THE INFLUENCE OF TRANSDUCER FREQUENCY ON ULTRASONIC PITCH-CATCH MEASUREMENT OF TWO-LAYER FIBER REINFORCED PLASTIC

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Keywords: Non-destructive testing, ultrasonic testing, pitch-catch measurement

ABSTRACT

Effective non-destructive testing to evaluate chemical tank made of fiber reinforced plastic is necessary, and ultrasonic testing is one of the promising methods. This research aims to investigate the influence of ultrasonic waves frequency on the thickness measurement result of FRP specimens. Testing using transducers with frequencies of 1 MHz and 2.25 MHz was performed on several specimens prepared using different resins and fibers. Frequency of 2.25 MHz provided results with a better resolution and higher accuracy, however, the attenuation of sound wave during its propagation in FRP medium resulted in returning sound waves with low amplitude, which caused difficulty in the wave reading and contributed to the measurement error. On the other hand, measurement using a lower frequency (1 MHz) resulted in a reflected sound wave with higher amplitude, which is easier to analyze, despite its lower accuracy. The measurement of FRP specimens using both 1 MHz and 2.25 MHz transducers resulted in a comparable accuracy, and improvement in the accuracy of the measurement is still required. Moreover, calculation of two-layer specimens thickness showed comparable results to those of one-layers specimens, and it shows the possibility of using the method for two-layer specimens.

1 INTRODUCTION

Fiber reinforced plastic (FRP) is commonly utilized as construction material for chemical storage tanks due to its mechanical strength and resistance against corrosive environments. However, application in highly severe environments for prolonged period will result in diffusion of water and chemicals into the resin matrix, which lead to the degradation of the resin matrix such as via hydrolysis and eventually leads to deterioration of material's strength. It is therefore necessary to conduct periodic inspection on the FRP tanks to ensure the safe operation of the equipment. Since the tanks are expected to be continuously used for their expected lifetime, a reliable non-destructive testing (NDT) method is necessary for the inspection.

One of the available techniques to perform NDT on FRP tanks is ultrasonic testing (UT) [1]. UT has been widely used for periodic inspection of metal tanks, however, more studies are necessary to extend the application of this technique to FRP tanks. Even though UT has already been used to detect defects such as cracks, delamination, voids, and foreign objects in composite materials [2, 3], so far there is no application of UT to measure the deterioration of FRP materials. The main deterioration modes of FRP are chemical diffusion and degradation of resin matrix, in which as the degradation progresses, a corrosion layer is formed in the material while the total thickness remains almost unchanged. The assessment of the deterioration degree of FRP tanks thus needs to be done by measuring the thickness of the remaining pristine layer, which cannot be done using conventional UT pulse-echo method. The measurement is further complicated by wide variation of velocity value at which sound waves propagate through FRP material, which is influenced by various factors such as resin curing degree and the presence of fibers. To address these problems, simultaneous measurement of material thickness and sound velocity in FRP is necessary.

Our research group showed the possibility to simultaneously measure material thickness and sound velocity in a medium using combination of UT pulse-echo and pitch-catch method for neat resin and degraded resin [4]. Even though theoretically the method can be applied for FRP materials as well, the presence of fibers in FRP can cause scattering and attenuation of sound waves, which can complicate the measurement. The degree of those effects varies on the frequency of the ultrasound used, therefore, this research aims to elucidate the influence of the transducer frequency on the UT measurement result of FRP material. Furthermore, to know whether the influence also applies to degraded FRP, measurement of two-layer FRP as a degraded FRP model was performed.

2 EXPERIMENTAL

FRP specimens were prepared from epoxy (EP) and unsaturated polyester (UP) resin as matrices and chopped mat (CM) and roving woven (RW) fibers as reinforced fibers. For comparison, neat epoxy resins were also prepared. As the model for degraded FRP, specimens made of two layers, the first layer containing CM and the second layer containing RW were prepared. The specimens were prepared in two thickness: 3 mm and 10 mm (Figure 1). In addition to FRPs specimens above, two pieces of two-layer specimens made of neat epoxy and graphene reinforced epoxy nanocomposites were prepared to imitate corroded chemical tank that has two layers of pristine layer and corroded layer. The difference between these two specimens is in the thickness of layers. In the text, the specimens are referred to as code listed in Table 1.

