Chapter 6

Fault Tree Analysis for Composite Structural Damage

Chapter Outline

6.1 INTRODUCTION

In the past decade, the use of composite materials in commercial aircraft has grown significantly. More than 50% of the Boeing 787 and Airbus 350 airframes are made of composite materials [10,11]. The main motive is that composite is a lightweight material with design diversity. By selecting fiber material, fiber orientation, matrix volume, and so forth, the designer can manipulate the local material properties to increase the strength and resistance of the required direction [45]. However, such powerful design capabilities also present considerable side effects. Various combinations and forming processes induce high scatter in material properties and lead to complex damage modes, causing difficulties in fault diagnosis and prognosis.

Composite structures are usually fatigue and corrosion resistant but are more susceptible to impact damage caused by bird strike, hail and tools impact, and so forth. The fracture of composite structures is due to multiple damage modes and their interactions. The damage modes depend on various parameters, such as

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the property of the fiber and matrix, fiber lay-up, cure procedure, environment, temperature, operating conditions, and so forth. Due to a large scatter in material properties, deterministic methodologies may lead to conservative results, such as excessive weight and frequent inspections without taking account of uncertainties. Alternatively, probabilistic methodologies were proposed considering different aspects of the composite damages incorporating cumulative damage, manufacturing defects, operating environment and laminate theory, and so forth [46,47]. However, most of the studies are on a microscopic level based on experiments, computer modeling, or mechanical theory. Various macroscopic damages obtained from operational aircraft have not been comprehensively addressed. In this chapter, typical in-service damages occurring in composite airframes are collected via a survey to an airline maintenance department. It is noted that "damage mode" can have different meanings in different situations. Herein, "damage mode" refers to the superficial damage characteristics that can be seen visually or by nondestructive devices.

Traditionally, fault tree analysis (FTA) is a method used for system failures, which can dig out root causes and identify the weak links of a large system either qualitatively or quantitatively. This chapter extends FTA to areas of composite structures. A variety of damage modes and damage causes can be synthesized in a tree structure and analyzed systematically on a macroscopic level. Main damage modes and damage causes can be prioritized through qualitative analysis and, therefore, this method can be used as a diagnostic tool to identify and correct causes of composites failure. It can help promote understanding on complex damages and their logic relationship leading to failure more intuitively. Also, this method can be used for Monte Carlo simulation and fuzzy comprehensive evaluation if detailed damage information is available. Engineers from airlines and manufacturers can evaluate the reliability of the structure and the damage severity through extended quantitative analysis.

6.2 BASIC PRINCIPLES OF FAULT TREE ANALYSIS

FTA is one of the most important logic and probabilistic techniques used in probabilistic risk assessment and system reliability assessment. It was first developed by AT&T's Bell Laboratories in 1962. Later in 1974, US Atomic Energy Commission published a report on risk assessment of nuclear power stations, in which FTA was extensively and effectively used and the development of FTA was promoted greatly since then.

FTA is a deductive, "top-down" system evaluation process that focuses on one particular undesired event and possible causes through a qualitative model. The analysis starts with an undesired event with top-level hazard and identifies all credible single faults and faults combinations at the subsequent level that lead to the top event in a systematic pathway. Then the analysis continues through successive levels until a basic cause is unfolded or until the specific requirement is met. Basic cause events are such events that cannot be further broken down, which may be malfunctioning from the system inside or from external damage [48].

In other words, a fault tree is a graphic model of the pathways in a system leading to a foreseeable, undesirable fault event. Events and conditions that contribute to the undesirable event are interconnected through various logic symbols along the pathways to reflect their cause-and-effect relationship. This qualitative model is capable of conducting quantitative evaluations provided that numerical probabilities of occurrence are input and propagated throughout.

6.2.1 Elements of FTA

Basically, three kinds of event term are used in FTA:

1. *Basic event*: The initiating fault event without further development.
2. *Intermediate event*: A fault resulting from the logical interaction of initiating faults.
3. *Top event*: The occurrence of an undesired event for the system as a result of the occurrence of several intermediate events. Several combinations of initiating faults lead to the event.

A fault tree comprises two kinds of symbols: logic and event. The events are connected by various logic symbols representing different relationships. There is no connection within logic symbols or events. The general rule of symbols is to keep them simple and clear. Common fault tree symbols are listed in Table 6.1.

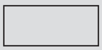
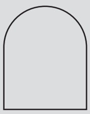
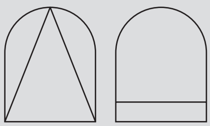
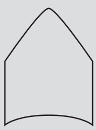
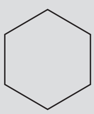
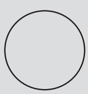
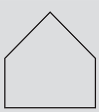
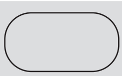
6.2.2 Boolean Algebra Theorems

Boolean algebra is used for set operation. Different from the common rule of operation, Boolean algebra can be used to analyze faults. In FTA, the occurrence of a top event can be described by combinations of occurrences of basic events. The minimal combination of basic events can be obtained through Boolean operation. Common Boolean operations are listed in Table 6.2.

