An Application of Failure Mode, Effects and Criticality Analysis (FMECA) for Composite Structures of Airplanes’ Wings

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Abstract. Composite structures have played a significant role in enhancing airplane’s performance. However, defects inside can be a potential threat to flight safety. To resolve the hazard, FMECA was applied to the defect analysis of composite structures on airplane’s wing. And the failure mode of the highest criticality was found to be the impact damage. Then impact test on typical composite laminates was carried out. The caused damage was qualitatively analysed and proved impact of low energy brings latent risk. Practical solution was put forward to improve the safety or reliability of the applied composites in the airplane.

1. Introduction
At present, the utilization of composite structures in the airplanes’ wings has been developed from the secondary bearing parts to the main bearing parts. However, defects inside threatened the flight safety. To reduce the risk, defect analysis of the composite structures.

FMECA has been a well-established method to evaluate defects, or in another way saying, failure modes of products. Duan Zhaobin and Zhang Peng applied FMECA and ontology to the fault diagnosis of flight control system. The share of the fault diagnosis information was realized among aviation manufacturers, users and researchers [1]. Hu Yifan carried out FMECA for an aero-engine spindle subsystem which contributing to the reliability optimization design [2]. So far, few researches on the defect analysis of composites structures by FMECA was studied. Therefore, an approach of FMECA on general and typical composite structures of the wings was advanced. Several failure modes and the causes were concluded. Then the criticality of each mode was evaluated and the highest one came to be impact damage. Thus, impact of different energy level on typical composite laminates was tested and the damage caused was qualitatively studied. Finally, available solution to risk reduction and safety restoration was proposed.

2. Composite structures of wings

2.1. Distribution and Description of Composite Structures on the Wing

A quite number of composites structures applied in aircraft wing and some of them were listed in Table 1.
Table 1. Composites structures of the wing

| Structure                  | Function                                                                 |
|----------------------------|--------------------------------------------------------------------------|
| Low and high-speed ailerons| Control aircraft rolling attitude.                                       |
| Flap track fairing         | Wrap flaps and block airflow ahead.                                      |
| Leading edge flap          | Increase the wing area and bending, improve lift coefficient.            |
| Inside and outside flaps   | Control aircraft rolling attitude during cruise and link with flaps at   |
|                            | low speed.                                                               |
| Spoiler                    | Disrupt the airflow and create a controlled stall zone on the back wing|
|                            | to dramatically reduce lift.                                             |
| Winglet                    | Weaken the effect of airflow around the top surface under wingtip and    |
|                            | reduce lift loss                                                        |

2.2. Common Defects of Composite Structures

Compared with traditional metal material, composites have great advantages in weight reduction but assuring the structural strength simultaneously. However, under the complicated influences of extreme flight environment accompanying material aging and human error, defects or structure failures could emerge with a high possibility. And the most common are delamination and impact damage which could seriously destroy composites’ mechanical performance.

Figure 1 is the sketch of delamination. In most case, the delamination was caused by unexpected applied force which leading to the failure of adhesive layer. Then the bonding interface would separate followed by gap generating. That is catastrophic to the composites wing skin in high altitude flying. The most dangerous situation could be a large area of stripped wing skin resulting in instantaneous lift loss during flight. In Figure 2, impact damage refers to surface damage along with internal defect of composites caused by instantaneous exterior force. Due to the characteristics of anisotropy and energy absorption, surface damage could be mild from visual observation while the interior could be rather serious [3, 4]. This feature made impact damage a latent trigger to unexpected structure failure. Therefore, to lessen the harm, adverse effects of the common defects should be evaluated by safety analysis method.

3. An Application Example of FMECA for Composite Structures of Airplanes’ Wings

3.1. The Procedures of FMECA

The procedures of FMECA followed below.[5]

1. System definition: analysis of product functions and hierarchy, that is, to determine the general function of the composite structure on the wing is to maintain the overall shape in flight and secure structural integrity. The hierarchy contains structural parts, wing and the aircraft.

2. Failure modes analysis: analyzing possible failure modes of product, that is, to find out every possible failure mode of aircraft wing composite structure.

