Delamination analysis of entry and exit surface with carbon-fiber-reinforced polymers composite materials (CFRP) in UAV

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Abstract. Drilling makes holes in aircraft components that aim to unite other structural parts to create a robust and reliable structure. The drilling process on composite materials does not always work well, resulting in the composite being damaged during the drilling process. One punching defect is delamination (a measure of the damaged area around the hole). This study focused on the composite materials used in aircraft, namely carbon fiber composites with an epoxy resin matrix. The drilling treatment method is directly or in stages and combine them with drilling parameters such as cutting speed and feed rate. The drilling treatment on the entry surface produces a value of F > F crit with a value of 10.3477 > 4.171 based on the hypothesis test using the F distribution that the P-value is 0.003 <0.05. then the exit surface drilling produces a value of F > F crit with a value of 5.4797 > 4.171 based on the hypothesis test using the F distribution that the P-value is 0.02 <0.05. Drilling treatment was reinforced by ANOVA calculations with the results that the P value on the entry and exit surface was less than 0.05, indicating that the drilling treatment affected the delamination results. 1.1983 and 1.2487, respectively. The highest levels of delamination occurred at the entry and exit surfaces at RPM 3500 by direct drilling with values of 1.3328 and 1.3827, respectively. With this result, the higher the RPM value, the resulting delamination effect increases both direct and gradual drilling.

Keywords: CFRP, delamination, two-way ANOVA.

1 Introduction

The development of the UAV (unmanned aerial vehicle) is increasing rapidly in structure, systems, and aerodynamics. Currently, the UAV skin structure uses a lot of composites because it has the advantage of a light yet robust design (1,2). This composite structure will be formed and combined in such a way, one of which is by drilling method, which can cause delamination of the structure. Delamination is a form of critical damage that often occurs in composite structures. Delamination can occur

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because, during the drilling process, it will cause a decrease in bearing strength and reduce durability due to fatigue loads (3,4). Drilling is an industrial method for producing holes to install two or more structures using rivets or bolts. It is known that the geometry of the drill bit can significantly affect the twist drill bit performance (5,6). Delamination due to the drilling process on the inlet side of drilling is called peel-up delamination, while on the exit side of drilling, it is called push-out delamination. Before delamination occurs, a slight bulge will appear in the drill axis, which will then expand in the direction of the fiber on the exit side of the drill. Minimizing and even avoiding the impact of delamination can be done in various ways, such as knowing the level of thrust generated during the drilling process and adjusting the feed rate, RPM, and spindle speed. (7,8,9) This study will examine the delamination effect of drilling with variations in spindle speed, feeding speed, drill diameter, and variations in the drilling process on Carbon Fiber Reinforced Polymer (CFRP) material made by the Vacuum Infusion method.

2 Delamination Analysis

Delamination can occur at the drill's entry or/and exit while drilling a composite laminate. As shown in Fig. 1, delamination occurring at the entrance of the drill is called peel-up delamination, and at the drill's exit is called push-out delamination. Damage due to delamination in a composite laminate lowers its bearing strength and deteriorates its durability under fatigue loads.

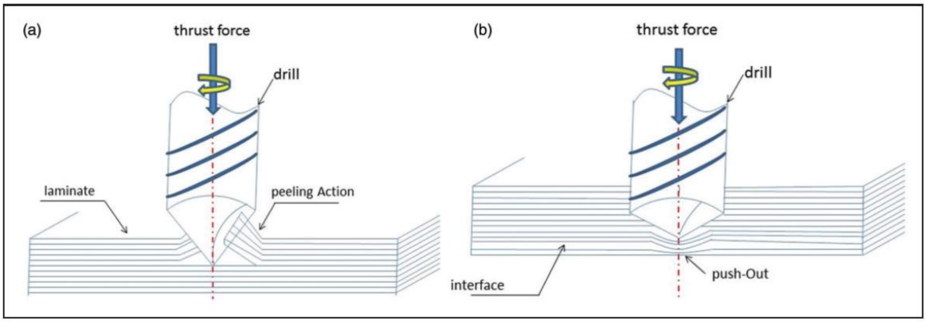


Fig. 1. Mechanism of delamination. (a) peel-up at the entrance of the drill into the composite laminate and (b) push-out at the exit of the drill from the composite laminate.