6.3 FTA FOR COMPOSITE DAMAGE

Consider the damage of a composite structure as a system. The failure of the system is defined as one or more damages occurring in the structure leading to repair or replacement of the structure. The failure of the system is assumed to be the top event causing by both external and internal damage. "External damage" refers to any surface damage that is visible or barely visible, whereas "internal damage" denotes any damage that occurs inside the structure or throughout the structure that is either visible or detectable. External damage and internal damage can be subdivided into different damage modes as intermediate events. These intermediate events have various root causes as basic events. Two types of logic gates are used to connect different layers of the tree: the "AND" gate allows the output of

TABLE 6.1 Fault Tree Symbols

Symbol	Name	Definition
	Description box	Description of an output of a logic symbol or an event
	AND gate	Boolean Logic gate—event can occur when all the next lower conditions are true
	OR gate	Boolean Logic gate—event can occur if any one or more of the next lower conditions are true
	Priority AND gate	Boolean Logic gate—event can occur when all the next lower conditions occur in a specific sequence (sequence is usually represented by a conditional event)
	Inhibit	Output fault occurs if the (single) input fault occurs in the presence of an enabling conditional event
	Transfer	Indicates transfer of information
	Basic event	Event which is internal to the system under analysis, requires no further development
	House	Event which is external to the system under analysis, it will or will not happen ($Pf = 1$ or $Pf = 0$)
	Conditional event	A condition that is necessary for a failure mode to occur

the event to occur only if all input events occur, which is equivalent to the Boolean symbol "·"; the "OR" gate allows the output of the event to occur if any one or more input events occur, which is equal to the Boolean symbol "+." A hierarchical fault tree can be established with proper gates connected. The advantage of this fault tree is that it provides an effective approach to synthesize various damage modes and damage causes in a systematic manner.

TABLE 6.2 Boolean Algebra Theorems

Name	Theorem description (*X, Y, Z* are sets)
Commutative law	$X \cdot Y = Y \cdot X, \quad X + Y = Y + X$
Associative law	$X \cdot (Y \cdot Z) = (X \cdot Y) \cdot Z, \quad X + (Y + Z) = (X + Y) + Z$
Distributive law	$X \cdot (Y + Z) = X \cdot Y + X \cdot Z, \quad X + (Y \cdot Z) = (X + Y) \cdot (X + Z)$
Absorption law	$X \cdot (X + Y) = X, \quad X + (X \cdot Y) = X$
Complementation law	$X + \overline{X} = U, \quad X \cdot \overline{X} = \Phi, \quad \overline{\overline{X}} = X$
Idempotency law	$X \cdot X = X, \quad X + X = X$
De Morgan's law	$\overline{(X \cdot Y)} = \overline{X} + \overline{Y}, \quad \overline{(X + Y)} = \overline{X} \cdot \overline{Y}$

A survey was conducted at an airline maintenance department to collect information on in-service damage in composite airframes. A typical composite laminated panel made of carbon fiber reinforced plastic (CFRP) was selected as an illustration. The overall organization of the fault tree is shown in Fig. 6.1.

The top event is the failure of the CFRP laminate panel, followed by external and internal damage connected by an AND gate as the first layer of intermediate events. The intermediate events on the second layer are various damage modes connected by two OR gates with the upper layer. The basic events are all

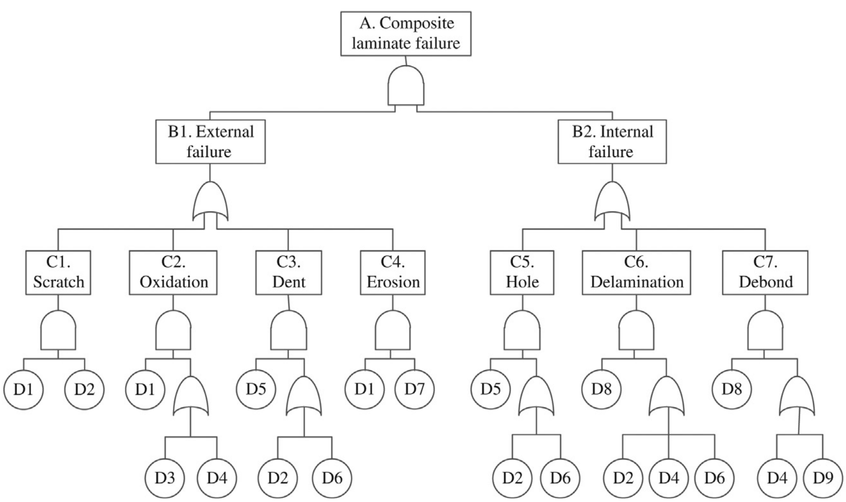


FIGURE 6.1 Fault tree construction of composite laminate structure. *D1*, Surface protection; *D2*, mishandling; *D3*, lightning strike; *D4*, heat; *D5*, material resistance; *D6*, natural object impact; *D7*, wind/sand/rain erosion; *D8*, manufacturing defects; *D9*, overloading.

