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Damage monitoring of CFRP plate using self-sensing TDR method*

Hiroumi Kurokawa*[1] Akira Todoroki*[2] and Yoshihiro Mizutani*[3]

*[1]Graduate student of Tokyo Institute of Technology

*[2] Department of Mechanical Sciences and Engineering

Tokyo Institute of Technology

2-12-1 Ookayama, Meguro, Tokyo 1528552, Japan

E-mail:atodorok@ginza.mes.titech.ac.jp

*[3] Department of Mechanical Sciences and Engineering

Tokyo Institute of Technology

Abstract

Laminated CFRP structures are applied to many aerospace structures. Although CFRP laminates have high specific strength and specific stiffness, an impact load easily creates damage such as delamination cracking, matrix cracking, and fiber breakage. Damage to laminated CFRP is usually difficult to detect by visual inspection. As a result, damage monitoring systems are required for large laminated CFRP structures. Many researchers have already proposed self-sensing monitoring systems which measure electrical resistance changes in the laminated CFRP. This method, however, requires a lot of electrodes. In the present study, a new time domain reflectometry (TDR) method using an electrical pulse signal and reinforcement carbon fiber sensors is adopted as a monitoring method. The method is applied to a 2-m long CFRP strip plate specimen to detect an ideal damage mechanical notch using a reflected pulse signal. In addition, the effect of the orthotropic conductance of the CFRP plate is experimentally investigated using multiple electrodes, and is shown to be negligible.

Key words: Composite Material, Smart Material, Damage Evaluation, Nondestructive Inspection

1. Introduction

Carbon Fiber Reinforced Polymer (CFRP) laminated composites have been widely adopted as primary structures for recent aircraft structural components. CFRP structures, however, have weak interlaminar strength and low velocity impact loads easily damage them as a result. Such damage causes degradation of compression strength. The Boeing 787 aircraft adopts highly toughened CFRP laminates that have thermo-plastic particles in the interlayer. The method is not perfect, and thus results in requirement of a CFRP structure damage monitoring system.

In the present study, a new self-sensing time domain reflectometry (self-sensing TDR) method is proposed in which reinforcement carbon fibers are adopted as sensors for damage monitoring of large CFRP structures. TDR is usually used to detect damaged points in a transmission line such as a coaxial cable using a pulse signal transmission: a pulse signal is sent in the transmission line and the reflected pulse signal is measured to obtain the locations of cable damage. Chen et al. used a TDR method to detect cracks in concrete structures by embedding a coaxial cable in the concrete [(1)]. Lin et al. proposed a new method to measure applied strain using TDR with a coaxial cable [(2)]. Okuhara et al. have

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applied TDR to detect damage in glass composites using a carbon fiber bundle as a sensor [(3)]. Obaid et al. have used a TDR method to measure delamination crack length using a cable attached to the specimen surface [(4)].

The present study uses the electrical conductivity of carbon fibers to build a transmission line of electromagnetic pulse waves on the CFRP structure to which the TDR method is then applied. Because the reinforcement carbon fibers are used as the transmission line, the method is herein called “self-sensing TDR”. Although ultrasonic testing methods or X-ray testing methods are applicable to CFRP structures, these require a long time to scan large aircraft structures. In contrast, TDR is able to inspect long structures within short time periods. Compared with previous research on the damage monitoring of CFRP plates using electrical resistance changes [(5)], the present TRD method significantly reduces the number of electrodes required. The conventional electrical resistance change method requires electrode spacing of approximately 30 mm, while the TDR method only requires 2 m spacing, removing approximately 70 electrodes (about 1/67). Optimization of the electric pulse wave attenuation enables us to detect the pulse wave reflected from the damage using a wider spacing of electrodes.

For actual thick CFRP laminated structures made from toughened CFRP plies, a large impact load is applied to the laminated CFRP surface to create damage. This usually creates a dent and fiber micro-buckling at the same time, breaking carbon fibers in that region. The present self-sensing TDR method is therefore used to detect such fiber breakages to identify damage to a 2-m-long CFRP plate structure. A transmission line is constructed using the CFRP plate and an aluminum plate. The detection performance of the TDR method is evaluated by experimental investigation in the fiber and transverse directions.