3. Failure cause analysis: that is to determine the cause of each failure mode.

4. Failure effects analysis: that refers to find out the adverse influence of each mode and determine its severity level.
5. Criticality analysis: comprehensive evaluation of the adverse influence of each mode according to its severity and occurrence level, and proposing improvement or compensation measures.

3.2. Severity and Occurrence Level Definition
The definitions were listed in Table 2 and Table 3.

| Severity level | Description | Explanation |
|----------------|-------------|-------------|
| I              | Catastrophic| Lead to casualty, products destruction, great property damage and environmental damage. |
| II             | Fatal       | Lead to human injury, products damage, mission failure, serious property and environmental damage. |
| III            | Medium      | Cause moderate injuries to personnel, delayed or degraded missions and damage to products, property and environment |
| IV             | Low         | Cause unplanned maintenance or repair |

| Occurrence level | Description | Occurrence probability (P) range |
|------------------|-------------|--------------------------------|
| A                | Frequently  | $P > 10^{-1}$                  |
| B                | Often       | $10^{-3} < P \leq 10^{-1}$     |
| C                | Occasionally| $10^{-5} < P \leq 10^{-3}$     |
| D                | Rarely      | $P \leq 10^{-5}$               |

3.3. FMEA Worksheet and CA
According to procedures, final FMEA results were shown in Table 4 listed in the next page. After the FMEA work, CA was carried out according to the severity and occurrence level. The criticality matrix was shown in Table 5.

| Occurrence level | Severity level |
|------------------|---------------|
|                 | I | II | III | IV |
| A                |   |    |    |    |
| B                | 5 | 6  | 3  |    |
| C                |   | 1  |    | 4  |
| D                | 7 |    | 2  |    |

In Table 5, the red area is unacceptable which means failure modes within is of great harm. The yellow represents the selective acceptance region. It refers to that the criticality of failure modes within can be controlled considering actual situation. While the green area is acceptable, that is, the impact of the failure mode inside can be well-controlled. It shows that the criticality of the failure mode No.5 is unacceptable because it’s in the red area. The criticality of No.1, No.6, and No.7 failure mode has to be considered according to the actual situation. The rest No.2, No.3, and No.4 are acceptable.
Table 4. Application of FMECA for composite structures of aircraft wings worksheet
Initial indenture level: Aircraft. Indenture level: wing. Mission: A single flight.

| No. | Name    | Function                                    | Failure mode | Cause                      | Failure effects                      | Severity level | Occurrence level |
|-----|---------|---------------------------------------------|--------------|----------------------------|--------------------------------------|----------------|------------------|
| 1   | Wing    | Increase wing area and lift                 | Jam          | Flap screw wears           | Flaps cannot retract properly        | Wing area Reduces | I                | C                |
| 2   | Aileron | Control differential deflection of left and right ailerons to generate rolling torque | Stuck        | Actuator keeps stuck       | Ailerons cannot deflect              | The wing cannot provide rolling torque | III              | D                |
| 3   | Spoiler | manoeuvring system provides lift power and improve the aircraft’s manoeuvrability. | Upturn       | Control pulley shaft fouling | The spoiler cannot be retracted to the correct position | The wing cannot take the lift off | IV               | B                |
| 4   | Winglet | Reduces drag and fuel consumption during flight | Structural fracture | Material fatigue crack | Structural fracture | The induced drag cannot be reduced | Aircraft induced drag increases | IV | C |
| 5   | Flap track fairing | Wrap the exposed flap support structure and drive mechanism | Impact damage | External impact damage | Internal damage of material | Internal structure exposure | Aircraft drag increases | I | B |
| 6   | Nacelle fairing | Adjust airflow and protect internal engine components | Crack | Composite delamination | Broken fairing | Engine components exposure | Form threats to the engine | III | B |
| 7   | Wing skin | Ensure the aerodynamic shape | Fall off | Composite delamination | Skin falls off | Internal structure exposure and aerodynamic shape damage | Lift reduces dramatically | I | D |

So, during the actual use of composite structures in aviation, impact damage with low energy is very common yet a potential threat. Therefore, the impact test of carbon fiber laminates already used in the wings were carried out to probe into the characteristics of the damage in different energy level. And measures were proposed to prevent the impact damage threatening safety in service [6].

