International Journal of Aeronautical and Space Sciences
https://doi.org/10.1007/s42405-024-00777-7

ORIGINAL PAPER

Investigation of the Laminating Characteristics of CFRP Plates with a Thin and Wide Configuration in Production for an Effective Inspection Process

Su-Heon Jeong[1]

Received: 25 June 2023 / Revised: 21 March 2024 / Accepted: 11 June 2024

Abstract

Carbon fiber-reinforced plastic (CFRP) products have a relatively high number of thickness irregularities. Such irregularities can be a critical problem in the production process. It requires strict production management, including quality assurance, which results in an increase in production costs. Hence, understanding factors affecting the laminating characteristics is necessary to enhance the inspection efficiency. This study investigated the laminating characteristics of the CFRP plate, which has a wide configuration and is composed of various layers. Fabrication parameters and plate configuration were selected as factors affecting CFRP thickness. The Taguchi method was employed to analyze the effect of fabrication parameters, and the configuration effect was verified by comparing an asymmetric plate with an axisymmetric plate in terms of thickness per ply (TPP). The results showed that the TPP of the thick layers tended to be higher than those of the thin layers in both the plates and the TPP of the asymmetric plate was lower than that of the axisymmetric plate. Among various fabrication parameters, the humidity of the lay-up process and the 1st heat-up time were identified as significant factors in TPP variance. In addition, an improved inspection process based on the verified laminating characteristics is suggested and discussed. The efficiency of inspection according to the confidence level of the objective CFRP products can be improved by applying the proposed inspection process.

Keywords Carbon fiber · Laminating characteristics · Taguchi method · Statistical methods · Inspection process

1 Introduction

Carbon fiber-reinforced plastic (CFRP) is used in various structures because of its excellent mechanical properties [1]. However, there are also disadvantages, and irregularity is one of them. CFRP products have relatively high irregularity in their mechanical properties, internal defects, and configuration [2]. Such irregularity between products comes from the material characteristics and fabrication process [3–6]. Irregularity is often the main factor of cost increases in the manufacturing process. CFRP requires post-processing such as edge cutting after the curing process to fulfill the dimensional requirements, because the CFRP shape has low accuracy and low precision due to configuration irregularities [7]. Moreover, inspection of internal defects by non-destructive testing (NDT) and strict inspection of the dimensions needs to be conducted [8–10] and can be a time-consuming process if the product has a wide and complex configuration. For example, CFRP skin for aeronautical use with a 100% confidence level, it needs measuring every layer to verify whether each layer satisfies the tolerance because it has such a high variance in thickness. In the same vein, proper tolerance design of the dimensions is also important because excessively tight tolerance can increase the scrap rate and excessively wide tolerance can deteriorate the designed performance of the products. These problems result in high costs that include material, time, and human resources. Therefore, an effective inspection process, including a suitable method and appropriate criteria, is essential for CFRP products [11]. Moreover, cost optimization is one of the important issues of the composite structure industry [12–14].

Communicated by Sang-Woo Kim.

Su-Heon Jeong
efcjung@gmail.com

[1] Korea Research Institute for Defense Technology Planning and Advancement, 402, Dongjinro, Jinju-Si 660-031, Gyeongsangnam-Do, Korea

To enhance inspection efficiency, several studies have focused on the detection method such as the eddy current [15, 16], excitation coil [17], electrical resistance change [18], etc. However, inspection methods based on the characteristics of the product and its fabrication conditions have not been studied. Previous studies have found that the mechanical properties of CFRP products depend on the fabrication parameters: lay-up direction of plies, temperature, pressure, etc. [19–21]. The curing quality and the stacking sequences also affect the CFRP product characteristics [22, 23]. Similarly, the fabrication parameters also affect the irregularity of the product configuration. This is because the parameters of the CFRP fabrication process, such as heat-up time and humidity, have suggested that the range and actual value of the parameters are differentiated for every product according to the environment and laminating conditions of the products. Hence, for effective inspection efficiency, it is necessary to verify the relationship between the dimensions and the variance of fabrication parameters.

In this study, we investigated the laminating characteristics of a CFRP plate made by the lay-up method for the fabrication parameters and configuration. We considered two types of CFRP plates for the skin of an aircraft tail wing that has a thin and wide shape with thickness variation along the surface, and we employed the Taguchi method to analyze the effect of the fabrication parameters on the CFRP thickness. We also investigated the configuration effect on the laminating characteristics. Based on the results, we propose an inspection process for the CFRP plates and evaluate and discuss its performance.

2 Experimental Details

2.1 Fabrication of CFRP Plates

In this research, we considered two different CFRP plates with a thin and wide shape. The plates were used as the skin of a tail wing structure, and the material was a unidirectional graphite/epoxy prepreg made at Cytec Engineered Materials and meets the FMS2023 standard. The two plates had different shapes and the number of plies laminated to each other. Each plate was assembled on the tail wing structure and its schematics are shown in the Figs. 1 and 2. Type I has 18 layers and 5 corners and the number of plies laminated together is irregular. Type II is similar in shape to a trapezoid shape and it has 23 layers. The number of laminated plies is shown in Table 1 and the maximum thickness of type I and type II are 13 mm and 8 mm, respectively. The fabrication process for the CFRP consisted of 3 main stages and its parameters were controlled to guarantee the prescribed quality for the strength, stiffness, thickness, etc.