2. Principle of TDR method

TDR uses a pulse signal in a transmission line, the reflected pulse signal from which is measured and plotted as a graph in which the abscissa is time and the ordinate is the voltage. TDR requires a wave generator, an oscilloscope, and a target cable, as shown in Fig. 1. The wave generator produces a pulse wave signal and sends it to the directional coupler, which allows the signal to propagate only into the target cable. Part of the signal is reflected at the input end of the cable due to the slight difference in characteristic impedance. The rest of the signal propagates in the target cable and is divided into a reflection and transmission at the damaged point. The reflected signal returns and is measured at the oscilloscope. The time difference between the input signal and reflected signal indicates the distance to the damaged point after it is multiplied by the speed. As a result, the existence of damage and its location can be determined. The distance L from the input end to the damage is calculated using the following equation [(6)].

$$L = \frac{V_p \Delta T}{2} \qquad (1)$$

where V_p is the transmission velocity and ΔT is the time difference between the input signal and the reflected signal. V_p is slightly slower than the velocity of light, approximately $0.6c$ to $0.9c$, due to the effect of the transmission line. In the present study, the cable is replaced by the CFRP plate.

When the cable is simply replaced by a CFRP plate, the characteristic impedance of CFRP plate is quite different from that of the coaxial cable used to connect the wave generator and oscilloscope. This causes perfect reflection at the input end of the CFRP plate, and the pulse signal does not propagate through the CFRP plate. An impedance matching process is therefore indispensable to achieve the TDR of CFRP plate. The effect of the anisotropic conductance of the CFRP plate is also unclear and is thus experimentally investigated in the present study.

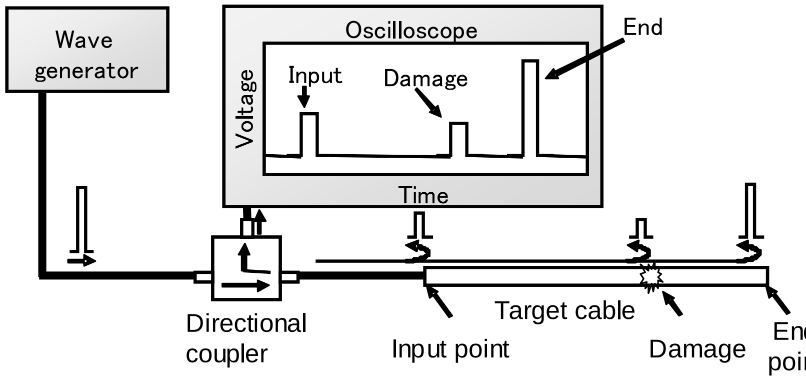


Fig. 1 Schematic illustrating the principle of the TDR method.

3. Specimens and test procedures

3.1 Fabrication of CFRP specimens

Mitsubishi Rayon PYROFIL MR380 prepreg was used to fabricate a CFRP plate with stacking sequence $[0_4]_T$, a length of 1980 mm, and width of 120 mm. Silicone rubber sheet type electrical heaters were used to cure the CFRP plate. The specimen was then sandwiched by aluminum plates, and glass fiber heat insulating material was used to keep the specimen at 130 °C for two hours.

The experimental configurations of the fabricated CFRP plates are shown in Fig. 2. Half of the specimen was cured and the rest of the specimen was left uncured to prevent a large curing cost. Before testing, it was confirmed that there was no difference of transmission velocity between the prepreg and cured CFRP plate. Therefore, prepreg sheet is used here to perform experiments without causing damage. In the present study, half of the plate was cured to prevent deformation of the resin when fiber breakage is caused. An electrode was created at the end of the CFRP plate using a copper plating method (7).

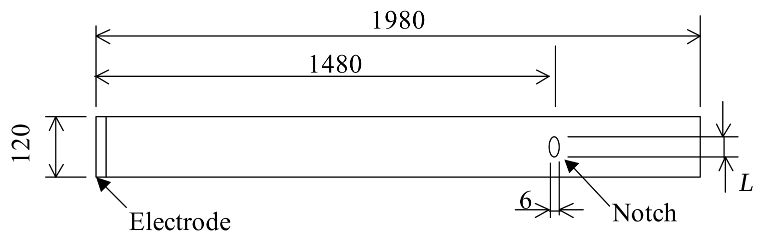


Fig. 2 Type A specimen configuration.