Sample	Code
One-layer specimens	
Neat epoxy	EP
Epoxy with chopped mat fibers	EP+M
Unsaturated polyester with chopped mat fibers	UP+M
Two-layer specimens	
Epoxy with chopped mat and epoxy with roving woven fibers	EP+M+R
Unsaturated polyester with chopped mat and unsaturated polyester with roving woven fibers	UP+M+R
Neat epoxy and graphene reinforced epoxy nanocomposites No. 1	EP+G1
Neat epoxy and graphene reinforced epoxy nanocomposites No. 1	EP+G2

Table 1. Code of specimens used in this investigation

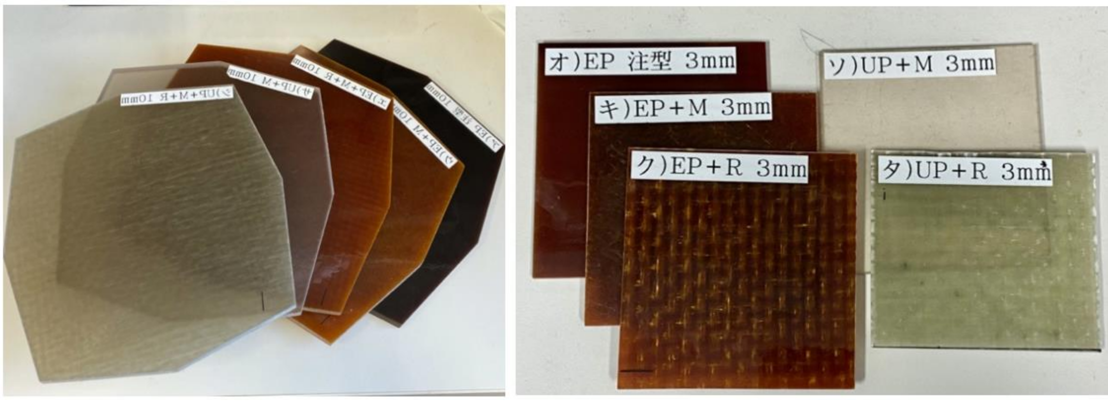

Figure 1: Specimens used in this study: 10 mm specimens (left), 3 mm specimens (right)

To study the influence of transducer frequency, measurements using two frequencies, 1 MHz and 2.25 MHz were conducted. The measurements were conducted using pulse-echo and pitch-catch methods. Thickness calculation was done using equations for one-layer and two-layer models as derived in previous work as follows [2].

For one-layer model (Figure 2):

1. Pulse-echo measurement:

$$T_{pe} = \frac{2L}{c} \tag{1}$$

where T_{pe} is time-of-flight for pulse-echo measurement, L is the thickness of material, and c is the sound velocity in the medium.

2. Pitch-catch measurement:

$$T_{pc} = \frac{2\sqrt{L^2 + X^2}}{c} \tag{2}$$

where the T_{pc} is time-of-flight for pitch-catch measurement and X is the distance between probes (other variables are the same as equation (1)). Equation (2) can be applied for several measurements with different values of X to obtain multiple equations and develop an equation system. By having the number of equations equal or more than the number of unknown variables in the equation system, the unknown variables can be calculated.