potential damage sources or root causes. Take C3 Dent as an illustration: it is caused by both D5 Material resistance and the other event, which is caused by either D2 Mishandling or D6 Natural object impact. According to the survey, C1 to C7 are seven of the most frequent damage modes that occurred in aircraft composite structures made of CFRP. Crack is not listed because the occurrence of several other damage modes, such as dent, hole, and delamination are accompanied by fiber buckling, matrix cracks, and even fiber breakage [49]. It should be mentioned that moisture and ultraviolet radiation is not included because carbon fiber reinforced plastics have low sensitivity to the environment [8]. If the selected composite panel is a honeycomb or is made of Kevlar, moisture ingress and ultraviolet radiation will be significant contributors to the damage. Most of the delamination and debonding is not only due to impact damage, heat, and overloading, but also caused by defects during manufacturing [50]. Therefore, manufacturing defect is considered as an important contributor. Impact damage, such as dent covers a wide variety of events including tool drop, cargo buggy strike, bird strike, and so forth. For the sake of simplicity, impact damage sources are divided into two categories: human errors and natural accidents. Meantime, other damage sources have been simplified to facilitate the qualitative analysis.

In addition to the damage sources, the properties of the composite material and surface protection are also taken into account as basic events. Material resistance is one of the inherent properties of composite laminates, which is the ability of the material to resist impact damage [51]. As to surface protection, abrasion resistant coatings, antierosion coatings, antistatic coatings, and so forth can effectively reduce the damage caused by scratching, lightning strike, and so forth.

6.4 QUALITATIVE ANALYSIS

The primary step of the qualitative process is to obtain a minimal cut set list, which provides key qualitative information. Three importance analyses including structure importance analysis, probability importance analysis, and relative probability importance analysis are performed sequentially on the basis of the minimal cut sets.

6.4.1 Minimal Cut Sets

The minimal cut sets for the top event are a group of sets consisting of the smallest combinations of basic events that result in the occurrence of the top event. They represent all the ways in which the basic events cause the top event [52]. The equivalent Boolean algebra function of Fig. 6.1 can be expressed as:

$$\begin{aligned} A &= \mathrm{B1} \times \mathrm{B2} = (\mathrm{C1+C2+C3+C4}) \times (\mathrm{C5+C6+C7}) \\ &= [\mathrm{D1D2+D1(D3+D4)+D5(D2+D6)+D1D7}] \\ &\quad \times [\mathrm{D5(D2+D6)+D8(D2+D4+D6)+D8(D4+D9)}] \end{aligned} \tag{6.1}$$

By applying the equivalent Boolean algebra operation, the final Boolean expression of the top event can be obtained as:

$$\begin{aligned} A = &(\mathrm{D2D5} + \mathrm{D5D6}) + (\mathrm{D1D2D8} + \mathrm{D1D4D8}) \\ &+(\mathrm{D1D3D6D8} + \mathrm{D1D3D8D9} + \mathrm{D1D6D7D8} + \mathrm{D1D7D8D9}) \end{aligned} \tag{6.2}$$

It can be seen from Eq. (6.2) that the top event is composed of two second-order minimal cut sets: $K_1 = \{\mathrm{D2, D5}\}$, $K_2 = \{\mathrm{D5, D6}\}$; two third-order minimal cut sets: $K_3 = \{\mathrm{D1, D2, D8}\}$, $K_4 = \{\mathrm{D1, D4, D8}\}$; and four fourth-order minimal cut sets: $K_5 = \{\mathrm{D1, D3, D6, D8}\}$, $K_6 = \{\mathrm{D1, D3, D8, D9}\}$, $K_7 = \{\mathrm{D1, D6, D7, D8}\}$, $K_8 = \{\mathrm{D1, D7, D8, D9}\}$. All the eight minimal cut sets are the premise of the following three importance analyses.

6.4.2 Structure Importance Analysis

Structure importance analysis is used to analyze the degree of importance of every basic event influencing the top event, from the perspective of the fault tree structure itself, regardless of the probability of the basic event [53]. There are two ways to perform the analysis. One is to calculate the structure importance coefficient for every basic event. The other is to estimate the importance by minimal cut sets. The complexity of the first method is increased by the growing number of basic events, in this case 29 combinations. Therefore, the second method by minimal cut sets is applied. The importance coefficient of the basic event X_i is estimated by:

$$I_{(i)} = \sum_{X_i \in K_j} \frac{1}{2^{n_i - 1}} \tag{6.3}$$

Where $I_{(i)}$ is the estimation value of the structure importance of the basic event X_i; $X_i \in K_j$ is the basic event X_i, which belongs to minimal cut set K_j; and n_i is the number of events in the minimal cut set containing X_i. Take D6, for example, the minimal cut sets containing D6 are K_2, K_5, and K_7. The number of events in each set is 2, 4, and 4, respectively. Thus, the structure importance coefficient $I_{(6)} = \frac{1}{2^{2-1}} + \frac{1}{2^{4-1}} + \frac{1}{2^{4-1}} = \frac{3}{4}$. After calculation, the results are shown in Table 6.3.