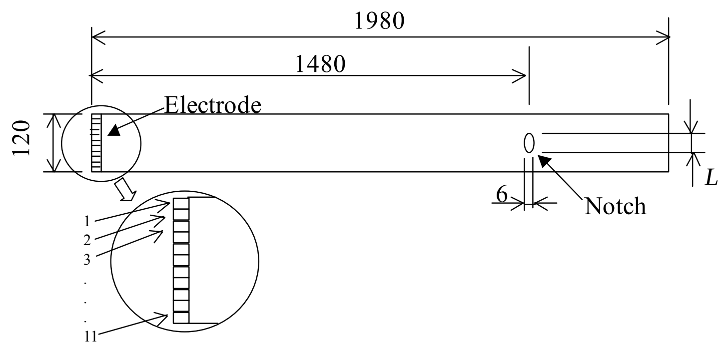


Fig. 3 Type B specimen configuration.

The type A specimen (Fig. 2) had a large electrode on the left end, prepared by copper plating a 10 mm length. Pulse signals were sent through the entire width of the type A specimen. A 6-mm-wide mechanical notch was made at the middle of the plate at a point 1480 mm in distance from the electrode. Eight notch lengths (L) were prepared: L = 6, 18, 30, 42, 54, 66, 78, and 120 (entire width of the specimen) mm, to determine the length limit of detection of the present TDR method.

The type B specimen (Fig. 3) was prepared to investigate the effect of anisotropic conductance in unidirectional CFRP. The electrode was divided into eleven parts as shown in Fig. 3. Each small electrode was individually electrically insulated using polymer tape. A notch 42 mm long was made 1480 mm from the electrode. The CFRP had a low electric conductance in the transverse direction: the ratio of the electric conductance in the transverse direction to that of the fiber direction (σ_{90}/σ_0) was approximately 0.03 [8]. If the pulse signal was found to propagate in the transverse direction in spite of the anisotropic electric conductance it would mean that anisotropic conductance does not affect the transmission of the pulse signal in the present method. If the pulse signal propagated in the longitudinal direction and not in the transverse direction, it would mean that the present TDR method is able to detect the location of transverse damage through use of the small divided electrodes.

3.2 Experimental equipments

The experimental setup is shown in Fig. 1. A function generator (1ch, Maximum 240 MHz, AFG3251, Tektronix) was used as a pulse generator to produce a rectangular pulse signal which was then divided by a power splitter (wide band, low loss 0.25 dB, ZAPD-21, Mini-Circuits). One of the divided pulse signals was input to the CFRP plate through a directional coupler (ZFDC-10-5, Mini-Circuits). The other pulse signal was measured using Ch#1 of the digital oscilloscope (TDS5034B, Tektronix). The directional coupler passed only the reflected pulse signal from the CFRP specimen, and the reflected pulse signal was measured using Ch#2 of the digital oscilloscope. The voltage of the rectangular pulse signal was 1 V, and the half-band width of the signal was 4 ns. The sampling frequency of the digital oscilloscope was 0.01 ns.

3.3 Impedance matching

The frequency of the rectangular pulse signal used in the present study was approximately 200 MHz, a wavelength of approximately 1.5 m. In general, when the length of an electric conductor is longer than 1 % of the wavelength, the conductor is considered to be a transmission line comprised of two electric conductors. When the characteristic impedance of the CFRP plate is quite different from that of the coaxial cable, the input pulse signal is perfectly reflected at the input end of the CFRP. The characteristic impedance of the coaxial cable used was 50 Ω. Impedance matching, therefore, had to be considered first.

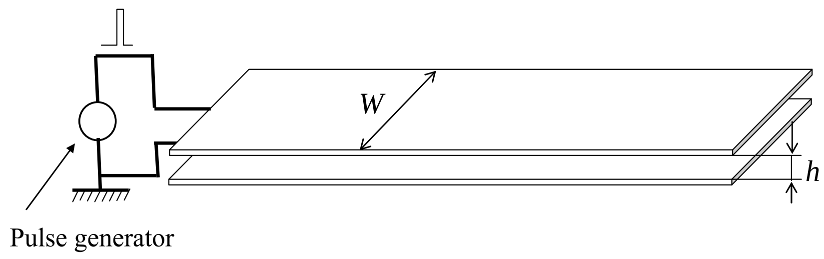


Fig. 4 Parallel strip model.

