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DAMAGE BEHAVIOR OF CFRP LAMINATE WITH A FASTENER SUBJECTED TO SIMULATED LIGHTNING CURRENT

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Abstract
This paper examine the damage behavior of CFRP laminate with a titanium blind fastener subjected to lightning current by performing a simulated lightning current test. The fit of the fastener is varied with different countersink depth. Resulting damage is analyzed by NDTs and microscopic sectional observation; and the results show a large variation in type and severity of damage. The fit of the fastener clearly affects the extent of the damage; especially the depth with respect to the surface has a large influence.

1 Introduction
The excellent specific properties of carbon fiber reinforced plastics (CFRP) enable us to reduce the structural weight of large-scale weight critical structures such as airframe. Unlike the often replaced aluminum alloy, CFRP skins require special attention in design regarding internal damage. Both mechanical impact and lightning strike are known to cause internal damage, which greatly reduces the residual strength [1,2]. Internal damage caused by impact has been investigated by a number of researchers, and detailed fracture mechanisms have been clarified [1–4]. The direct effect of lightning strikes on laminated composite structures and their fracture behavior have also been investigated [5,6]. For an effect of fastener installation, results have shown that the presence of a fastener increases both the damage and the reduction in residual compressive stress due to a lightning test [3].
Since fasteners are often present in the outer skin of aircraft and they are therefore likely to be struck by lightning, it is essential to understand the resulting damage. The investigation presented here focuses on understanding the effect of the fit of the fastener on the damage caused by an artificial lightning strike.
The lightning struck specimens have been examined by visual, non-destructive and micrographic inspection

2 Experiments
2.1 Specimens
The laminates are made of prepregs composed of IMS60 carbon fiber and #133 epoxy resin produced by Toho Tenax. Prepreg molding in an autoclave was followed by a recommended cure cycle. The layup of the laminates is $[45/0/-45/90]_{4s}$ and the applied fastener is

MAXIBOLT CR7770S-06 100º flush head titanium blind fastener produced by Cherry Aerospace. The shaft diameter is 5.03±0.025mm.
For fastener installation, the fastener hole diameter (D_1) is 5.1mm according to installation guideline; and the countersink diameter (D_2) have been varied, see Figure 1. The countersink diameter was varied according to drilling the countersink 0.5 mm too shallow, the recommended depth or 0.5 mm too deep (8.6, 9.8 and 11.0 mm respectively, see Table 1).
The outer dimensions of the specimens are 150.0 by 100.0 mm.

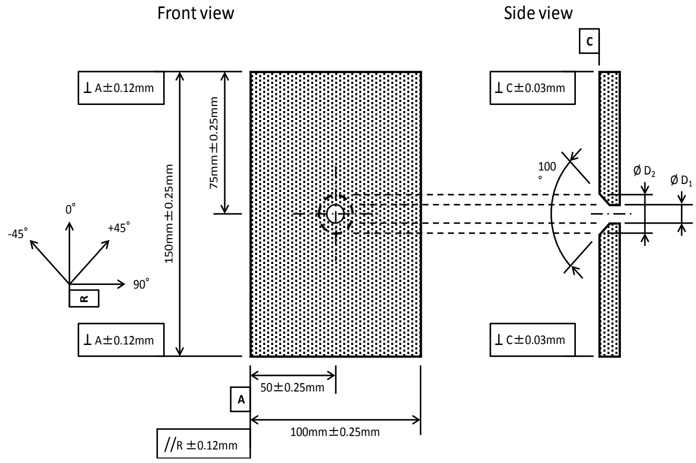


Figure 1. Schematic representation of the specimen and the fastener hole

Countersink	shallow	
	Recommend	
	Deep	

Table 1. Schematic of the condition of the fastener install

2.2 Experimental setup

In order to simulate natural lightning strikes, an impulse high-current generator (ICG) produced by Haefely Test AG. Figure 2 was applied. The specimens are clamped in a grounded copper jig inside the test chamber, as shown in Figure 3. The picture frame clamp covers only the outer edge, so the top and bottom surface in the middle are free. The discharge probe in the test chamber is connected to the ICG. It is placed 3 mm above the specimen surface (or the protruding rivet head in case of the shallow countersink).
The applied artificial lightning waveform is exponential, which can be characterized by the time to peak current (t_1) and the time required for the wave to decay to one-half of its maximum amplitude (t_2). In this case $t_1/t_2 = 8/20$ [μs]. The peak currents applied are 40 and 70 kA, which are not as high as components A or D in the SAE report [7], but high enough to damage these small size specimens. The peak current was selected so as to avoid the excessive damage of specimen without lightning protection.
In order to examine the effect of existence of fastener and fastener hole on lightning damage behavior, the specimens without fastener install were also tested with the same simulated lightning condition here. The number of specimen of each fastener installation and testing conditions are listed in Table 2.