This table illustrates that surface protection (D1), material resistance (D5), and manufacturing defects (D8) play the most important roles. In terms of the

TABLE 6.3 Results of Structure Importance Analysis

1	Surface protection (D1)	Material resistance (D5)	Manufacturing defects (D8)	
3/4	Mishandling (D2)		Natural object impact (D6)	
1/4	Lightning (D3)	Heat (D4)	Wind erosion (D7)	Overloading (D9)

accidental damage sources, impact damage caused by mishandling and natural object impact is the main cause. Other damage sources are relatively less important.

6.4.3 Probability Importance Analysis

Probability importance is the derivative of the probability of the top event to the basic event, thereby reflecting the influence of the unreliability of the basic event to that of the top event. If the probability of the top event is $P(A) = Q(p_1, p_2, \cdots p_n)$, $n \in N^+$, the probability importance of the basic event D_i is expressed as:

$$I_p(\mathrm{D}_i) = \frac{\partial Q(p_1, \cdots p_n)}{\partial p_i} \quad i = 1, \cdots, n \tag{6.4}$$

Let $p(X_i)$ denote the probability of the basic event X_i, then the probability of the top event A is calculated as:

$$\begin{aligned} P(A) = {} & \sum_{i=1}^{8} p(K_i) - \sum_{i<j=2}^{8} p(K_i K_j) + \sum_{i<j<k=3}^{8} p(K_i K_j K_k) - \sum_{i<j<k<l=4}^{8} p(K_i K_j K_k K_l) \\ & + \sum_{i<j<k<l<m=5}^{8} p(K_i K_j K_k K_l K_m) - \sum_{i<j<k<l<m<n=6}^{8} p(K_i K_j K_k K_l K_m K_n) \\ & + \sum_{i<j<k<l<m<n<o=7}^{8} p(K_i K_j K_k K_l K_m K_n K_o) + p(K_1 K_2 K_3 K_4 K_5 K_6 K_7 K_8) \end{aligned} \tag{6.5}$$

where $p(K_i)$ can be obtained by Eq. (6.6):

$$p(K_i) = \prod_{i \in K_i} p(X_i) \tag{6.6}$$

where K_i is the ith minimal cut set, $i = 1, 2, ..., 8$.

According to the rare event approximation [54], *P(A)* can be approximated to its first item $\sum_{i=1}^{8} p(K_i)$. Therefore, the probability importance of each basic event is calculated as:

$$\begin{aligned} I_p(\mathrm{D1}) = {} & p(\mathrm{D2})p(\mathrm{D8}) + p(\mathrm{D4})p(\mathrm{D8}) + p(\mathrm{D3})p(\mathrm{D6})p(\mathrm{D8}) \\ & + p(\mathrm{D3})(\mathrm{D8})(\mathrm{D9}) + p(\mathrm{D6})p(\mathrm{D7})p(\mathrm{D8}) + p(\mathrm{D7})p(\mathrm{D8})p(\mathrm{D9}) \end{aligned}$$

$$I_p(\mathrm{D2}) = p(\mathrm{D5}) + p(\mathrm{D1})p(\mathrm{D8})$$

$$I_p(\mathrm{D3}) = p(\mathrm{D1})p(\mathrm{D6})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D8})p(\mathrm{D9})$$

$$I_p(\mathrm{D4}) = p(\mathrm{D1})p(\mathrm{D8})$$

$$I_p(\mathrm{D5}) = p(\mathrm{D2}) + p(\mathrm{D6})$$

$$I_p(\mathrm{D6}) = p(\mathrm{D5}) + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D7})p(\mathrm{D8})$$

$$I_p(\mathrm{D7}) = p(\mathrm{D1})p(\mathrm{D6})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D8})p(\mathrm{D9})$$

$$\begin{aligned} I_p(\mathrm{D8}) = {} & p(\mathrm{D1})p(\mathrm{D2}) + p(\mathrm{D1})p(\mathrm{D4}) + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D6}) \\ & + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D9}) + p(\mathrm{D1})p(\mathrm{D6})p(\mathrm{D7}) + p(\mathrm{D1})p(\mathrm{D7})p(\mathrm{D9}) \end{aligned}$$

$$I_p(\mathrm{D9}) = p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D7})p(\mathrm{D8})$$

Except for D1 Surface protection, D5 Resistance, and D8 Manufacturing defects, all the other basic events are in practice small probability events. Thus, it is relatively easy to make qualitative comparisons.