To obtain the characteristic impedance of the CFRP plate, a parallel-plate-transmission-line model was considered, as shown in Fig. 4. The characteristic impedance of the parallel plate model was obtained as follows [9].

$$Z_0 = \frac{h}{W}\sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}} \quad (2)$$

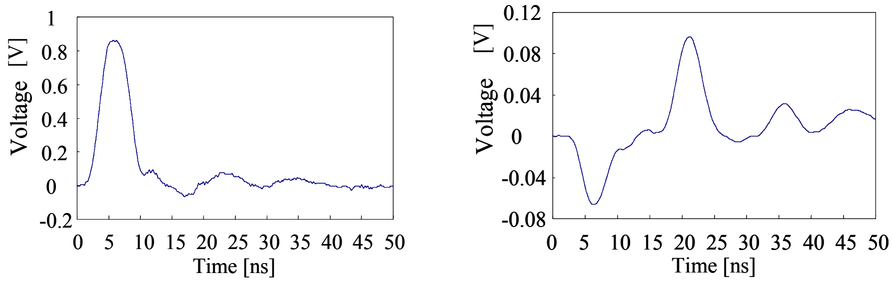
where h is the spacing between the two parallel plates, W is the width of the plate, μ_0 is the permeability ($4\pi \times 10^{-7}$ H/m), ε_0 is the permittivity ($8.85418782 \times 10^{-12}$ F/m) and ε_r is the relative permittivity of the dielectric material between the parallel plates. When there is only one CFRP plate, $h \to \infty$ and the characteristic impedance becomes infinity. As a result, the pulse signal is perfectly reflected at the input end of the CFRP plate. Therefore, in the present study, an aluminum plate parallel to the CFRP plate was prepared and impedance matching was performed. The aluminum plate was used as the ground and the spacing between it and the CFRP plate (h) was tuned. To obtain a clear reflected signal at the input end, a characteristic impedance of 30 Ω was selected: this value was slightly different from the characteristic impedance of the coaxial cable of 50 Ω. To obtain a practical spacing, a rounded figure of h = 10 mm was used, which gave a characteristic impedance value of 32 Ω .

From a practical point of view, such a parallel aluminum plate is not always required. Equation (2) shows that smaller W gives smaller spacing h in the transmission line. For example, the small-width-copper-mesh strip typically used for anti-lightning systems would be an appropriate material to construct the transmission lines. If a resin rich layer of insulator material could be applied, the CFRP laminate could be used as the transmission line directly. Although we herein focus on the parallel plate model, these proposed alternatives will be subjects of future work.

4. Results and discussion

4.1 Impedance matching

First, measurements of the reflected pulse signals were performed without use of the parallel aluminum plate to investigate the effectiveness of the impedance matching. Figure 5 (a) shows the results obtained without the parallel aluminum plate. The abscissa is the time, and the ordinate is the measured voltage. The pulse wave at 6 ns corresponds to the input signal, while the wave at 22 ns is the reflected signal at the end of the CFRP. Although the ideal characteristic impedance of the single CFRP plate is infinity, the experimental results showed that a small signal propagates in the CFRP plate. This is because the CFRP plate had non-infinity characteristic impedance. The CFRP plate and the floor of the experimental room may have made a transmission line. Although a small reflected signal was obtained, it was quite difficult to distinguish the reflected signal from the noise. The results obtained with impedance matching using the parallel aluminum plate are shown in Fig. 5 (b). A very clear reflected pulse signal was obtained at approximately 22 ns when impedance matching was used. The pulse signals observed after 22 ns were the results of multiple reflections. These results clearly indicate that impedance matching using the parallel aluminum plate was quite effective for TDR of CFRP plate.



(a) Without aluminum plate (b) With aluminum plate

Fig. 5 Effect of impedance matching on TDR measurement.

4.2 Performance of damage detection

The type A specimen was used to conduct detections of notches of eight different lengths. The resulting measured reflected pulse signals are shown in Fig. 6.