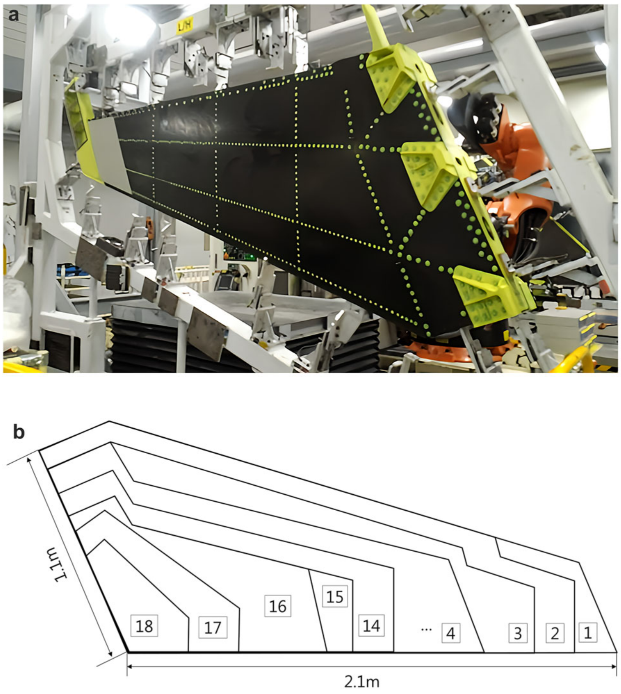

Fig. 1 **a** CFRP assembly **b** Schematics of type I plate

In the lay-up stage, prepreg pieces cut by an ultrasonic cutter were laminated by hand in a clean room with a maximum humidity of 60% and a temperature of 23 ± 3 °C. The sum of the same level prepreg pieces makes a ply, the stack of plies with the same shape makes a layer, and the stack of layers make a plate. Vacuum compaction was carried out per every 4 plies. Thermocouples were installed at the maximum and minimum thickness layers between the laminated plies in order to measure the temperature change of the CFRP during the curing process in an autoclave. The area where the thermocouples were attached was removed in the edge cutting process.

Next, curing was conducted according to the cure cycle with fabrication conditions as shown in Table 2. The heat-up process was conducted in two steps to reduce the temperature variance along the surface caused by the thin and wide shape of the plate. The soak was begun when the temperature of the slowest heating part in the load reached the required temperature.

The final stage of the CFRP production was the inspection. First, the thickness of the plates was measured at six different positions with a micrometer and it needed to be at the prescribed thickness. The ply had upper and lower thickness limits, and the thickness tolerance of each layer was determined by multiplying the number of plies and the upper and lower thickness limits of the ply. Then internal defects, such as void, porosity and delamination, were inspected by ultrasonic detection methods, A-scan and C-scan. The C-scan was

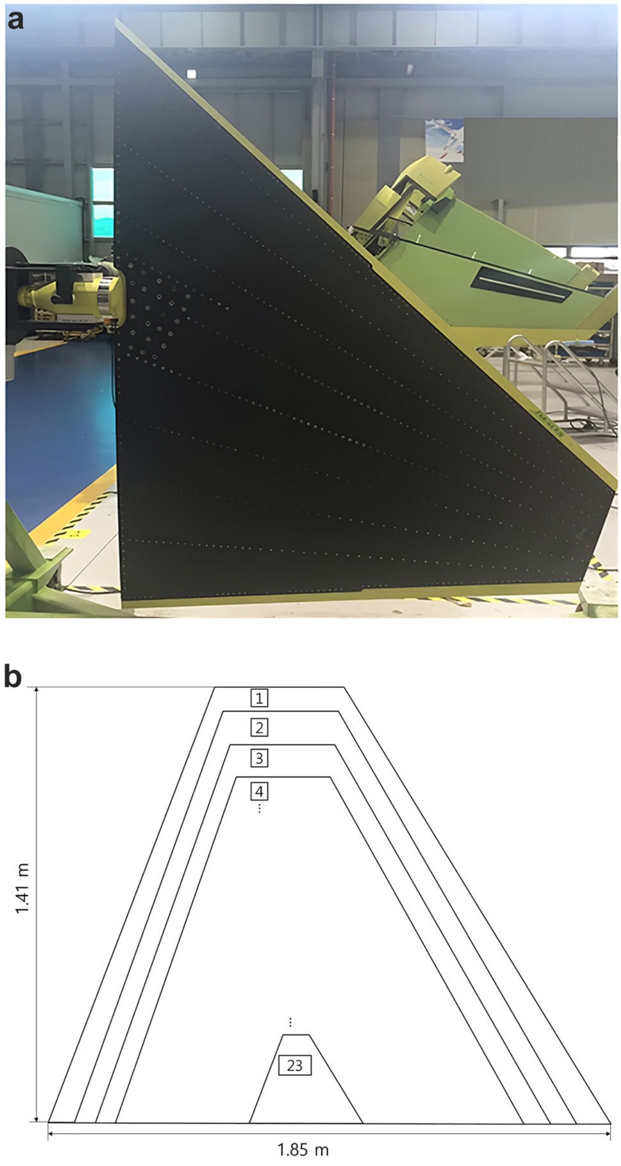

Fig. 2 **a** CFRP assembly **b** Schematics of type II plate

Table 2 Fabrication conditions

Stage	Parameter	Condition
Lay-up	Temperature	23 ± 3 °C
	Humidity	Max. 60%
Cure	Vacuum	585 ± 35 kPa
	1st heat-up	40–100 min
	1st soak temperature	132 ± 13 °C
	1st soak time	85–95 min
	2nd heat-up	13–85 min
	2nd soak temperature	180 ± 4 °C
	2nd soak time	120–150 min
	Cooling rate	2 °C/min

primary and the A-scan was optional to make a final pass/fail decision when any defect was detected by the C-scan. In this study, we analyzed the thickness measurement results of 50 products, 43 type I and 7 type II, to investigate the laminating characteristics, and we employed the results of 6 type I products and 2 type II to evaluate the proposed inspection process.