Delamination measures the damaged area around the hole caused by the drilling process. Delamination is caused by the bond separation between fiber layers due to greater cutting force. Drilling-induced delamination occurs both as it enters and exits the workpiece. Delamination occurs when the actual thrust exceeds the threshold value. The delamination factor (Fd) is used to characterize the degree of damage to the workpiece at the inlet and outlet of the drill. The image below shows a delamination visualization scheme. The delamination factor (Fd) in equation (1) according to Fig. 2 can be calculated from the ratio of the maximum diameter (Dmax) of the delamination zone to the bore diameter (D).

$$F_d = D_{max}/D \quad (1)$$

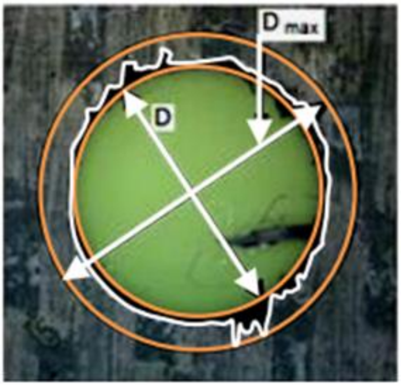


Fig. 2. Measurement of Delamination Factor (Fd)

3 Experimental Setup

3.1 Specimen Preparation

Prepare the tools and materials needed, such as molds, carbon fiber, resin and hardener, vacuum infusion machines, flow mesh peel ply, and vacuum plastic. The preparation of the layer on the mold is carbon, peel ply, flow mesh, release film, and vacuum plastic after applying glaze wax and PVA, connecting the vacuum infusion machine to the mold, and checking for leaks. If there is no leakage, the resin and hardener mixture is withdrawn into the mold. When the resin mixture has filled the mold, the remaining resin will enter the reservoir tube. Wait until the resin hardens, then remove the composite from the mold. Perform drilling according to DoE (Design of Experiment) in Fig. 3. On the horizontal axis are numbers 1 to 6 from left to right, and on the vertical axis are A to F from top to bottom.

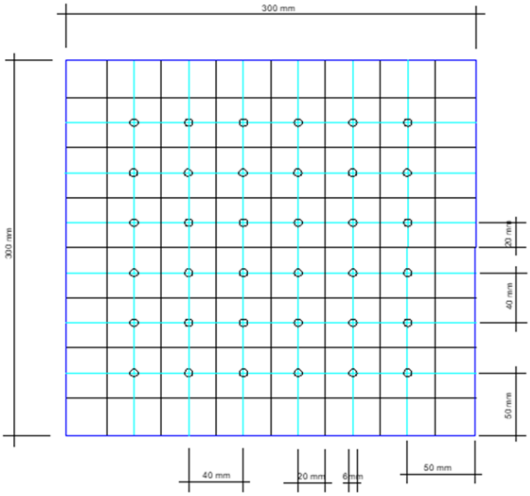
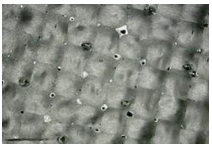
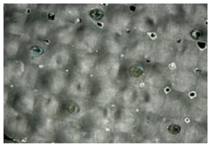
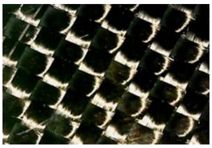


Fig. 3. Design of experiment, the circle represents the point of drilling spot.

Observation of composite results using Image Raster software synchronized with a calibrated metallographic microscope so that the observations follow actual conditions. Due usage of release film, bubbles are formed on the composite structure. As the bubble will affect the composite structure, the molding process must repeat without release film. The result of the composite surface without release film shows no bubbles, as seen in Table 1.

Table 1. Composite results seen on the metallographic microscope

	Entry	Exit
With release film		
Without release film		

3.2 Drilling Test

The drilling test uses a CNC machine, twists drill bit with diameters of 3mm and 6mm, and with variations in Rpm and drilling treatment. HSS (High-Speed Steel) Twist drill bit is used in this study. Each variation has six samples so that the results of the drilling quality can be seen for all the samples using a fixed feed rate of 0.038.