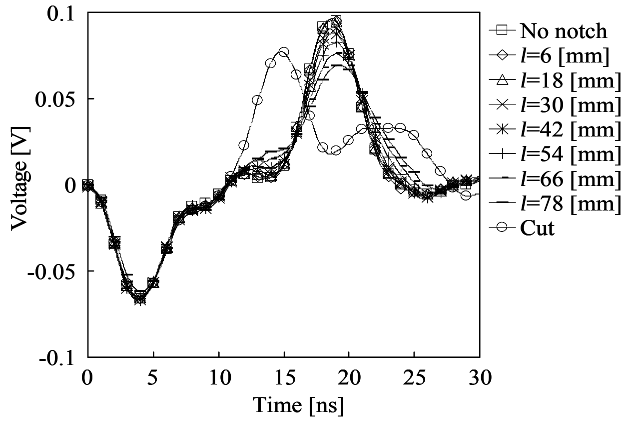
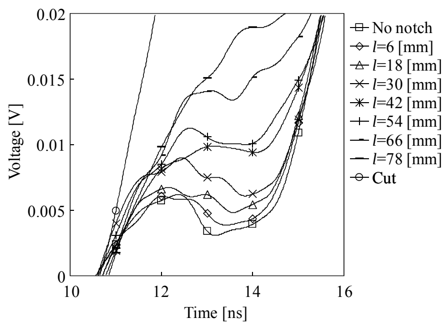
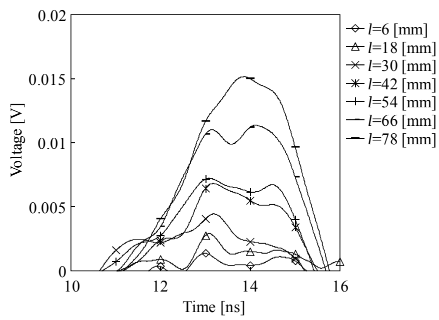


Fig. 6 Detection of various notches using TDR.

In Fig. 6, the open circles indicate results measured for a specimen that was cut to a length of 1480 mm to confirm the time at which the reflected signal was reflected by the damage (cut signal). The results show that the damage reflected signals were located at approximately 14 ns. The notch-reflected signals were smaller than the cut signal. For more detailed investigation, the reflected signal results are magnified in Fig. 7 (a). The differences of the notch reflected signals from that of the no-notch case are shown in Fig. 7 (b).



(a) Reflected waves (10–16 ns)



(b) Measured voltage differences

Fig. 7 Magnification of reflected waves from the notches.

Figure 7 (a) shows that simple magnification of the reflected signal enabled us to detect damage larger than 30 mm (cross symbols in Figure 7 (a)). Figure 7 (b) indicates that all reflected signals occurred at the same time, with larger damage appearing to produce a larger reflected signal. When the notch length was 6 mm or 18 mm, it was quite difficult to detect the reflected signal from the simple magnification (Fig. 7 (a)) or voltage difference (Fig.7 (b)). For these two cases, therefore, cross-correlation analysis was performed[10].

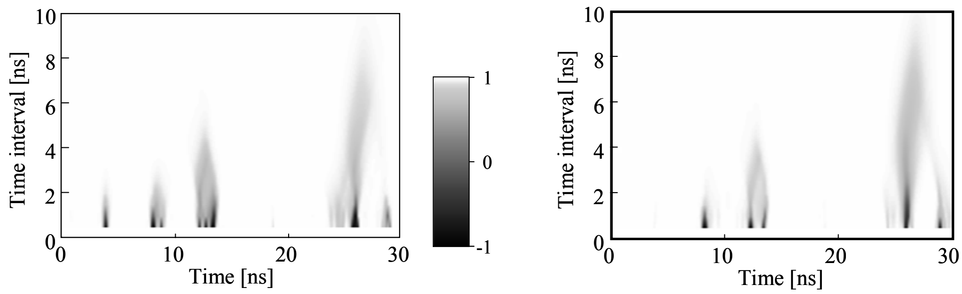
In the present method, time information is very important to determine the location of damage. Cross-correlation analysis of the entire data length results in the loss of the time information, although the analysis is robust against noise. In the present study, therefore, narrow band cross-correlation analyses were performed by trial and error to find an appropriate time interval.

Let us consider the case that we have two sets of time-series signals $\boldsymbol{a}=\{a_i\}$ and $\boldsymbol{b}=\{b_i\}$ (i=1,2,….,n). The cross-correlation of these two signals is expressed as follows.