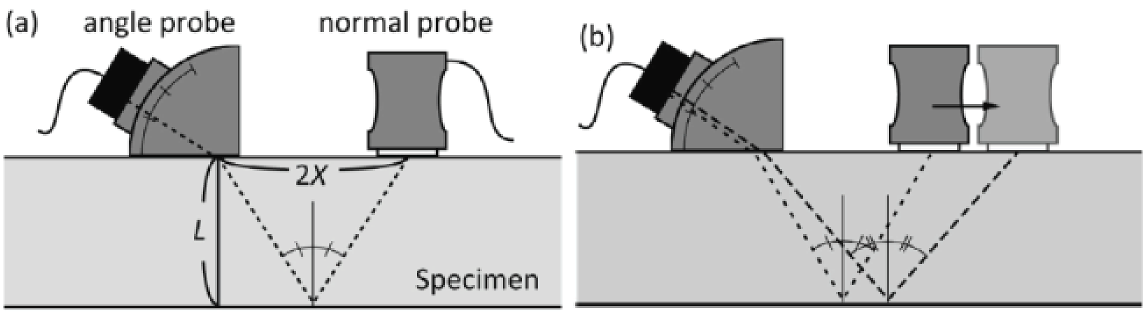

Figure 2. Measurement using pulse-echo (left) and pitch-catch (right) methods for one-layer model

For two-layer model (Figure 3):

1. Pulse-echo measurement:

$$T_{pe} = \frac{2l_1}{c_1} + \frac{2l_2}{c_2} \tag{3}$$

where T_{pe} is time-of-flight for pulse-echo measurement, c_1 is the sound velocity in the layer 1, c_2 is the sound velocity in the layer 2, l_1 is thickness of layer 1, and l_2 is thickness of layer 2.

2. Pitch-catch measurement:

$$X = x_1 + x_2 \tag{4}$$

$$T_{pc} = \frac{2\sqrt{l_1^2 + x_1^2}}{c_1} + \frac{2\sqrt{l_2^2 + x_2^2}}{c_2} \tag{5}$$

where X is the distance between probes and T_{pc} is time-of-flight for pitch-catch measurement (other variables are the same as equation (3)). The variables x_1 and x_2 are as shown in Figure 3. Similar to one-layer model, equation (4) and (5) can be applied for several measurements with different values of X to obtain multiple equations and develop an equation system.

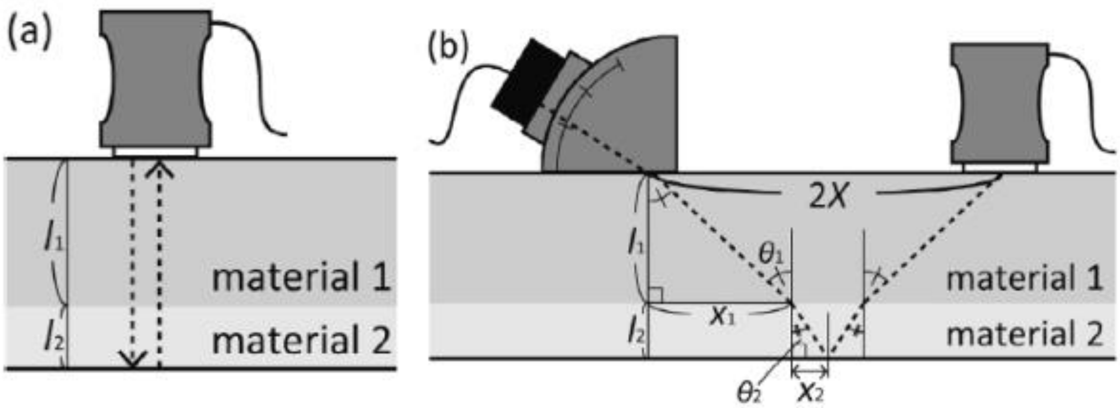

Figure 3. Measurement using pulse-echo (left) and pitch-catch (right) methods for two-layer model

3 RESULTS AND DISCUSSION

3.1 Measurement using Pulse-Echo Method

The UT measurement results using 1 MHz transducer are shown in Figure 4. The position where the sound wave entered the specimen is marked red, while the back-wall echo is marked blue. The back-wall echo can be identified easily on all the specimens, however, for the case of specimens containing roving woven fibers (two-layer specimens), the back-wall echo almost overlapped with other waves. These waves might come from the reflection of soundwave in the interface between the first and the second layer. The second layer contains roving woven fibers which is denser than chop mat fibers, therefore, the sound impedance between the two layers is significant and resulting in partial reflection of the soundwave.