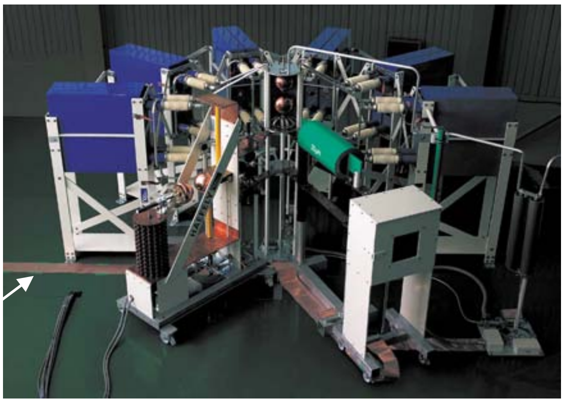


Figure 2. Schematic of impulse current generator ICG

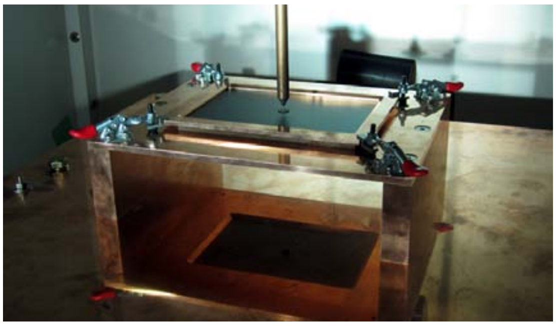


Figure 3. The grounded copper jig with a clamped specimen and the discharge probe above it.

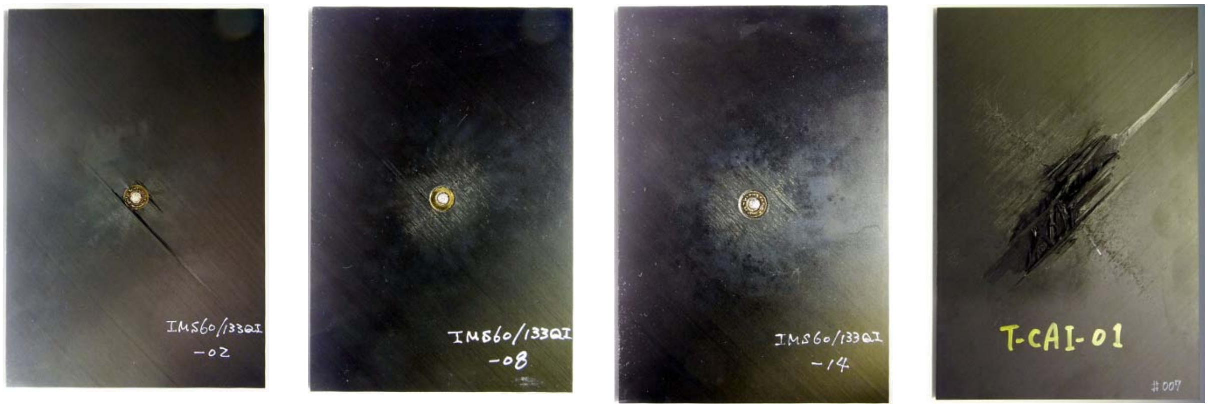
	Fastener install condition				Simulated lightning current condition		
	shallow	**recommend**	**deep**	**w/o fastener**	**Wave from [μs]**	**Peak current [kA]**	**Action Integral [kJ/Ω]**
Number of Specimen	3	3	3	2	8/20	40	28.4
	3	3	3	2		70	87.0