2.2 Experimental Methods

To investigate the laminating characteristics, we chose the fabrication parameters and plate configuration, which we analyzed as factors affecting the thickness of the CFRP plate. The thickness per ply (TPP) was employed to evaluate the influence of those factors. By applying the TPP, we were able to compare the layers in the same plate, which had different thickness tolerances. In addition, the pass conditions of the CFRP plate were changed from every layer within the limits of each dimension to the ply limits. There were discrepancies between the TPP of layers and the ply limits for over or under compression of the layer. The TPP close to the upper limit indicates that it is under compressed and if it is close to the lower limit, it means that the layer is over compressed. We verified the effect of the fabrication parameters based on the Taguchi method and investigated the configuration effect by comparing type I and type II plates.

2.3 Taguchi Method

The Taguchi method, a design-of-experiment method, was applied to analyze the effect of the fabrication parameters on the plate thickness. The first step of the Taguchi method was selection of the experimental objectives and characteristics

Table 1 The number of laminated plies according to the layer

Plate		The number of laminated plies (N = Layer number)							
Type I	N	1	2 – 12	13	14	15	16	17	18
		20	12 + N × 5	78	80	84	86	90	92
Type II	N	1 – 23	10 + N × 2						

among the ‘lower-the-better’, the ‘nominal-the-better’, and the ‘higher-the-better’. The experimental objective was to determine which fabrication parameters affect the TPP of the layers, and we selected the ‘nominal-the-best’ characteristic as the thickness of the layer that must satisfy the tolerance. The next step was the selection of the experiment parameters and their level. As described in Table 2, the fabrication process for the CFRP was composed of various parameters. Among the parameters, humidity, 1st heat-up time, and 2nd heat-up time were selected with two levels among the parameters because other parameters showed a negligible discrepancy between the products. For example, a change in vacuum pressure during the lay-up process was within 7 kPa although the pressure range was 585 ± 35 kPa. Our analysis was based on the L4 orthogonal arrays and measurements of the layer thickness were considered as the noise factor and independent experiments because each layer needed to satisfy the thickness tolerance. The SN ratio and sensitivity were calculated to find the optimum conditions, and an analysis of variance (ANOVA) of the SN ratio and sensitivity was carried out to verify the contribution of each parameter. The SN ratio and sensitivity are related to the standard deviation (STDEV) and the average, respectively.

2.4 Comparison of Different Configurations

We assumed that the thickness of the layer was affected by the fabrication conditions, namely, the compaction pressure, curing time and curing temperature. Although the fabrication parameters were under control, conditions such as temperature and compaction pressure were distributed along the surface due to the thin and wide shape, which means that the plate configuration causes different conditions along the surface during fabrication. As shown in Figs. 1 and 2, type II is closer to axisymmetry than type I based on the center line of the layer with the maximum thickness. Hence, the effect of the CFRP configuration can be verified by comparing two plates in terms of the TPP and the STDEV. To consider the effect of the configuration without the effect of the fabrication parameters, CFRP plates manufactured under the same conditions were selected as test samples.

3 Laminating Characteristics of CFRP Plates

Figure 3 shows the TPP average and the STDEV of both plates according to the number of layers. The average of the TPP tends to have a higher value at the thick layer. We assumed that repetition of compaction decreases the TPP of the thin layer. For example, the compaction of the minimum thickness layer is 23 times more than that of the maximum thickness layer. On the other hand, the STDEV does not reflect any trend with respect to the number of plies. The laminating characteristics according to the fabrication parameters and plate shape are described in more detail as follows.

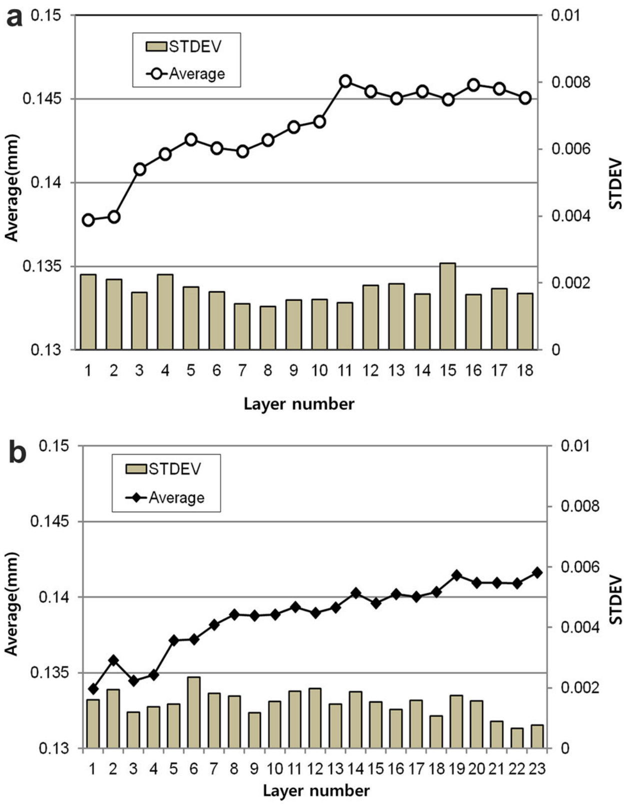

Fig. 3 Average and Standard deviation of CFRP TPPs: **a** Type I, **b** Type II

Table 3 Experimental parameters

Factors	Level 1	Level 2
A: Humidity	0–30%	31–60%
B: 1st heat-up time	80–90 min	91–100 min
C: 2nd heat-up time	30–40 min	41–75 min

3.1 Effect of Fabrication Parameters

The Taguchi method for the ‘nominal-the-best’ characteristic is composed of two steps. First, we found the levels of factors which achieved the maximum SN ratio. Second, the calculation was carried out based on the sensitivity in finding the average control factors that can reduce the discrepancy between the average of the experimental result and the objective of the experiments.