A similar phenomenon can also be observed in the results of measurement using 2.25 MHz transducer (Figure 5). For the specimens containing roving woven fibers (two-layer specimens), the back-wall echoes are almost indistinguishable, because they overlapped with reflective waves from the interface between the two layers (layer containing chop mat fibers and layer containing roving woven fibers). For the case of 2.25 MHz transducer, the amplitude of the back-wall echoes is smaller, which can be easily covered by other overlapped waves and thus reduced the observability.

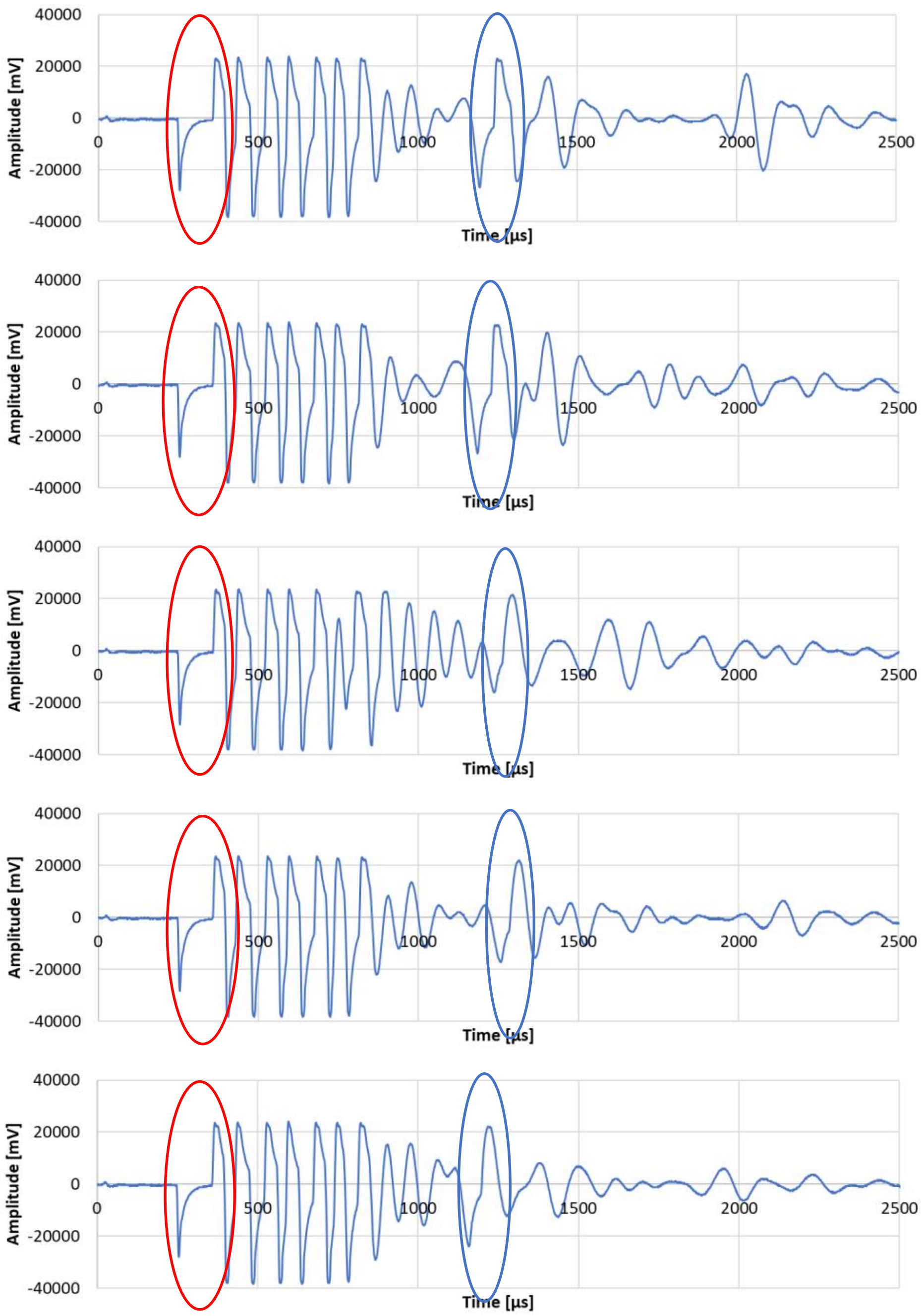

Figure 4. The UT observation result of the 10 mm specimens using 1 MHz probe. From top to bottom: EP, EP+M, EP+M+R, UP+M, UP+M+R. The point where the sound wave enters the specimen is marked red, while the back-wall echo is marked blue.

The reason for the low amplitude of back-wall echo of soundwave with a frequency of 2.25 MHz is because soundwaves with higher frequency are more susceptible to attenuation. However, despite this drawback, the usage of high frequency ultrasonic is desirable, Soundwave with a higher frequency has a shorter wavelength, which will provide a sharper wave that can lead to a more accurate measurement. This can be observed by comparing the results in Figure 4 and 5, in which the soundwaves in Figure 5 showed a sharper wave (sharper peak and valley) compared to those in Figure 4. This will lead to a higher reading accuracy for Figure 5 compared to Figure 4.