Table 2. Number of specimen and the testing condition

3 Results and Discussion

3.1 Visual inspection

Visual inspection of the post-lightning specimens shows the resin vaporized area around fastener head where lightning current attached; this is observed for all tested specimen and both current intensities. The appearances of the post-lightning specimens are shown in Figure 4. Each figure represents overhead view of the typical result of the specific test condition. Also observed especially among the shallow countersink specimens is outer ply separation; strips of the outer +45° layer have separated. The separation starts at the fastener hole and continues up to the clamped edge for some of these specimens. The width of the separated region is not much wider than the hole, see Figure 4 (a and (e. For comparison, lightning test results of the specimen without fastener install are shown in Figure 4 d) and (h. In case of the specimen without fastener, fiber brakeage and ply lift of the outer layer is observed at the lightning current attached point. The width of the fiber damage is much wider than that of fiber separation of the shallow countersink specimens. Around the fiber damage area, resin vaporized area can be observed the same as fastener installed specimens.



a) Shallow, 40kA b) Recommend, 40kA c) Deep, 40kA d) W/O fastener, 40kA

e) Shallow, 70kA f) Recommend, 70kA g) Deep, 70kA h) W/O fastener, 70kA

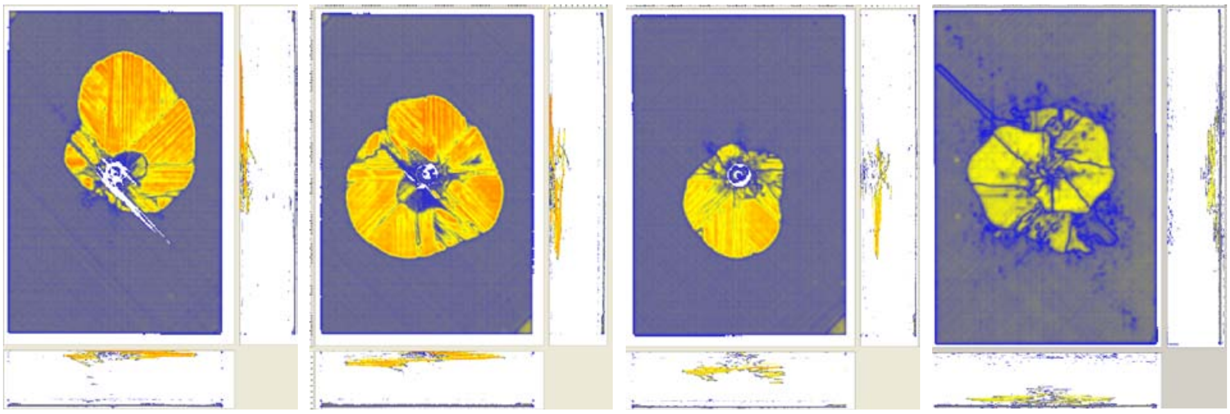
Figure 4.

3.2 Non-destructive Inspection

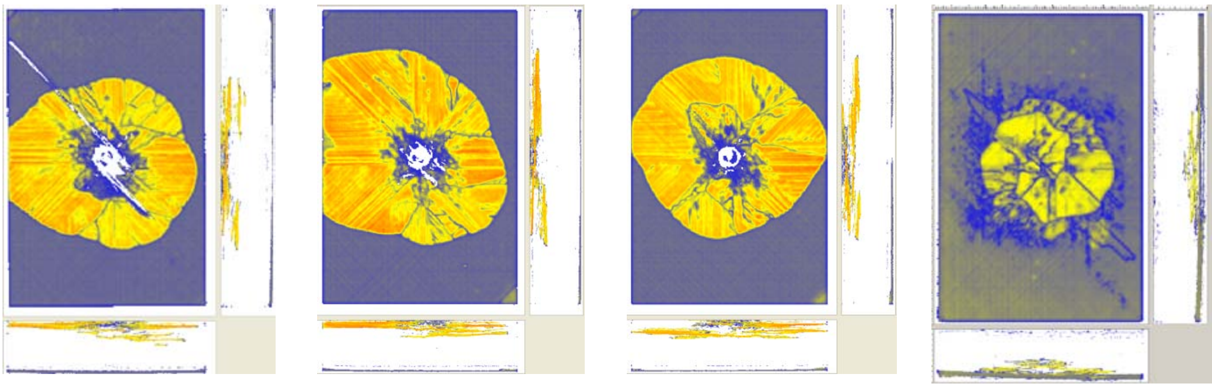
To analyze internal damage an ultrasonic flaw detector HIS3 produced by Krautkramer Gmbh is used. Here, 3.5 MHz focusing ultrasonic transducers are used. The observed shapes of damage differ for different countersink types and the applied current intensity. Figure 5 shows an example of a c-scan obtained from post-lightning specimens. For comparison, ultrasonic testing result for the post-lightning specimen without fastener installation is shown in Figure 5 (d and (h.