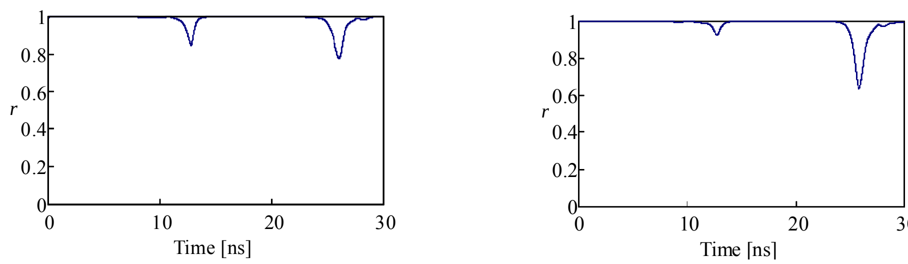
$$r = \frac{\sum_{i=1}^{n}(a_i-\bar{a})(b_i-\bar{b})}{\sqrt{\sum_{i=1}^{n}(a_i-\bar{a})^2}\sqrt{\sum_{i=1}^{n}(b_i-\bar{b})^2}} \qquad (3)$$

where $\overline{a}$ and $\overline{b}$ are the averaged values of the each time-series signal. When the r value of Eq. (3) is equal to 1, the two times-series sets are completely identical. When the r value is less than 1, the two time-series signals have less correlation. Cross-correlation analysis was applied to the time-series data of the no-notch, 18 mm, and 6 mm damage cases. Because the information of time is lost when the entire data is analyzed with the cross-correlation, narrow-band cross-correlation analysis was applied (short time band width).

The results of the cross-correlation analysis for a damage length of 18 mm are shown in Fig. 8 (a), and those for a damage length of 6 mm are shown in Fig. 8 (b). In these figures, the abscissa is the middle time of the time band width and the ordinate is the time interval used for the narrow-band cross correlation analysis. Grayscaling of the figures indicates the value of r, where r=1 is white and r= –1 is black. The cross-correlation value becomes r=1 with increasing time interval, because the difference caused by the damage was very small compared with the entire signal. This means that the two signals were similar. In contrast, the cross-correlation analysis results decrease with time interval because of the effect of noise. In these figures, we could neglect the results after 20 ns because the data included the reflected signal from the end of the specimen.



(a) Notch length 18 mm. (b) Notch length 6mm.



(c) Notch length 18 mm. (Time interval 4 ns) (d) Notch length 6 mm. (Time interval 4 ns)

Fig. 8 Narrow band cross-correlation analysis.

4.3 Signal diffusion in transverse direction

The effect of signal diffusion in the transverse direction was experimentally investigated using the type B specimen. Because the measured results were symmetric at electrode number 6, the only results from electrodes 1 to 6 are shown in Fig. 9. Small reflection signals were observed in all results at 13 ns, but no difference in measured signal between electrodes was apparent. To further investigate any difference between the measured results, calculated voltage differences from the initial results (no damage) are shown in Fig. 10. In Fig. 10, the ordinate is the difference in voltage for each electrode from the initial no-damage result. It can be seen that there was no difference between the measured voltages. Cross-correlation analysis comparing the results of each electrode with that of electrode number 6 was performed using a 4 ns time interval at 13 ns time (Fig. 11).

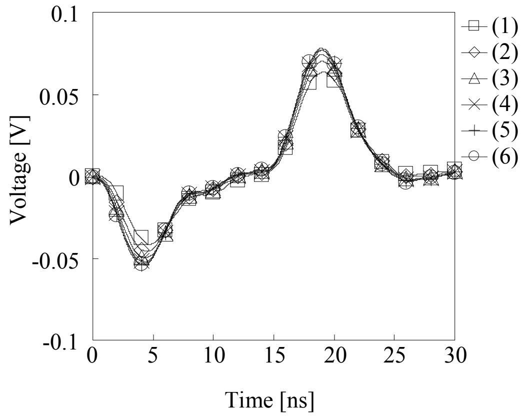


Fig. 9 Measured reflected waves for type B specimen.

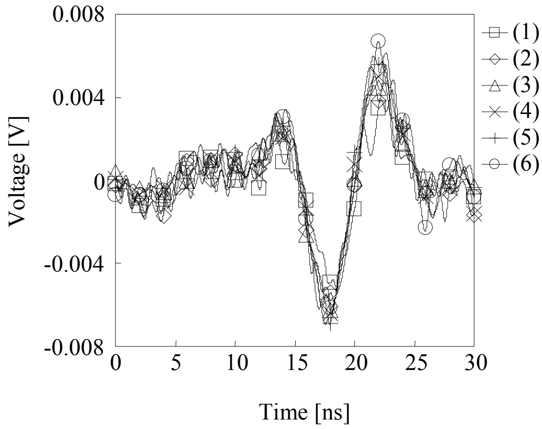


Fig. 10 Difference of measured voltage for type B specimen.