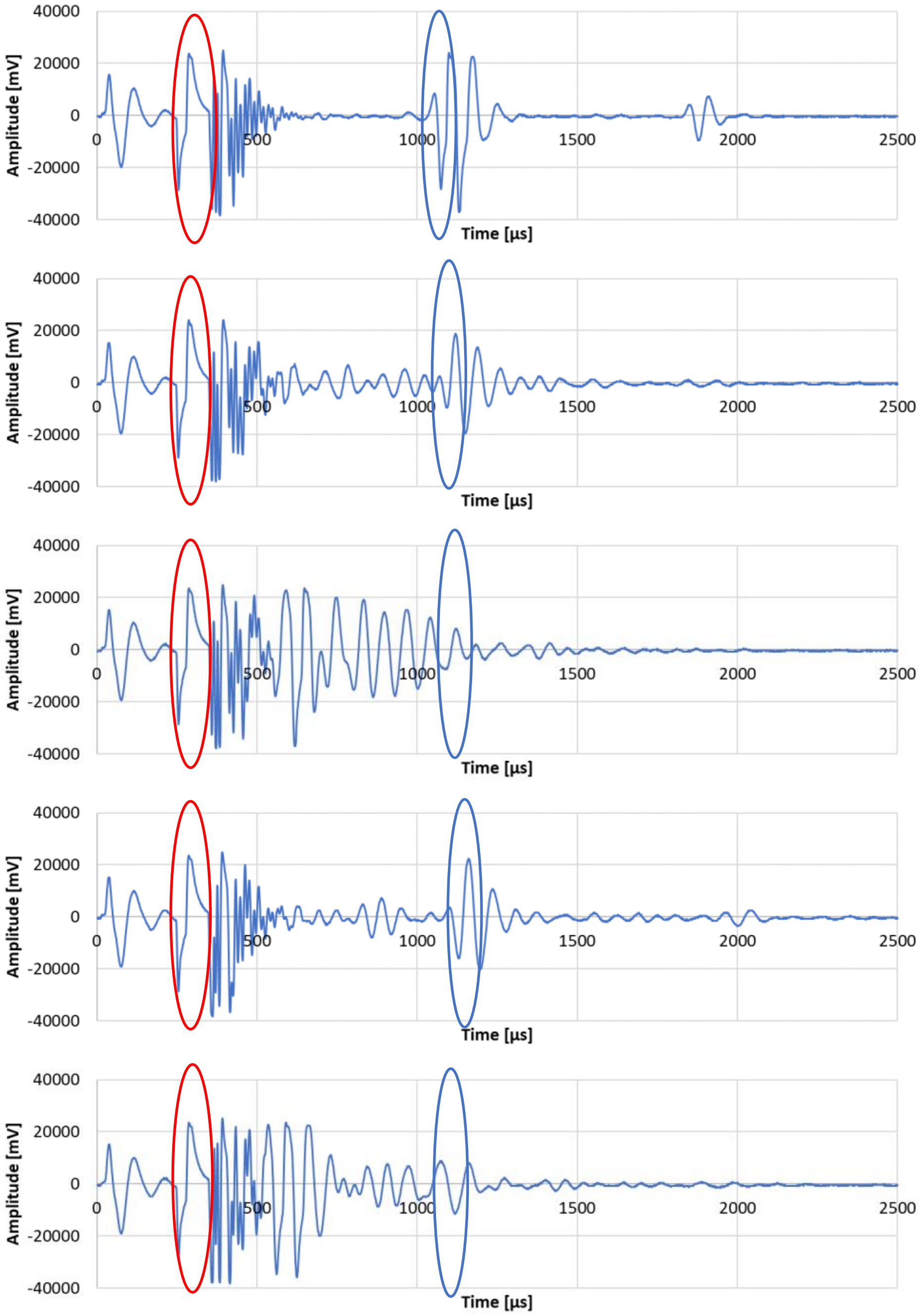

Figure 5. The UT observation result of the 10 mm specimens using 2.25 MHz probe. From top to bottom: EP, EP+M, EP+M+R, UP+M, UP+M+R. The point where the sound wave enters the specimen is marked red, while the back-wall echo is marked blue.

Since the thicknesses of the specimens are known, for the case of one-layer specimens, the sound velocity can be calculated using equation (1) by using the time-of-flight value obtained from Figure 4 and 5. The calculation results are shown in Table 2. It can be observed that for the case of specimens prepared from the same resin (EP and EP+M), the sound velocity does not vary much. This suggests that the existence of fibers does not significantly influence the sound velocity. The measurement using different frequency resulted in a different value, and the difference might have originated from the difference in accuracy of measurement (higher frequency has higher accuracy).

Sample		EP	EP+M	UP+M
Sound Velocity	1 MHz	2280	2317	2216
	2.25 MHz	2451	2475	2346

Table 2. Calculated sound velocity of the specimens (m/s)

3.2 Measurement using Combination of Pulse-Echo and Pitch-Catch Methods