The experimental parameters and ANOVA table of the SN ratio are shown in Tables 3 and 4, respectively. The results demonstrate that the humidity and 2nd heat-up time were the

Table 4 ANOVA table of the SN ratio

Factor	Sum of square	Degree of freedom	Mean square	F-value	*P*-value	% Contribution
A	5.4885	1	5.4885	587.3821	0.022	58.54
B	0.0066	1	0.0066	Pooled		
C	3.8696	1	3.8696	833.1105	0.026	41.25
Error (B)	0.0066	1	0.0066			0.21
Total	9.6738	3				100

Table 5 ANOVA table of sensitivity

Factor	Sum of square	Degree of freedom	Mean square	F-value	*P*-value	% Contribution
A	0.0046	1	0.0046	29.3235	0.0325	90.42
B	0.0002	1	0.0002	Pooled		
C	0.0001	1	0.0001	Pooled		
Error (B, C)	0.0003	2	0.0002			9.58
Total	0.0050	3				100

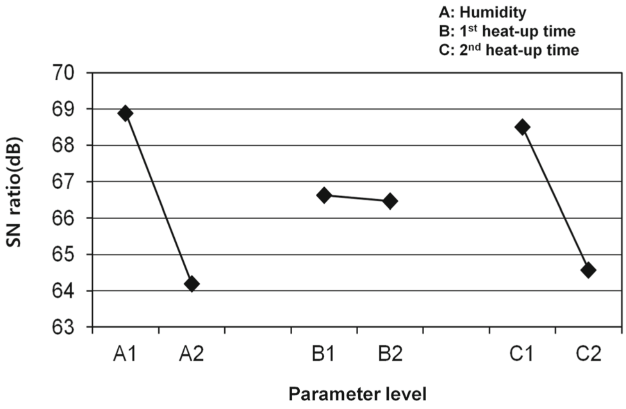

Fig. 4 SN ratios for fabrication parameters

significant factors with humidity being the most significant on the STDEV of the TPP of the layers. The 1st heat-up time was pooled and considered to be in error because it indicated a low contribution. Level 1 of each parameter decreased the STDEV between the TPP of the layers based on the SN ratio as shown in Fig. 4 from the CFRP inspection point of view. From the ANOVA table of sensitivity (Table 5), the 2nd heat-up time was verified as a critical factor of the average of the TPPs. Its Level 1 made the average of the TPP closer to the median of the boundary range. From the inspection point of view, it is advantageous to have a low STDEV and an average close to the median. The results indicate that Level 1 humidity and Level 1 2nd heat-up time were the optimum inspection conditions.

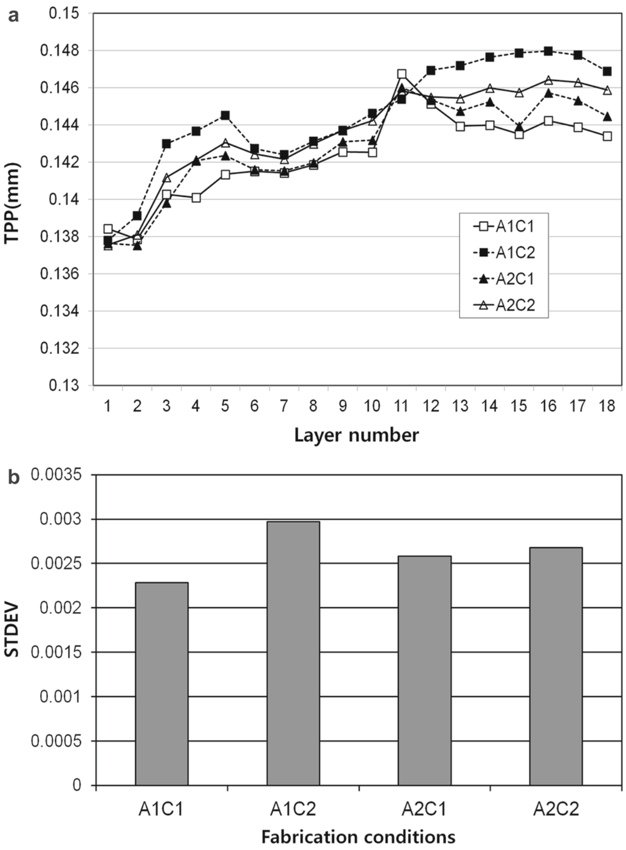

Fig. 5 Verification of optimum conditions: **a** Average of TPPs, **b** Standard deviation of TPPs

The effect of the optimum conditions was confirmed by verifying the difference between CFRP products manufactured under different conditions. As shown in Fig. 5, products with the optimum conditions achieved the best results in terms of the average and STDEV. Additionally, the thickness of the last layer with low humidity (Level 1) tended