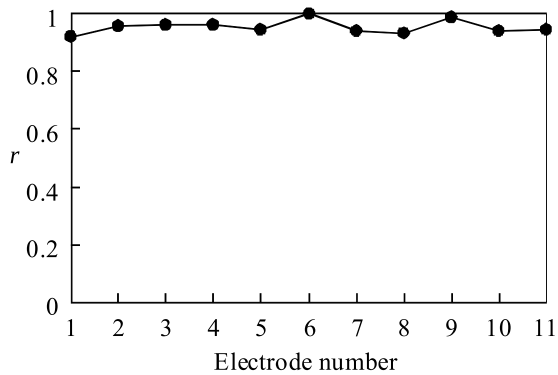


Fig. 11 Cross-correlation analysis of the type B specimen at around 13 ns.

As shown in Fig. 11, the lack of difference in *r* between electrodes shows that the pulse signal was completely diffused in the transverse direction even though the electrical conductivity of the CFRP plate was very small. To investigate this signal diffusion effect in detail, computer simulations of the transmission line solving the Maxwell's equations are required. These results indicated that another method is required to determine the transverse location of damage in CFRP plate using TDR. The computer simulations will be the subject of future work.

5. Conclusions

In the present study, a self-sensing TDR method using carbon fiber sensors was evaluated for its applicability the detection of damage to a 2-m-long CFRP plate was experimentally investigated. The results obtained were as follows.

(1) Impedance matching using an aluminum parallel plate enabled us to detect damage to the CFRP plate using the present TDR method.
(2) Narrow band cross-correlation analysis was used to detect the 6-mm-long damage to the CFRP plate.
(3) Using multiple narrow width electrodes, the effect of signal diffusion in the transverse direction of the CFRP plate was experimentally investigated. It was found that the signal diffused through the entire width of the 120-mm-wide CFRP strip studied. Use of multiple electrodes did not enable us to detect the location of damage in the transverse direction.

References

(1) G..D.Chen, S.S.Sun, D.Pommerenke, J.L.Drewniak, G.G..Greene, R.D.McDaniel, A.Belarbi, and H.M.Mu, Crack detection of a full-scale reinforced concrete girder with a distributed cable sensor, Smart Materials and Structures, Vol.14, No.3, (2005), S88-S97.
(2) M.W.Lin, J.Thaduri and A.O.Abatan, Development of an electrical time domain Reflectometry (ETDR) distributed strain sensor, Measurement Science and Technology, Vol.16, No.7, (2005), pp.1495-1505.
(3) Yoshiki Okuhara, Soon-Gi Shin, Hideaki Matsubara, Hiroaki Yanagida and Nobuo Takeda, “Development of conductive FRP containing carbon phase for self-diagnosis structures”, Proceedings of SPIE Smart Structures and Materials, Vol.4328, Issue1, (2002), pp.314-322.
(4) A. Abu Obaid, S. Yarlagadda, M.K. Yoon, N.E. Hager, III, and R.C. Domszy, “A time-domain Reflectometry method for automated measure met of crack propagation in composites during mode I DCB testing”, J. Composites Materials, Vol.40, No.22, (2006), pp. 2047-2066.
(5) Kevin M. O’Connor, Charles H. Dowding, “GeoMeasurements by Pulsing TDR Cables and Probes”, CRC Press (1999), pp. 15-35.
(6) Akira Todoroki, Kensuke Suzuki, Yoshihiro Mizutani and Ryosuke Matsuzaki, “Durability Estimates of Copper Plated Electrodes for Self-sensing CFRP Composites”, Journal of Solid Mechanics and Materials Engineering, Vol.4, No.6, (2010) pp.610-620.
(7) Akira Todoroki, Miho Tanaka and Yoshinobu Shimamura, “Measurement of orthotropic electric conductance of CFRP laminates and analysis of the effect on delamination monitoring with electric resistance change method”, Composites Sciences and Technology, Vol.62, No.5 (2002), pp. 619-628.
(8) Andrew F. Peterson and Gregory D. Durgin, “Transient Signals on Transmission Lines An Introduction to Non-Ideal Effects and Signal integrity Issues in Electrical Systems” , Morgan&Claypool Publishers, (2009), p.20.
(9) Isao Noda and Yukihiro Ozaki, “Two-Dimensional Correlation Spectroscopy: Applications in Vibrational and Optical Spectroscopy”, John Wiley and Suns Ltd, West Sussex England, (2002) pp.31-38.