In general it can be said though that the damage progresses outward from the fastener hole in radial direction. If there is large outer ply separation, the damage extending in that direction (+45°) is less than in the other directions. The delamination propagates in the shape of a pair of fans along the fiber direction starting from the fastener or the lightning attachment point in each interlayer. In some cases, the damage is neither equally large in all directions, nor symmetric with respect to the other side of the fastener. This trend can be observed only in fastener installed specimens.

Focusing on the B-scope result, it can be observed that the location of largest delamination is differ for different countersink types while internal damage area of the specimen without fastener installation is limited to the vicinity of the specimen surface of lightning attached side. Looking at the projected damage area as a function of the countersink depth (Figure. 7), shows that the recommended countersink depth is not the best from a damage area point of view; the deepest countersink has the smallest projected area for both 40kA and 70kA current intensity. Compared with the result of the specimen without fastener, it is understood that the result of all tested specimen with fastener install show large scatter in any countersink condition and current intensity.

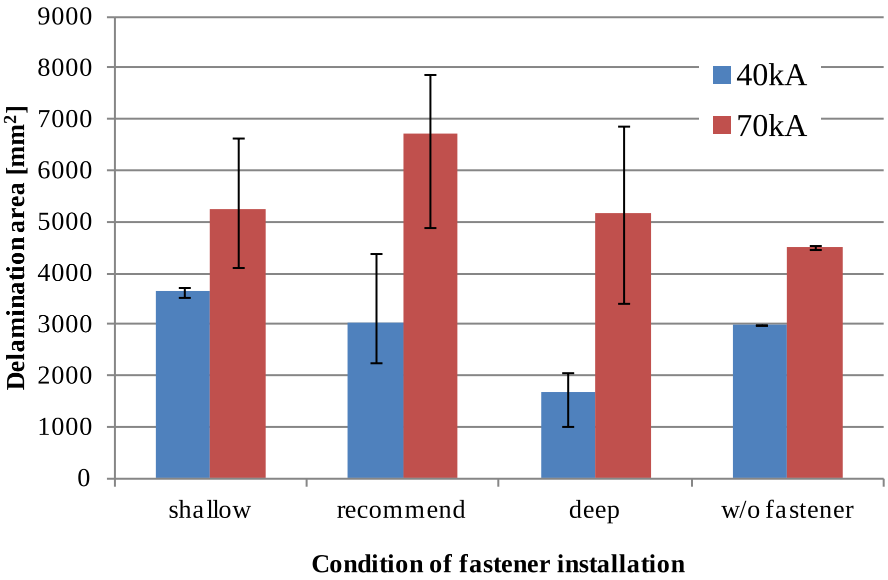


a) Shallow, 40kA b) Recommend, 40kA c) Deep, 40kA d) W/O fastener, 40kA



e) Shallow, 70kA f) Recommend, 70kA g) Deep, 70kA h) W/O fastener, 70kA

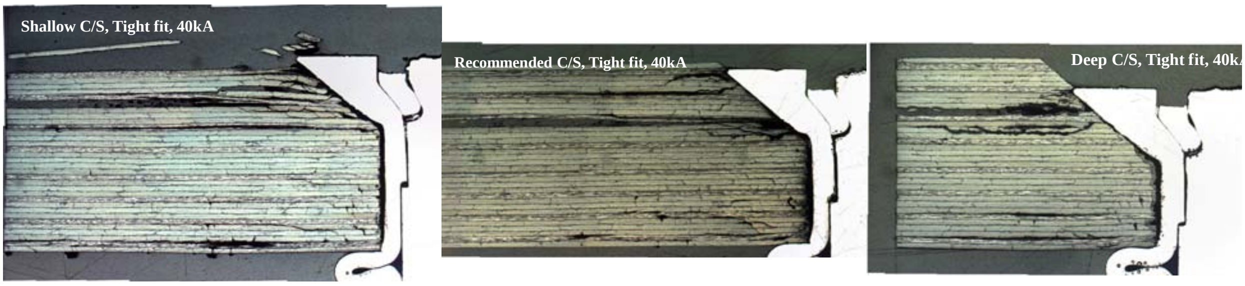
Figre 5. Typical C-scan images of post-lightning specimen



Fiugre 6. Projected damage area vs. countersink install condition.