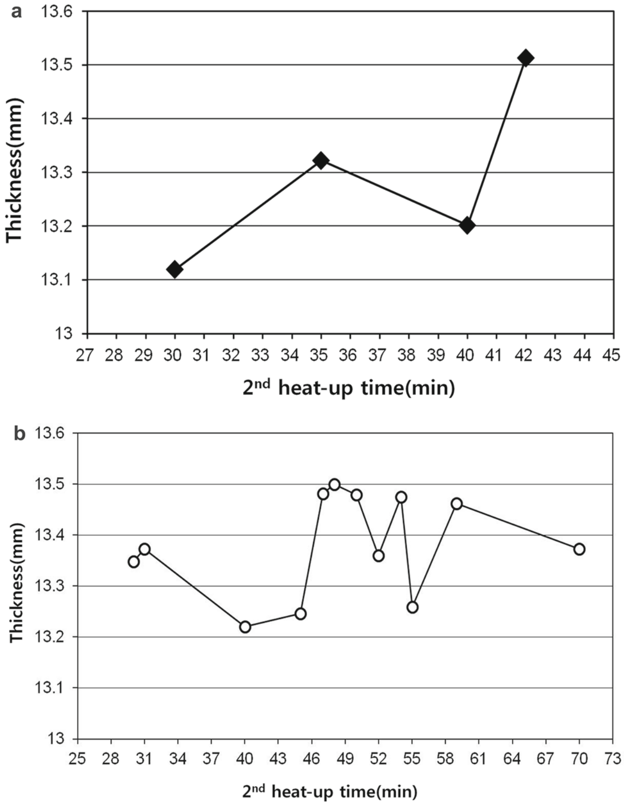

Fig. 6 Effect of humidity and 2nd heat-up time on thickness: **a** Level 1 humidity, **b** Level 2 humidity

to be proportional to the 2nd heat-up time (Fig. 6a). In contrast, the thickness of the last layer with high humidity (Level 2) did not show any trend with the 2nd heat-up time (Fig. 6b), which confirmed that optimum conditions verified by Taguchi method agreed with the detection results of actual products.

The effect of the parameters can be explained from the vacuum compaction and heat transfer points of view. Generally, high humidity makes vacuum compression difficult, which in turn decreases uniformity between compaction of plies during the lay-up process and results in the high irregularity of the plates. The heat-up time depends on the thermal resistance and heat capacity. The thermal resistance and heat capacity is proportional to the thickness and a low thickness leads to a short heat-up time. Hence, the short heat-up time indicates the average of the TPP to be closer to the median because the type II plate tends to be thick.

3.2 Effect of Plate Configuration

The configuration effect on the laminating characteristics was verified by comparing type I with type II. The fabrication conditions of both plates had Level 2 humidity, Level 2 1st heat-up time, and Level 1 2nd heat-up time. To verify the configuration effect, we compared the layers of type II with the layers of type I in terms of the TPP average and STDEV. The compared layers of each plate have the same number of laminated plies but the layers of type I have more compaction times than those of type II because type I is thicker than type II.

Figure 7 shows the results of the comparison. Although type I experienced the much more compaction, type I tends to have a larger TPP and STDEV than type II. The difference increased as the number of the laminated plies increased. The results indicated that an axisymmetric shape is easier to compress than an asymmetric shape and is more effective in decreasing irregularity in the CFRP plate. Moreover, it revealed that plate configuration is also a significant factor for the CFRP design and production. To observe the effect of the configuration more clearly, a comparison between test

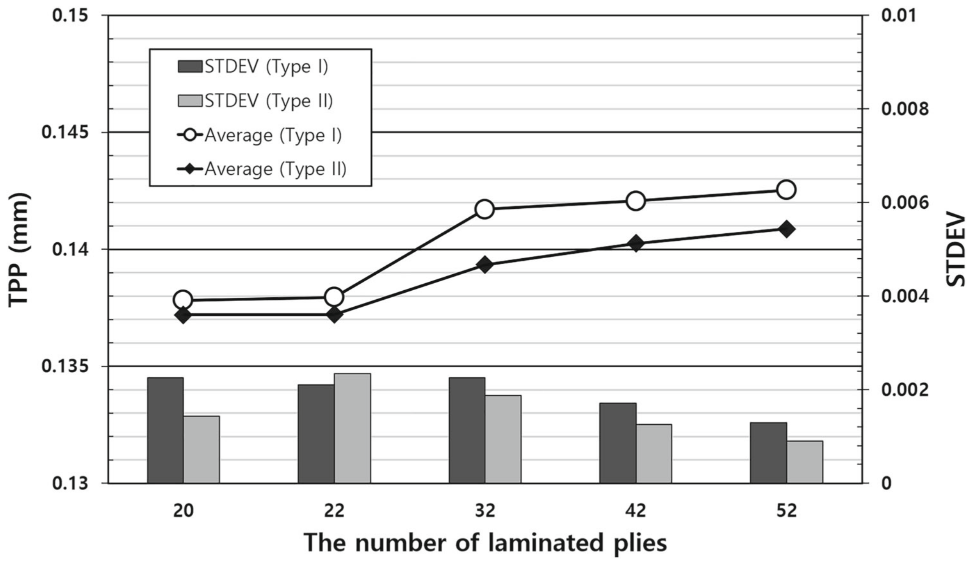

Fig. 7 Effect of plate configuration

samples with only a difference in configuration needed to be carried out.

4 Improvement of Inspection Method

4.1 Optimization of the Inspection Process

The quality inspection criteria of the CFRP configuration are the TPP of layers within the upper and lower limits. The existing inspection method involves measuring the thickness of every layer. To reduce the production cost, we propose a more effective inspection method based on the laminating characteristics of the CFRP. Our method results in a reduction in the number of required measurements.

