour for all cases, except delamination located at 0.50 mm, which shows the least forward amplitudes. This is strictly related to the changing in the velocity of sub-plates upper and below delamination, where the velocity is reduced with the increasing fiber arrangement in 90° direction. From this study, the influence of depth variations has been clearly identified and could be used as a future reference for the development of the GUW method for NDE approach in composite structures.

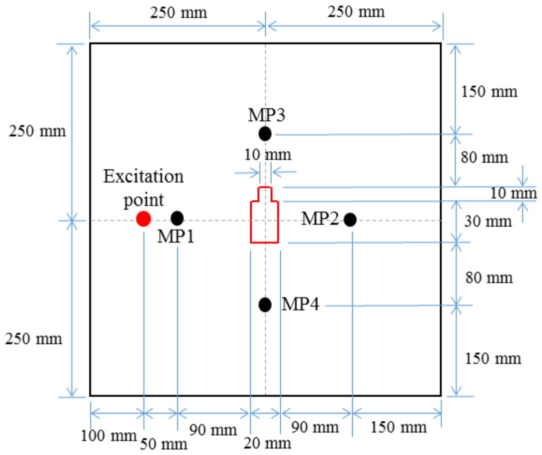

Fig. 4. Different locations of monitoring points at carbon epoxy/plate with irregular-shaped multimode defect.

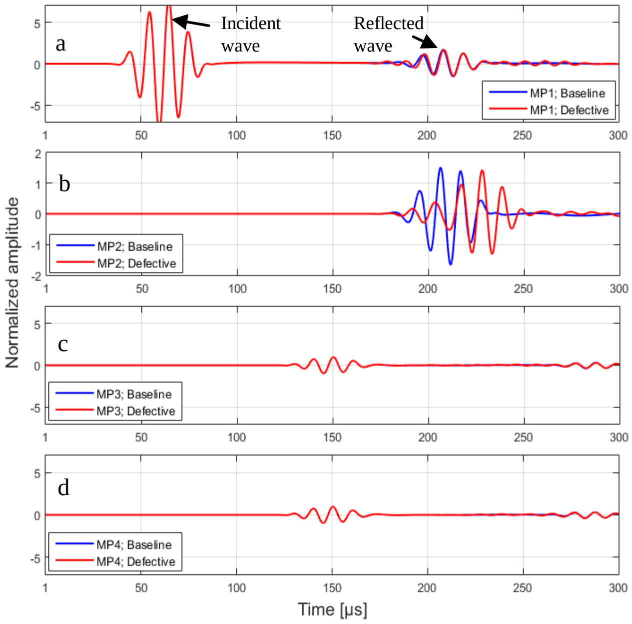

Fig. 5. Received guided wave signals from different monitoring points: a) MP1, b) MP2, c) MP3, d) MP4; comparison between baseline (plate without defect) and defective (plate with defect).

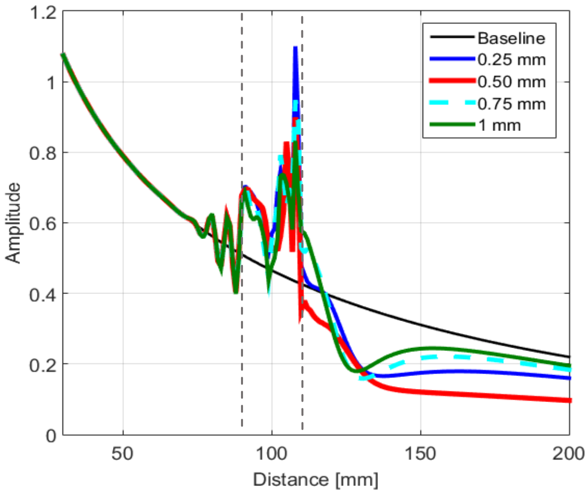

Fig. 6. Maxima amplitudes of guided wave signals across carbon/epoxy plates with different delamination depths.

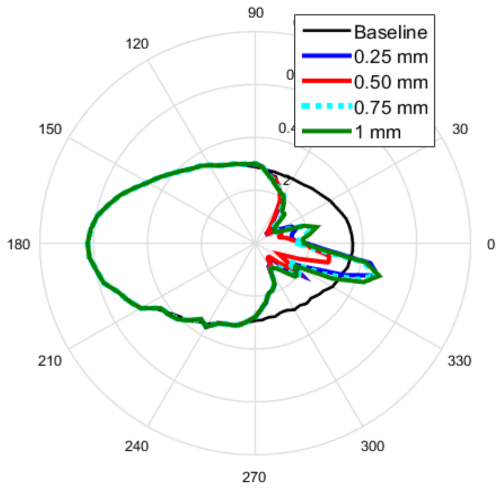

Fig. 7. Wave scattering around defect for carbon/epoxy plates with different delamination depths; measures every 5^{o} at 30 mm radius around defect.