Since

$$I_p(\mathrm{D3}) = I_p(\mathrm{D7}) = p(\mathrm{D1})p(\mathrm{D8})[p(\mathrm{D6}) + p(\mathrm{D9})]$$

According to the associative law of addition,

$$I_p(\mathrm{D9}) = p(\mathrm{D1})p(\mathrm{D8})[p(\mathrm{D3}) + p(\mathrm{D7})]$$

Generally, D6 Natural object impact is one of the main damage sources with a frequency that is much higher than D3 Lightning, D7 Erosion, and D9 Overloading. So,

$$p(\mathrm{D6}) + p(\mathrm{D9}) > p(\mathrm{D3}) + p(\mathrm{D7})$$

Thus,

$$I_p(\mathrm{D3}) = I_p(\mathrm{D7}) > I_p(\mathrm{D9})$$

Because of the small probability principle,

$$p(\mathrm{D5}) + p(\mathrm{D1})p(\mathrm{D8}) > p(\mathrm{D5}) + p(\mathrm{D1})p(\mathrm{D8})[p(\mathrm{D3}) + p(\mathrm{D7})]$$

$$p(\mathrm{D1})p(\mathrm{D8}) > p(\mathrm{D1})p(\mathrm{D8})[p(\mathrm{D6}) + p(\mathrm{D9})]$$

Therefore,

$$I_p(\mathrm{D2}) > I_p(\mathrm{D6})$$

$$I_p(\mathrm{D4}) > I_p(\mathrm{D3})$$

Since D5 Material resistance is one of the inherent properties of the composite structure, which is difficult to change. $p(\mathrm{D5})$ is considered as a large probability. Then

$$p(\mathrm{D5}) + p(\mathrm{D1})p(\mathrm{D8})[p(\mathrm{D3}) + p(\mathrm{D7})] > p(\mathrm{D1})p(\mathrm{D8})$$

TABLE 6.4 Results of Probability Importance Analysis

High	Mishandling (D2)	Natural object impact (D6)	
Medium	Lightning (D3)	Heat (D4)	Erosion (D7)
Low	Overloading (D9)		

So,

$$I_P(\text{D6}) > I_P(\text{D4})$$

The final inequality and the results are obtained and shown in Table 6.4.

$$I_p(\text{D2}) > I_p(\text{D6}) > I_p(\text{D4}) > I_p(\text{D3}) = I_p(\text{D7}) > I_p(\text{D9}) \tag{6.7}$$

This table suggests that D2 Mishandling and D6 Natural object impact are the most critical damage sources, followed by D4 Heat, D3 Lightning, and D7 Erosion. D9 Overloading ranks last. According to the survey, most mishandlings lead to either apparent damage, such as scratch, dent, or internal damage, such as delamination. Natural object impact, such as runway debris is less likely to happen compared to human error. These two damage categories by human behavior and natural accidents are the most severe damages, which are of particular concern.

It should be noted that since D1 Surface protection, D5 Resistance, and D8 Manufacturing defects are inherently related to material properties or manufacturing process. It is difficult to define their probabilities, which will be discussed separately.

6.4.4 Relative Probability Importance Analysis

Probability importance analysis determines the influence of the probability change of the basic event on that of the top event, but cannot represent the difficulty of different basic events' improvement. Relative probability importance analysis is introduced to measure the variation of the top event probability from the aspects of sensitivity and probability of the basic event itself [55,56].

$$I_c(D_i) = \frac{p_i}{Q(p_1,\cdots p_n)} \cdot \frac{\partial Q(p_1,\cdots p_n)}{\partial p_i} \quad i = 1,\cdots,n \tag{6.8}$$

From Eq. (6.8), the relative probability importance of each basic event is calculated as follows:

$$\begin{aligned} I_c(\text{D1}) = [&p(\text{D1})p(\text{D2})p(\text{D8}) + p(\text{D1})p(\text{D4})p(\text{D8}) + p(\text{D1})p(\text{D3})p(\text{D6})p(\text{D8}) \\ &+ p(\text{D1})p(\text{D3})(\text{D8})(\text{D9}) + p(\text{D1})p(\text{D6})p(\text{D7})p(\text{D8}) \\ &+ p(\text{D1})p(\text{D7})p(\text{D8})p(\text{D9})]/Q\left(p_1,\cdots,p_n\right) \end{aligned}$$

$$I_c(\mathrm{D2}) = [p(\mathrm{D2})p(\mathrm{D5}) + p(\mathrm{D1})p(\mathrm{D2})p(\mathrm{D8})]/Q(p_1,\cdots,p_n)$$

$$I_c(\mathrm{D3}) = [p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D6})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D8})p(\mathrm{D9})]/Q\left(p_1,\cdots,p_n\right)$$

$$I_c(\mathrm{D4}) = p(\mathrm{D1})p(\mathrm{D4})p(\mathrm{D8})/Q\left(p_1,\cdots,p_n\right)$$

$$I_c(\mathrm{D5}) = [p(\mathrm{D2})p(\mathrm{D5}) + p(\mathrm{D5})p(\mathrm{D6})]/Q\left(p_1,\cdots,p_n\right)$$

$$\begin{aligned} I_c(\mathrm{D6}) = {} & [p(\mathrm{D5})p(\mathrm{D6}) + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D6})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D6})p(\mathrm{D7}) \\ & p(\mathrm{D8})]/Q\left(p_1,\cdots,p_n\right) \end{aligned}$$