If we know the maximum and minimum TPP of layers, just two measurements are enough to determine the CFRP plate acceptance, but that was impossible due to its irregularity. Instead, we were able to divide the layers into several groups and find the groups that were most likely to contain the layers with the maximum or minimum TPP. In the proposed method, we first divide the layers into three groups: thin, middle, thick, according to the layer thickness. From the above experiments, we know that the TPP tends to be proportional to the number of plies, which indicates that layers that are contained in the thin and thick groups are more likely to exceed the limits than those in the middle group. Therefore, we were able to omit the inspection of the middle group if we adjusted the layers belonging to it appropriately. When adjusting the middle group, we considered the fabrication conditions of the objective plate because the laminating characteristics were affected by the conditions. To prevent a decrease in the confidence level, the TPP of the middle group layer must be normally distributed and the probability of exceeding limits must be within an acceptable range.

Second, the number of layers to be measured can be reduced by prediction of the TPP range. The TPP range of each layer can be determined by the TPP of neighboring layers as in the equation bellow due to the lay-up process where N is the number of layers and n is the number of laminated plies.

$$TPP(N-1) \times (n-1)/n < TPP(N) < TPP(N+1) \times (n+1)/n. \qquad (1)$$

The equation shows that the maximum range of TPP(N) can be identified if the thickness of a neighboring layer is measured. If the range of TPP(N) is within the limits, it is not necessary to measure the TPP(N). When predicting the minimum TPP in the thin group, the two terms on the right side of the equation were applied. Similarly, the two terms on the left side of the equation were applied to predict the maximum TPP in the thick group.

Table 6 Middle group adjustment according to the fabrication conditions

Type of test sample (Fabrication conditions)	Middle group layers (Number)	
	Initial	Adjusted
Type I (A1C1)	7–13	2–10
Type I (A2C1)		3–10
Type I (A2C2)		3–10
Type II (A2C1)	9–16	5–21

As a result, our improved inspection process is proposed as below.

Step 1. Divide the layers into three groups according to the thickness: thin, middle, thick).
Step 2. Adjust the layers belonging to the middle group until it is normally distributed and its failure probability is lower than the acceptance level. The acceptance level should be determined by considering the features of the product and cost.
Step 3. Determine the middle group according to the fabrication parameters.
Step 4. Measure and predict the unknown TPP of the thin and thick groups by using the measured TPP. If the predicted range exceeds the limit, measure and check the actual TPP value of the layer.

Through this procedure, we determined the middle group according to the fabrication conditions as shown in Table 6. Based on the above measurement result, the composition of the initial layers of each group was adjusted until the middle group was normally distributed, and the probability that the TPP exceeded 0.132–0.148 mm was controlled to be less than 1% in order to prevent the omission of layers exceeding the thickness limitations. Figure 8 represents the change in the probability function of the middle group of the CFRP plate with A1C1(low humidity and short 2nd heat-up time) according to the adjustment of the layers.

4.2 Evaluation of the improved Method

The proposed inspection method was applied and evaluated in terms of the measuring efficiency and the accuracy of the acceptance decision compared to the total inspection. Eight CFRP plates with different fabrication parameters were used to verify the proposed method. First, we divided the layers of the plate into three groups based on Table 6 with the fabrication conditions of each plate. Second, we measured

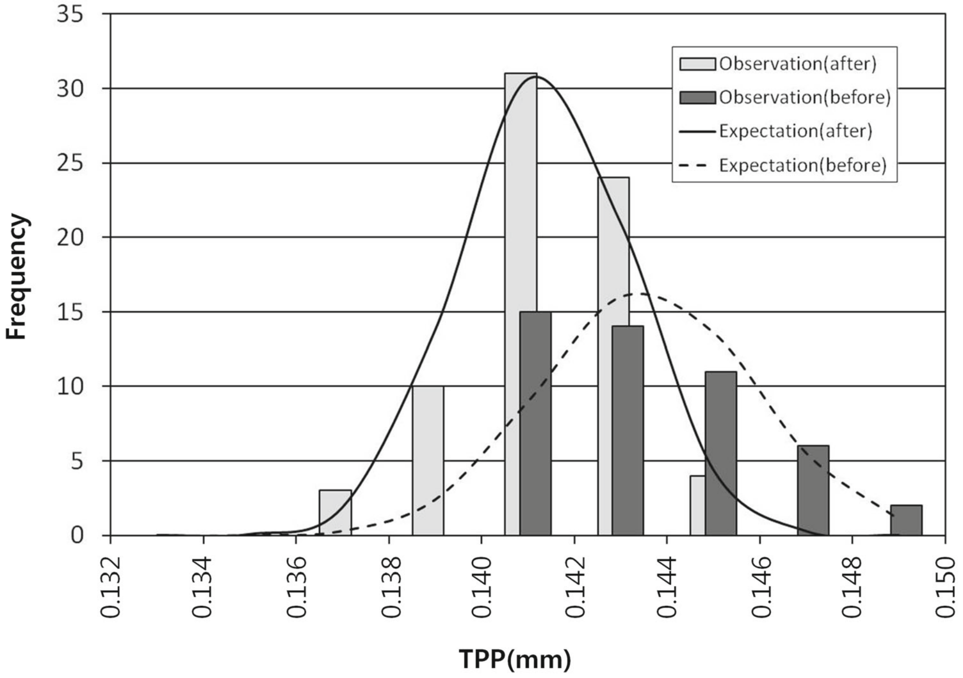

Fig. 8 Frequency and probability change of middle group of CFRP plates with A1C1 condition after layer adjustment

Table 7 Effect of the proposed inspection methods

Type of test sample (Fabrication conditions)	Measurement rate (%)		
	Present	Suggested	Measured layers number
Type I (A1C1)	100%	33.3%	1, 11, 12, 14, 16, 18
Type I (A2C1)		38.9%	1, 2, 11, 12, 14, 16, 18
Type I (A2C2)		50.0%	1, 2, 11, 12, 14, 15, 16, 18
Type II (A2C1)	100%	26.0%	1, 2, 3, 4, 22, 23

the thickness of the 1st layer and the last layer and carried out the TPP prediction. In this experiment, since the minimum and maximum TPP only appear in the thin and thick groups, respectively, the minimum and maximum TPP predictions were performed only for the thin and thick groups, respectively. Finally, we measured every layer and verified the measuring efficiency and accuracy of the acceptance decision of the proposed method.