Drilling treatment in this study is divided into two, direct (using a 6mm drill bit) and gradual (a 3mm then a 6mm drill bit). After the drilling process, further observations were made using a metallographic microscope with a magnification of 100x to find out how much damage or defects were produced. The results of the observations will be processed using Image Raster software which has been synchronized with a calibrated metallographic microscope so that the observations are in accordance with the real conditions. Figure 4 is sample numbering, and Fig. 4 is one of the drilling results on sample A1.

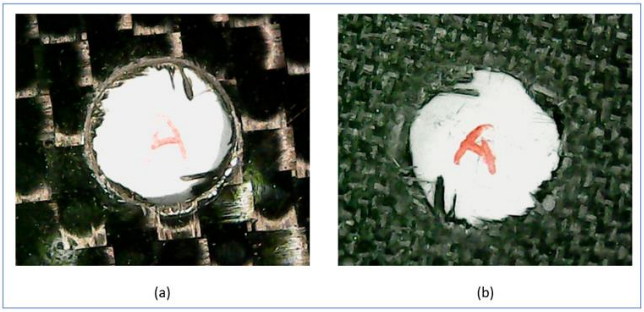


Fig. 4. Delamination result of A1 sample where (a) at the entry and (b) at the exit of the drill from composite laminate.

4 Result And Discussion

Table 2 shows the diameter after the drilling process. The image raster software calculates the diameter, and analyses are carried out using MATLAB to determine the value of the damage or defects produced.

Next is to determine whether RPM and drilling treatment will affect the delamination using two-way ANOVA. The results of two-way ANOVA calculations for delamination in the entry of composite laminate regarding the significance of delamination in Table 3. In Table 3, based on the hypothesis test using the F distribution, the P-value on the spindle speed is 0.006 <0.05 with a value of F > F crit with a value of 23.883 > 15.767.

Table 2. Delamination Factor Calculation

HOLE		Feed rate	RPM	drilling treatment	D	entry		exit	
						Dmax	Fd	Dmax	Fd
1	A	0.038	1500	gradually	0.611	0.708	1.159	0.772	1.264
	B					0.737	1.207	0.752	1.231
	C					0.746	1.222	0.757	1.238
	D					0.740	1.212	0.778	1.273
	E					0.734	1.201	0.752	1.230
	F					0.726	1.189	0.768	1.256
2	A	0.038	2500			0.757	1.239	0.789	1.292
	B					0.723	1.184	0.813	1.331
	C					0.744	1.218	0.781	1.278
	D					0.752	1.231	0.758	1.240
	E					0.738	1.207	0.786	1.286
	F					0.738	1.207	0.792	1.296
3	A	0.038	3500			0.861	1.408	0.841	1.376
	B					0.767	1.255	0.834	1.365
	C					0.793	1.298	0.806	1.319
	D					0.782	1.279	0.838	1.371
	E					0.762	1.247	0.796	1.303
	F					0.784	1.283	0.768	1.257
4	A	0.038	1500	direct		0.764	1.251	0.834	1.365
	B					0.734	1.202	0.762	1.247
	C					0.751	1.228	0.773	1.265
	D					0.758	1.241	0.820	1.341
	E					0.745	1.219	0.795	1.301
	F					0.754	1.234	0.752	1.230
5	A	0.038	2500			0.741	1.213	0.778	1.273
	B					0.806	1.319	0.794	1.299
	C					0.761	1.245	0.793	1.298
	D					0.754	1.233	0.847	1.385
	E					0.798	1.306	0.795	1.302
	F					0.776	1.270	0.789	1.292
6	A	0.038	3500			0.775	1.269	0.845	1.383
	B					0.818	1.339	0.932	1.525
	C					0.805	1.318	0.794	1.299
	D					0.825	1.350	0.813	1.331
	E					0.855	1.399	0.819	1.341
	F					0.808	1.322	0.866	1.417