4. Impact Damage Test

4.1. Impact test design

In order to make impact energy level the controlled variable, three carbon fiber laminate samples of the same size and thickness were chosen in this test. All of the three were made on aircraft production line. The size of a sample is 150mm×100mm and the thickness is 3mm. A sketch and real photo of these samples were shown in Figure 3.
The chosen platform was CEAST9350 drop hammer impact test machine from Impact Mechanics Laboratory of Xi’an Jiaotong University. To the three samples, three energy level of impact was set and each sample corresponded to each level. By adjusting the velocity of the hammer, the energy of impact could be altered as needed. The weight of the hammer is 5.41kg and other parameters were listed in Table 6.

| Table 6. Impact test parameters settings |
|-----------------------------------------|
| The impact order of samples             | #1  | #2  | #3  |
| Impact energy (J)                       | 15  | 20  | 25  |
| The velocity of the hammer (m/s)        | 2.35| 2.72| 3.04|

4.2. Analysis of test results

Test results were shown in Figure 4. (a) and (e) are results of sample #1 with 15J energy impact. On the top surface (a) of sample #1, dent of a small size could be hardly seen yet ambient fiber breaks were observable. Meanwhile, from the undersurface (e), the observation of a slight crack along the fiber direction and surface swelling was even harder.

(b) and (f) are the results of the 20J energy impact. Comparing the result (b) of 15J, the dent and damage crack on the top surface could be easily seen. And the crack amount was apparently greater than that of sample #1. Cracks around the dent propagated along with the fiber direction. From the bottom surface (f), a huge fiber crack emerged conspicuously which made great contrast to (e) of sample #1. Moreover, the length of crack also increases dramatically and the bulge was obvious.

(c) and (g) are the results of the 25J energy impact. Because of the highest impact energy applied in this test, damage caused was further aggravated reflecting in the deepest and largest dent as well as the greatest number of cracks emerged in the top surface (c). While, on the back side (g), the bulging area was also of the largest size and the length of the cracks was the longest. What’s more, the delamination damage becomes visible to the naked eye.

Above all, the larger impact energy is, the greater damage is. By comparing the test results of different impact energy, it can be found that the low-velocity impact (15J) caused a potential threat because the damage presented differentiate greatly in the top and bottom surface. The defects inside caused by the impact were complicated and invisible to the naked eye. Therefore, corresponding measures must be taken to reduce or even eliminate the threat of the low-velocity impact.

![Figure 4. The top and bottom surfaces of samples after impact:](image-url)
5. Corresponding Measures: NDT (non-destructive testing) Technology

At present, a number of the NDT technologies have been actually leveraged in the aviation. S. Gholizadeh reviewed advantages and disadvantages of various NDT methods for the evaluation of composite materials [7]. Among these methods, air-coupled ultrasonic testing technology has realized the defect detection of composite structures in many aircrafts, such as the trailing edge and tail of the Boeing 737’s wing, the Airbus A320 aileron and the Black Hawk helicopter rotor [8]. The aforesaid impact damage of composite structures can be successfully detected by NDT technology to determine the basic information of its location, area, depth, etc. And suitable maintenance measures can be taken by considering the obtained information.

6. Conclusion

To eliminate the potential safety threat of composite structures failure on aircraft, FMECA was used to conduct the defect analysis and failure modes of typical structures were found out. The cause and adverse impact of each failure mode were concluded. According to the severity level and occurrence level, the criticality matrix was drawn and the most critical one was found out to be the impact damage. The FMECA results indicated that unexpected impact on composite structures could be a potential threat to flight safety. Therefore, the impact damage test was carried out on carbon fiber laminates to probe into the damage features in different impact energy. It was found that both the internal and external damage were serious and obvious under the impact energy of 20J and 25J. While when the energy is 15J, damage on the top surface and bottom surface differentiated greatly and the damage inside was invisible which commit to be a safety hazard. Thus, NDT technology were proposed to determine the damage firstly and based on detection results, appropriate maintenance measures could be taken to restore or improve the structure reliability which finally ensures flight safety.

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