Table 7 shows the group composition and inspection efficiency of the proposed method. The results indicate that the fabrication conditions and configuration of the CFRP plates affect the composition of the middle group and the efficiency of inspection. In addition, the final measurement number of the proposed method was reduced compared with the total inspection without a decrease in the confidence level. As shown in Fig. 9, measurement of the thick group was reduced by the TPP prediction based on the TPP range. Such a reduction was greater in the CFRP plate with A1C1 than with A2C2 because the A1C1 condition was beneficial to decreasing the TPP. Consequently, the experiments successfully demonstrated that the laminating characteristics of layers can be used to improve efficiency of an inspection method in terms of measurement numbers.

5 Conclusion

We investigated the laminating characteristics of CFRP with a thin and wide shape in terms of the TPP (thickness per ply). We considered the fabrication parameters and configuration of the CFRP as effective factors. The TPP of CFRP plates tends to be highly proportional to the number of laminated plies due to the compaction process. In addition, the CFRP thickness was affected by the fabrication parameters and shape of the CFRP plates. Based on the results of this study, was proposed and discussed an effective inspection process.

We analyzed the effect of fabrication parameters on the CFRP thickness by the Taguchi method. Humidity and 1st heat-up were identified as factors affecting the laminating characteristics of the plates. The verified optimum conditions with the 'nominal-the-best' characteristic are low humidity and a short 2nd heat-uptime.

We verified the configuration effect by comparing an asymmetric plate with an axisymmetric plate and found that an axisymmetric shape had an advantage in achieving a lower

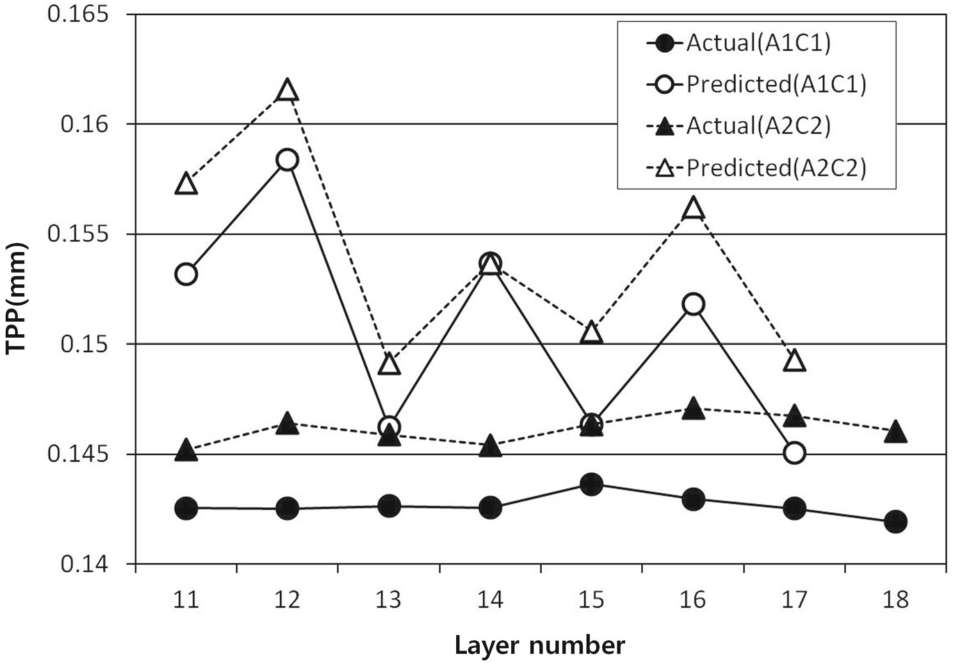

Fig. 9 Prediction of unknown TPP based on the TPP range

TPP and a lower standard deviation than an asymmetric shape. The result revealed that the shape of the CFRP plate is one of the significant factors which should be considered in its design and inspection process.

The main strength of this paper is that it presents a method that can be used for inspection of CFRP during production, and the proposed method is based on statistical methods. Hence, the results can be applied without any additional production equipment changes.

The limitation of this research is that it only covers CFRP made by the lay-up method and the same configuration test samples were used in the experiments and the evaluation. Further studies will investigate the laminating characteristics of CFRP made by other methods, such as resin transfer molding, hot press, and filament winding. It is also necessary to verify the effectiveness of the proposed method through specimens with different configurations and fabrication processes.

The proposed verified laminating characteristics can be used to improve the inspection process for CFRP plates with a thin and wide shape. The results of this study confirmed that the inspection process can be optimized according to the fabrication parameters and plate configuration. We believe that the verified laminating characteristics of CFRP plates can be applied to design a proper inspection process with the required confidence level and efficiency for the specified products. The results can also be applied to the design stage of CFRP plates to achieve uniform quality and save inspection cost.

Data availability The data in this article are available from the corresponding authors upon a reasonable request.