As explained in the experimental section, the combination of Pulse-Echo and Pitch-Catch methods can be used to measure the sound velocity and specimen thickness simultaneously. The results of calculation are shown in Table 3 for 3 mm specimens and Table 4 for 10 mm specimens. For the measurement, the value of probe separation (X) were 25mm, 30mm, and 35mm for 1 MHz transducer and 20mm, 25mm, and 30mm for 2.25 MHz transducer, respectively.

Sample	Actual Thickness (mm)	1 MHz			2.25 MHz		
		Sound velocity (m/s)	Calculated Thickness (mm)	Error (%)	Sound velocity (m/s)	Calculated Thickness (mm)	Error (%)
EP	3.28	2860	3.94	20.22	2747	4.04	23.27
EP+M	3.25	2717	5.05	55.41	2601	5.08	56.31
UP+M	2.96	2511	3.85	29.95	2620	3.38	14.08

Table 3. Calculation result for 3 mm specimens

Sample	Actual Thickness (mm)	1 MHz			2.25 MHz		
		Sound velocity (m/s)	Calculated Thickness (mm)	Error (%)	Sound velocity (m/s)	Calculated Thickness (mm)	Error (%)
EP	9.51	2537	8.95	5.89	2566	9.45	0.63
EP+M	10.11	2577	9.95	1.58	2403	10.63	5.18
UP+M	10.03	2179	11.37	13.33	1879	8.63	13.92

Table 4. Calculation result for 10 mm specimens

For all the cases, both 1 MHz and 2.25 MHz transducers showed comparable results. However, the errors for 3 mm specimens generally are higher than those of 10 mm specimens. These high errors mainly come from the difficulty in determining the position of back-wall echo. For thinner specimens, the possibility of the back-wall echo overlapping with other waves, such as the waves reflected by the interface between resin and chop mat fibers, are higher.