$$I_c(\mathrm{D7}) = [p(\mathrm{D1})p(\mathrm{D6})p(\mathrm{D7})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D7})p(\mathrm{D8})p(\mathrm{D9})]/Q\left(p_1,\cdots,p_n\right)$$

$$\begin{aligned} I_c(\mathrm{D8}) = {} & [p(\mathrm{D1})p(\mathrm{D2})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D4})p(\mathrm{D8}) + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D6})p(\mathrm{D8}) \\ & + p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D8})p(\mathrm{D9}) + p(\mathrm{D1})p(\mathrm{D6})p(\mathrm{D7})p(\mathrm{D8}) \\ & + p(\mathrm{D1})p(\mathrm{D7})p(\mathrm{D8})p(\mathrm{D9})]/Q\left(p_1,\cdots,p_n\right) \end{aligned}$$

$$I_c(\mathrm{D9}) = [p(\mathrm{D1})p(\mathrm{D3})p(\mathrm{D8})p(\mathrm{D9}) + p(\mathrm{D1})p(\mathrm{D7})p(\mathrm{D8})p(\mathrm{D9})]/Q\left(p_1,\cdots,p_n\right)$$

Similar comparisons can be made and it is shown that D2 Mishandling and D6 Natural object impact rank the highest irrespective of the particular group of events mentioned previously (D1, D5, and D8).

6.5 QUANTITATIVE ANALYSIS

The survey collected damage records on aircraft structures made of composite materials. Wing structural damage (ATA Chapter 57) of two types of aircraft fleet (Boeing 737-800 and Boeing 757-200) recorded over a 10-year period were obtained. A breakdown of damage categories and their numbers of occurrence on composites made with CFRP are plotted in Fig. 6.2. It is shown that dent is the most frequent damage mode followed by painting peel-off. Due to the inconsistency of maintenance recording, damages, such as dent, scratch, erosion, and so forth can all lead to painting peel-off. To facilitate the following analysis, painting peel-off caused by scratch is assumed to take up approximately half of the percentage, rounding to 12%.

A statistical analysis was performed aiming at the selected laminated CFRP panel. Twelve occurrences of the primary damage mode dent were recorded in the CFRP panel in 6 Boeing 737-800 aircraft. The design life of Boeing 737-800 is 100,000 flight hours and the composite panel is assumed to have the same design life as the airplane. Therefore, the average number of dent events per flight hour is 2e-5. According to the percentage distribution of each damage mode in Fig. 6.2, the average numbers of occurrence for the seven damage modes per flight hour were calculated with some rounding and are shown in Table 6.5.

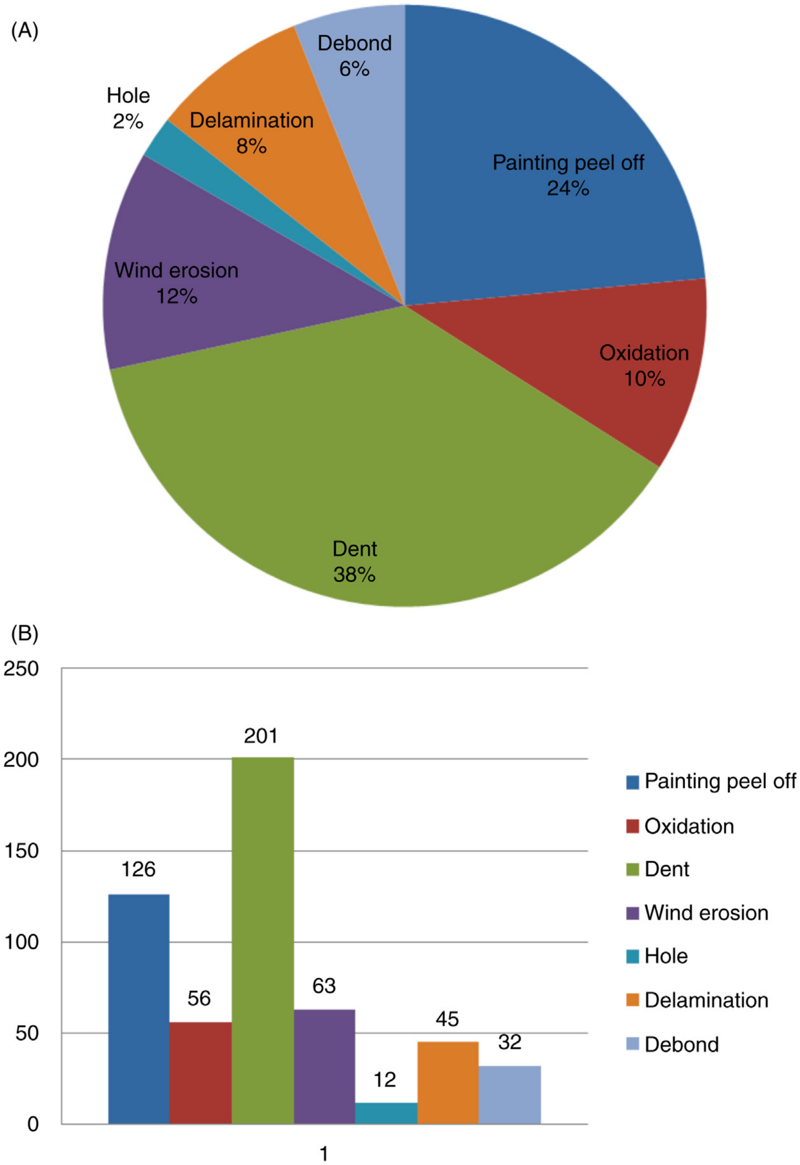


FIGURE 6.2 (A) Damage category and (B) occurrence number of CFRP composites.