V. EFFECT OF THICKNESS VARIATIONS

In this study, the defective FE models were varied with different thicknesses: 2 mm, 4 mm and 6 mm. It should be noted that the delamination is placed consistently at mid-plane, and the cracks are located throughout the thickness direction. This study is important in order to investigate the capability of the GUW method in detecting defects that lie beneath in thick composite structures such as in the oil pipeline and wings of an airplane. Referring to the line scan results in Fig. 8, the 2 mm plate thickness shows the highest wave amplitude while the 6 mm plate thickness shows the lowest. The same observation can also be seen in Fig. 9. This is as expected since a thicker material would have much higher material damping and higher energy absorption, resulting in low wave intensity. A similar report on this behavior, but, on a non-defective composite model is reported here [21]. From this study, one interesting signal characteristic can be observed. Although the thicker plate increased the wave attenuation, the wave scattering by defects can still be observed quite clearly from both line (Fig. 8) and circular scans (Fig. 9). The amplitudes fluctuate around 5 to 10% from their attenuating wave, and the distance of the fluctuation area reasonably matched the 20 mm width of the defects. It can also be seen here that the amplitude drop past defective region is not significant, which makes an NDT detection method using this signal marker quite impossible in a thicker plate. However, one thing could be done to improve the detection or amplify the signal intensity: by lowering the excitation frequency, so the attenuation loss due to the frequency is less.

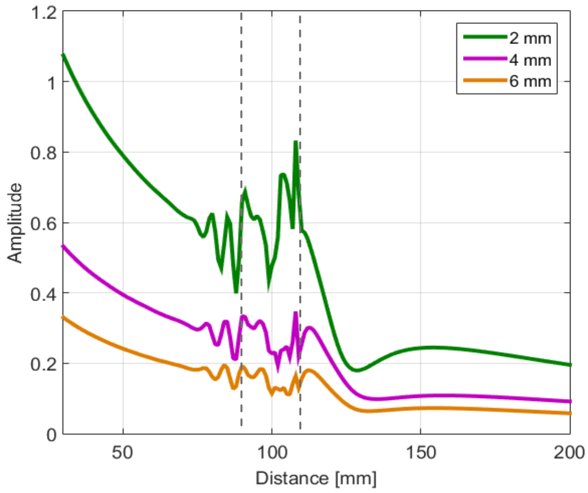

Fig. 8. Maxima amplitude signal across carbon/epoxy plates with multi-mode defects; different plate thicknesses.

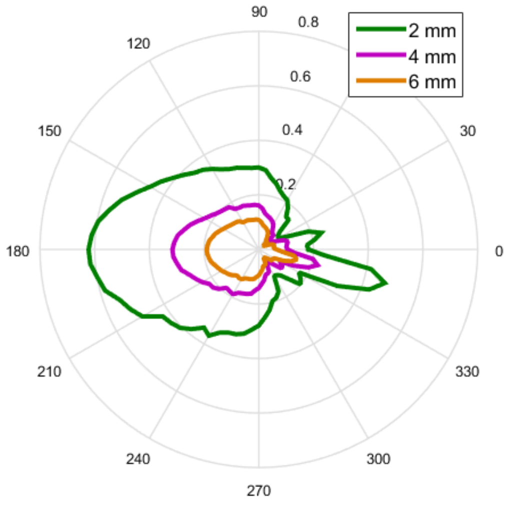

Fig. 9. Wave scattering around multi-mode defects in carbon/epoxy plates with different thicknesses; measured every 5^{o} at 30 mm radius around defect.

VI. CONCLUSION

This study presents the influence of variations in locations and plate thicknesses on the GUW propagation in composite plates with impact damage via 3D FEM simulations. In the first part of the study, it has been demonstrated that the single detection at monitoring points placed outside the damaged region could not easily classify or characterize the impact damage clearly. However, the slower arrival time of GUW signals captured behind the delamination might be useful for the defect detection, as it can be used to estimate any velocity changes. It is also demonstrated here that the through-thickness irregular-shaped defects have a quite big influence in the amplitude profiles, in which the shape can cause the wave to scatter into certain directions. Meanwhile, the delamination depth has shown a small influence on the signal profiles. Higher amplitudes fluctuation can be observed when delamination is located closer to the plate surface. In the final part of this study, the results show that although the thicker plate increased the wave attenuation, the wave scattering by defects can still be observed clearly. The defects can still be detected by the obvious pattern of high amplitude fluctuation within the defective region.

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