In general, the errors of measurement using the frequencies of 1 MHz and 2.25 MHz originated from the influence of wavelength and amplitude of the back-wall echo. For the case of 1 MHz frequency, the back-wall echo has a relatively high amplitude, however, the longer wavelength contributed to the lower resolution of the wave and the lower accuracy of measurement. On the other hand, a frequency of 2.25

MHz produces a back-wall echo with smaller wavelength and higher resolution, however, its lower amplitude resulted in the difficulty of determining the position, especially when the wave overlaps with other waves.

3.2 Experiment using Two-Layer Specimens

The specimens used in the measurement for two layers measurement were EP+M+R, UP+M+R, EP+G1, and EP+G2). Similarly, 1 MHz and 2.25 MHz transducers were used to investigate the effect of frequency on the measurement.

Sample	Actual Thickness (mm)	1 MHz			2.25 MHz		
		Sound velocity (m/s)	Calculated Thickness (mm)	Error (%)	Sound velocity (m/s)	Calculated Thickness (mm)	Error (%)
EP+M+R	l_1: 5.90 l_2: 4.30	c_1: 2387 c_2: 2017	l_1: 5.95 l_2: 2.48	0.85 42.33	c_1: 2136 c_2: 1584	l_1: 6.01 l_2: 2.94	1.86 31.63
UP+M+R	l_1: 6.10 l_2: 3.50	c_1: 2930 c_2: 1997	l_1: 6.31 l_2: 4.27	3.44 22.00	c_1: 2440 c_2: 2011	l_1: 5.44 l_2: 2.46	10.82 29.71
EP+G1	l_1: 2.00 l_2: 1.70	c_1: 1768 c_2: 1035	l_1: 2.06 l_2: 1.84	3.00 6.36	c_1: 1616 c_2: 1032	l_1: 2.28 l_2: 1.72	14.00 0.58
EP+G2	l_1: 3.90 l_2: 1.90	c_1: 1825 c_2: 1084	l_1: 3.88 l_2: 1.99	0.26 4.19	c_1: 1152 c_2: 746	l_1: 3.61 l_2: 1.60	7.20 15.98

Table 5. Calculation result for two-layer specimens

The results show that despite a more complex computation, calculation results for two-layer specimens showed a comparable accuracy to those of one-layer specimens, especially for EP+G1 and EP+G2 specimens. The higher errors shown by EP+M+R and UP+M+R are thought to be influenced by the presence of roving woven fibers, which cause more reflection on soundwave inside a layer and introduce difficulty in reading the back-wall echo. For the case of EP+G1 and EP+G2, because the specimens consist of epoxy and nanocomposite, the specimens can be said to be almost uniform in each layer and thus there were small number of reflections of soundwave inside a layer. This assumption is supported by the high error shown by the calculation result of layers containing roving woven fibers, which indicates that the fibers contributed to the error in measurement.

4 CONCLUSION

The influence of ultrasonic waves frequency on the thickness measurement result of FRP specimens was studied. Frequency of 2.25 MHz provided results with a better resolution and higher accuracy, however, the attenuation of sound wave during its propagation in FRP medium resulted in back-wall echo with low amplitude, which caused difficulty in the wave reading and contributed to the measurement error. On the other hand, measurement using a lower frequency (1 MHz) resulted in a back-wall echo with higher amplitude, which is easier to analyze, despite its lower accuracy. The measurement of FRP specimens using both the frequencies of 1 MHz and 2.25 MHz resulted in comparable accuracy. Moreover, calculation of two-layer specimens thickness showed comparable results to those of one-layers specimens, which supports the possibility of using the method for two-layer specimens. The errors for the two-layer specimens' calculation also originated from the presence of roving woven fibers.

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