Further, the probability of occurrence for damage modes was distributed to various damage causes by engineering experience from the airline. The distribution law is based on the Boolean operation in the fault tree structure in Fig. 6.1. Take C3 Dent as an illustration: it is caused by both D5 Material resistance and the other intermediate event, which is caused by either D2 Mishandling or D6 Natural object impact. Then we have the following relationship:

TABLE 6.5 Probability of Occurrence for Damage Modes

Damage mode	Number of occurrence per flight hour (probability)
C1 scratch	0.6e-5
C2 oxidation	0.5e-5
C3 dent	2e-5
C4 erosion	0.6e-5
C5 hole	0.1e-5
C6 delamination	0.4e-5
C7 debond	0.2e-5

$$P(C3) = P(\mathrm{D5}) \times [P(\mathrm{D2}) + P(\mathrm{D6})] \tag{6.9}$$

Replacing by numerical values, the allocated probability of occurrence for every basic event is obtained in the fault tree as listed in Table 6.6.

Once the probability distributions were assigned to every basic event, Monte Carlo simulation was then conducted as a validation of the previous qualitative analysis. Its principle is to simulate the occurrences of the primary events by a random number generator. In each trial, the primary event is simulated by generating a random number in the interval [0, 1], and if the number is no larger than the probability assigned, the event is reckoned to occur. Then the fault tree is evaluated for the top event probability and the contributions of the primary events by a large number of trials. In this analysis, the primary concern is the

TABLE 6.6 Probability of Occurrence for Damage Causes

Damage cause	Number of occurrence per flight hour (probability)
D1 surface protection	0.05
D2 mishandling	1.2e-4
D3 lightning strike	0.5e-4
D4 heat	0.5e-4
D5 material resistance	0.1 for dent/0.005 for hole
D6 natural object impact	0.8e-4
D7 wind erosion	1.2e-4
D8 manufacturing defects	0.02
D9 overloading	0.5e-4

probability importance of every basic event instead of the probability of the top event. Monte Carlo simulation was performed and the number of trials was set to 1e + 6; a table of the failure contribution towards the top event and the importance value of each basic event (damage cause) are obtained as discussed in the following section.

6.6 DISCUSSION

For quantitative analysis, current statistical damage data obtained from the survey is still not comprehensive. Some data needs to be either idealized or hypothesized based on engineering experience, such as the probability distributions of C1 Scratch, D1 Surface protection, D5 Material resistance, and D8 Manufacturing defects.

D5 Material Resistance is one of the inherent properties of composites, its resistance to low energy impact causing dent is weak whereas the resistance to large energy impact causing hole is relatively strong. Therefore, two discrete values are assigned to D5 for these two situations.

It should be noted that in Table 6.7 numerical values of failure contribution less than 1e-5 are neglected due to the program precision and thereby the corresponding D3, D7, and D9 with very low importance are set to 0. Overall, the importance ranking of damage causes is D5 > D8 > D2 > D6 > D4 = D1 > D3 = D7 = D9.

Previous qualitative analyses rank the importance of every basic event from three aspects. Structure importance analysis is based on the fault tree structure itself. Probability importance analysis reflects the unreliability of the basic event to the top event. Relative probability importance analysis was performed as a supplement measuring sensitivity. Rankings of the damage causes were obtained in Table 6.3 and Table 6.4. Compared with the results of the

TABLE 6.7 Importance of Damage Causes

Damage cause	Failure contribution	Importance
D1 surface protection	5.170e-5	9.66
D2 mishandling	3.057e-4	57.10
D3 lightning strike	<1.000e-5	0
D4 heat	5.170e-5	9.66
D5 material resistance	6.634e-5	123.81
D6 natural object impact	1.984e-4	37.06
D7 wind erosion	<1.000e-5	0
D8 manufacturing defects	4.482e-4	83.71
D9 overloading	<1.000e-5	0

numerical example, excluding the particular group (D1, D5, and D8) mentioned in the previous section, the importance ranking for the damage causes is D2 > D6 > D4 > D3 = D9 = D7, which is consistent with inequality Eq. (6.7), demonstrating the feasibility of the FTA on composite damages.

The benefits of the method are summarized as follows:

- A wide variety of composite damage modes and damage causes can be synthesized into a tree that is intuitive and systematic.
- Without sufficient information on damages, qualitative analysis can be performed to identify main contributors and then targeted actions and resources can be prioritized.
- With sufficient data available, quantitative analysis can be conducted. Either constant probabilities or time-related probabilities can be calculated to obtain the top event frequency, occurrence rates of damages, damage severity, and so forth, providing valuable information to maintenance and reliability departments.