From these results, RPM certainly has a significant effect on delamination. The most considerable delamination value was obtained at RPM 3500 with a value of 1.295. It can be concluded that the greater the spindle speed value, the higher the delamination value. The next parameter is the drilling treatment which produces a value of F > F crit with a value of 10.3477 > 4.171 based on the hypothesis test using the F distribution that the P-value is 0.003 <0.05. With this value, it can be concluded that by giving the drilling treatment in stages, the damage caused is slight, with an average value of 1.1983 at RPM 1500. The higher the RPM value, the resulting delamination effect increases.
The results of ANOVA calculations regarding the significance of the delamination on the exit surface can be seen in Table 4. Based on the hypothesis test using the F distribution, the P-value for spindle speed is 0.00049 <0.05 with F > F crit with a value of 9.9177 > 3.3158. From these results, RPM certainly has a significant effect on delamination. The most considerable delamination value was obtained at RPM 3500 with a value of 1.3827 with direct drilling treatment. Therefore, it can be concluded that the greater the spindle speed value, the higher the delamination value.

Table 3. Two-Way ANOVA Calculation On Entry

Anova: Two-Factor With Replication

SUMMARY *1500 rpm (X)*	gradually (A)	direct (B)	Total
Count	6	6	12
Sum	7.190	7.375	14.565
Average	1.198	1.229	1.214
Variance	4.927E-04	2.966E-04	6.180E-04
2500 rpm (Y)			
Count	6	6	12
Sum	7.286	7.586	1.487
Average	1.214	1.264	1.239
Variance	0.000385467	1.749E-03	1.652E-03
3500 rpm (Z)			
Count	6	6	12
Sum	7.770	7.997	1.577
Average	1.295	1.333	1.314
Variance	3.416E-03	1.825E-03	2.773E-03

ANOVA

Source of Variation	SS	*df*	*MS*	*F*	*P-value*
RPM	6.500E-02	2	3.250E-02	2	6.237E-02
Drilling treatment	1.408E-02	1	1.408E-02	1	3.101E-03
Interaction	5.644E-04	2	2.822E-04	0.207365	8.139E-01
Within	4.083E-02	30	1.361E-03		

Table 4. Two-Way ANOVA Calculation on Exit

Anova: Two-Factor With Replication

SUMMARY *1500 rpm (X)*	gradually (A)	direct (B)	Total
Count	6	6	12
Sum	7.492	7.749	1.524
Average	1.249	1.292	1.270
Variance	3.311E-04	2.882E-03	1.961E-03
2500 rpm (Y)			
Count	6	6	12
Sum	7.723	7.849	1.557
Average	1.287	1.308	1.298
Variance	8.666E-04	1.525E-03	1.208E-03
3500 rpm (Z)			
Count	6	6	12
Sum	7.991	8.296	1.629
Average	1.332	1.383	1.357
Variance	2.236E-03	6.569E-03	4.707E-03

ANOVA

Source of Variation	SS	*df*	*MS*	*F*	*P-value*
RPM	4.764E-02	2	2.382E-02	9.918E-00	4.940E-04
Drilling treatment	1.315E-02	1	1.315E-02	5.475E-00	2.614E-02
Interaction	1.431E-03	2	7.150E-04	2.979E-01	7.446E-01
Within	7.205E-02	30	2.402E-03		

The following parameter is the drilling treatment which produces a value of F > F crit with a value of 5.4797 > 4.171 based on the hypothesis test using the F distribution that the P-value is 0.02 <0.05. With this value, it can be concluded that by giving the drilling treatment in stages, the damage caused is slight, with an average value of 1.2487 at 1500 RPM with the drilling treatment in stages. Then the delamination effect is also influenced by the RPM value, as seen from the graph in Figure 4.5. the higher the RPM value, the resulting delamination effect increases. The higher the RPM, the higher the delamination value.

5 Conclusion

The drilling treatment greatly influences the results obtained. From previous calculations, the average value of damage to each RPM with the drilling treatment in stages is smaller than that of the damage in stages. This was reinforced by two-way ANOVA calculations with the result that the P value on the entry and exit surface was less than 0.05, indicating that the drilling treatment affected the delamination results. The highest level of delamination occurred at the entry surface at RPM 3500 with direct drilling treatment with a value of 1.3328 and the lowest at RPM 1500 with gradual drilling with a value of 1.1983. Then the highest level of delamination occurs on the exit surface at RPM 3500 with direct drilling treatment with a value of 1.3827 and the lowest value at RPM 1500 with gradual drilling with a value of 1.2487.

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