References

1. Shafi Ullah KHAN, Kim J-K (2011) Impact and delamination failure of multiscale carbon nanotube-fiber reinforced polymer composites. Int J Aeronaut Spa Sci. https://doi.org/10.5139/IJASS.2011.12.2.115
2. Andrea Corrado, Wilma Polini, Luca Sorrentino, Costanzo Bellini, Geometrical deviation analysis of CFRP thin laminate assemblies: Numerical and experimental results, Compos Sci Technol. https://doi.org/10.1016/j.compscitech.2018.09.003
3. Agarwal K, Kuchipudi SK, Girard B, Houser M (2018) Mechanical properties of fiber reinforced polymer composites: a comparative study of conventional and additive manufacturing methods. J Compos Mater 52:3173–3181. https://doi.org/10.1177/0021998318762297
4. Hojo M, Mizuno M, Hobbiebrunken T et al (2009) Effect of fiber array irregularities on microscopic interfacial normal stress states of transversely loaded UD-CFRP from viewpoint of failure initiation. Compos Sci Technol. https://doi.org/10.1016/j.compscitech.2008.08.032
5. Rimašauskas M, Jasiūnienė E, Kuncius T et al (2022) Investigation of influence of printing parameters on the quality of 3D printed composite structures. Compos Struct. https://doi.org/10.1016/j.compstruct.2021.115061
6. Zhou K, Enos R, Zhang D, Tang J (2022) Uncertainty analysis of curing-induced dimensional variability of composite structures utilizing physics-guided Gaussian process meta-modeling. Compos Struct. https://doi.org/10.1016/j.compstruct.2021.114816
7. Robert Voss, Lukas Seeholzer, Friedrich Kuster, Konrad Wegener, Influence of fibre orientation, tool geometry and process parameters on surface quality in milling of CFRP, CIRP J Manuf Sci Technol https://doi.org/10.1016/j.cirpj.2016.10.002

8. Kordatos EZ, Aggelis DG, Matikas TE (2012) Monitoring mechanical damage in structural materials using complimentary NDE techniques based on thermography and acoustic emission. Compos B Eng. https://doi.org/10.1016/J.COMPOSITESB.2011.12.013
9. Karabutov AA, Podymova NB (2014) Quantitative analysis of the influence of voids and delaminations on acoustic attenuation in CFRP composites by the laser-ultrasonic spectroscopy method. Compos B Eng. https://doi.org/10.1016/J.COMPOSITESB.2013.08.040
10. Heuer H, Schulze M, Pooch M et al (2015) Review on quality assurance along the CFRP value chain - Non-destructive testing of fabrics, preforms and CFRP by HF radio wave techniques. Compos B Eng. https://doi.org/10.1016/j.compositesb.2015.03.022
11. Schmidt C, Schultz C, Weber P, Denkena B (2014) Evaluation of eddy current testing for quality assurance and process monitoring of automated fiber placement. Compos B Eng. https://doi.org/10.1016/J.COMPOSITESB.2013.08.061
12. Kaufmann M, Zenkert D, Mattei C (2008) Cost optimization of composite aircraft structures including variable laminate qualities. Compos Sci Technol. https://doi.org/10.1016/j.compscitech.2008.05.024
13. Curran R, Gomis G, Castagne S et al (2007) Integrated digital design for manufacture for reduced life cycle cost. Int J Prod Econ. https://doi.org/10.1016/J.IJPE.2006.11.010
14. Scanlan J, Rao A, Bru C et al (2006) DATUM Project: cost estimating environment for support of aerospace design decision making. J Aircr doi 10(2514/1):17362
15. Machado MA, Antin KN, Rosado LS et al (2021) High-speed inspection of delamination defects in unidirectional CFRP by non-contact eddy current testing. Compos B Eng. https://doi.org/10.1016/J.COMPOSITESB.2021.109167
16. Abrantes RF, Rosado LS, Piedade M, Ramos PM (2016) Pulsed eddy currents testing using a planar matrix probe. Measurement. https://doi.org/10.1016/JMEASUREMENT.2015.09.026
17. Pasadas DJ, Ramos HG, Baskaran P, Ribeiro AL (2020) ECT in composite materials using double excitation coils and resonant excitation/sensing circuits. Measurement. https://doi.org/10.1016/J.MEASUREMENT.2020.107859
18. Todoroki A, Mizutani Y, Suzuki Y, Haruyama D (2013) Fatigue damage detection of CFRP using the electrical resistance change method. Int J Aeronaut Spa Sci. https://doi.org/10.5139/IJASS.2013.14.4.350
19. Arao Y, Koyanagi J, Utsunomiya S, Kawada H (2011) Effect of ply angle misalignment on out-of-plane deformation of symmetrical cross-ply CFRP laminates: accuracy of the ply angle alignment. Compos Struct. https://doi.org/10.1016/J.COMPSTRUCT.2010.10.019
20. Markatos DN, Tserpes KI, Rau E et al (2013) The effects of manufacturing-induced and in-service related bonding quality reduction on the mode-I fracture toughness of composite bonded joints for aeronautical use. Compos B Eng. https://doi.org/10.1016/J.COMPOSITESB.2012.05.052
21. Aydın MD, Temiz Ş, Özel A (2007) Effect of curing pressure on the strength of adhesively bonded joints. J Adhes. https://doi.org/10.1080/00218460701453536
22. Yao R, Shi J, Zheng J (2022) Curing quality monitoring and loading detection of composite structures with embedded capacitive sensor array. Mater Des. https://doi.org/10.1016/j.matdes.2021.11032123
23. Todoroki A (2010) Self-Sensing Composites and Optimization of Composite Structures in Japan. Int J Aeronaut Spa Sci. https://doi.org/10.5139/IJASS.2010.11.3.155