6.7 POTENTIAL SOLUTIONS

According to both qualitative and quantitative fault tree analyses on CFRP composite damages, contributions of various damage causes have been prioritized. This method can be used as a proactive tool to prevent the occurrence of the top event from those main contributors. Several solutions addressing different damage causes are proposed in order to improve the reliability of composite structures.

6.7.1 Material Design

To improve the poor material resistance (D5) to impacts, great efforts should be paid to developing 3D composites, which can not only enhance through-thickness resistance, but also prevent from delamination propagation [51]. Typical examples are Z pinned composite and 3D fiber structures as shown in Fig. 6.3. However, there is still a long way to go before 3D structures are widely used by aircraft industries due to cost and efficiency. Economic manufacturing processes and new airworthiness regulations specific to 3D composites should be developed at the same time.

6.7.2 Fabrication Process

Different from traditional metallic components manufacturing, there are various forming processes for composites, such as autoclave forming, vacuum bag molding, pultrusion, filament winding, and resin transfer molding. After forming, machining is applied including cutting, trimming, drilling, and reaming [57]. Inherent flaws like voids, filament spacing, misalignment, imperfect interface bonding, residual stress, and so forth are introduced occasionally during the fabrication process.

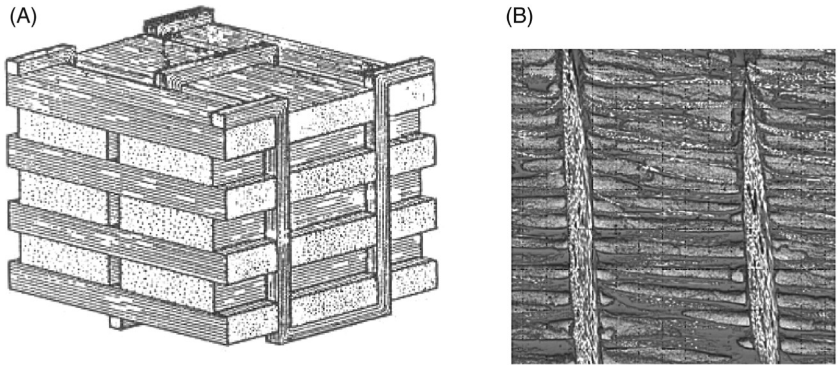


FIGURE 6.3 (A) 3D fiber structure and (B) Z-pins composite.

To reduce the manufacturing defects (D8), more accurate manufacturing process should be implemented. New techniques, such as a drilling method that can prevent laminate from edge fuzz and an exact temperature control in autoclave forming can be developed. Meanwhile, a more strict quality certification procedure should be applied to enhance manufacturing quality control.

6.7.3 Personnel Training

Since accidental damage from natural sources is hard to predict, great attention should be paid to the improvement of technical skills of the operating personnel to reduce the human mishandling (D2). From the previous analysis, human mishandling (D2) makes a significant contribution in damage threats, such as ground vehicle collisions, tools dropping, and so forth. The qualification required to maintain composites is much higher than that to maintain traditional materials. Targeted training procedures should be further studied and implemented. Maintenance workload should be reduced and the working environment should be improved to avoid unnecessary mistakes.

6.7.4 Surface Protection

Adequate surface protection (D1) is one of the key factors in scheduled maintenance. Efforts should be put to investigating main damage causes occurring in different locations of aircraft so that targeted protective coating can be applied to effectively reduce specific damages due to lightning, erosion or moisture. The development of new coating techniques with multiple protective functions is encouraged.

6.7.5 Damage Evaluation and Life Prediction

Except for inherent reasons (D1, D5, and D8), impact damage is the most significant cause of the composite structural failure. Compared to the understanding of metal crack propagation due to fatigue, the deterioration for composites after impact is yet to be determined. Investigations into the mechanisms of composite damage accumulation should be continued to characterize the relationship between the size of the impacted area and the residual strength in order to make more accurate life prediction. Then, optimized inspection intervals can be determined to monitor the composite structural health, satisfying both safety and economic requirements.

6.8 CONCLUSIONS

This chapter proposed a new FTA to synthesize a diversity of damage modes and damage causes of the composite structure in a systematic manner on a macroscopic level. A typical composite panel made of CFRP was selected and three importance analyses including structural importance analysis, probability importance analysis, as well as relative probability importance analysis were conducted to rank various damage causes. The applicability of the FTA on composites was validated through a numerical example based on statistical data and engineering experience from survey. Potential solutions aiming at improving the reliability of composite structures were proposed accordingly. Engineers from airlines can apply this method to discover the main damage modes and damage causes for different composite structures through operational monitoring so that pertinent preventative actions can be performed. Manufacturers can combine this approach with other methodologies, such as fuzzy comprehensive evaluation, back-propagation network, and so forth to develop composites' rating system for more efficient maintenance schedules.