3.3 Sectional observation

To analyze internal damage in thickness direction, sectional microscopic observation is performed. The typical observation results for different countersink condition with 40kA simulated lightning current test are shown in Figure 7. Generally, post-lightning specimen have delaminations close to the surface on the lightning attachment side, i.e. in the



a) Shallow, 40kA **b)** Recommend, 40kA **c)** Deep, 40kA

Figure 7. Typical sectional microscopic observation results

countersink region and also near the back surface where the fastener head is in contact with the laminate. In case of the specimen without fastener installation, delamination could find only vicinity of the specimen surface where simulated lightning current was attached. This fact indicate that the damage initiation of the specimen with fastener install is caused by arching between the fastener and fastener hole edge. As shown in the result of sectional microscopic observation in Figure 7, largest delamiantion is observed in different position in the thickness direction; the largest delamination can be observed in the middle of the countersink in case of shallow countersink (Figure 7 (a), in case of recommend countersink, that can be observed in the end of countersink (Figure 7 (b), and in case of deep countersink, that can be observed in the top of fastener head (Figure 7 (c).

The location of first arcing point between fastener and fastener hole differ from the difference of fastener install condition; when applying the simulated lightning current, the location where has the strongest electric field intensity is governed by the positional relationship between fastener head and countersink. A large amount of electrical energy is likely to deliver to CFRP laminate through the ionized leader channel formed by the arcing; the joule heating caused by the electrical current generate the internal delamination. [X] Thus, the position in the thickness direction of resulting delamiantion is strongly affected by the fastener install condition of countersink.

Looking at the gap between the fastener shaft and wall of the fastener hole, it is observed that the contact between them is unsteady, thought fastener head and sleeve end show a good electrical contact with countersink and backside surface, respectively (See. Figure 7). This is because fasteners are installed as clearance fit, in this study. This means that the center of the fastener is not always located in the center of the fastener hall; the circumferential direction clearance between the faster shaft and fastener hole is uneven. It is considered that this uneven contact in the circumferential direction is the main cause of the large scatter of delamination projection area and the unsymmetrical delamination progress in an inter-lamina with respect to the fastener.

4 Conclusions

The fit of the fastener is varied with different countersink depth and the results show a large variation in type and severity of damage.

In general, projection area of the resulting delamination of the specimen with fastener show large scatter compared with that of the specimen without fastener.

It can be said that a too small countersink depth leads to increased surface damage compared to the other two countersink depths, in some cases including separation of the outer plies. The largest countersink depth shows the smallest projected internal damage area for both current intensities. Looking at the cross-sectional images reveals that the largest delaminations is concentrated at the countersink and at the rivet-head at the back surface.

The fit of the fastener clearly affects the extent of the damage; especially the depth with respect to the surface has a large influence.

References

[1] Hirano Y., Katsumata S., Iwahori Y., Todoroki A., Artificial lightning testing on graphite/epoxy composite laminate. *Composites Part A*, **41**, 10, pp 1461-1470 (2010).

[2] Feraboli P., Kawakami H., Damage of carbon/epoxy composite plates subjected to mechanical impact and simulated lightning. *Journal of Aircraft*, **47**, 3, pp 999-1012 (2010).

[3] Ishikawa T, Sugimoto S, Matsushima M, Hayashi Y., Some experimental findings in CAI tests of CF/PEEK and conventional CF/EPOXY flat plates, *Compos Science and Technology*, **55**, 349–60 (1995).

[4] Ishikawa T, Aoki Y., Suemasu H., *Pursuit of mechanical behavior in compression after impact (CAI) and open hole compression (OHC)*, in “Proceedings of *ICCM-15*, urban, South Africa, (2005).

[5] Ogasawara T., Hirano Y., and Yoshimura A., Coupled thermal-electrical analysis for carbon fiber/epoxy composites exposed to simulated lightning current, *Composites Part A*, **41**, 8, pp973-981 (2010).

[6] Feraboli P., Miller M., Damage resistance and tolerance of carbon/epoxy composite coupons subjected to simulated lightning strike, *Composites: Part A*, **40**, 6-7, pp 954-967 (2009).

[7] SAE Committee report, AE4L-97-4. *Aircraft lightning environment and related test waveforms standard* (1997).