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Statistics and Analysis of Manufacturing Defects and Damage of Helicopter Composite Structures

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Abstract

The manufacturing defects (MDs) and damage of thin layered composite structures widely used in helicopters are of great concern to researchers. In this paper, over two hundred concession sheets of helicopter composite parts and assemblies in recent years were collected from manufacturers, and the defects and damage and their characteristics were classified and statistically analyzed. The results show that 27 types of MDs in composite parts and 5 types of assembly problems can be assorted, and 11 types of damage and defects induced by human operation errors are identified. Among them the resin richness, delamination, thickness out-of-tolerance, excessive assembly tolerance, ply wrinkle and disbond are the main defect types, which account for over 55% of all defect/damage counts recorded in the concession sheets. Besides, the primary causes leading to defects and damage and their corresponding repair methods were analyzed.

Keywords: manufacturing defects, delamination, disbond, composite repair.

1. Introduction

Continuous fiber-reinforced composites have received wide usage in aerospace industry to produce lighter and more durable load-bearing structures. However, manufactures and designers must pay much attentions to the MDs of composite parts or components, as they could apparently affect the macroscopic performance of composites and sometimes even lead to product rejection.

Composite production is a special addictive process as the material and final product are manufactured simultaneously, in which the product quality may be affected by process parameters and human operating factors. Manufactures have adopted many online defect monitoring technologies and continuously made improvement in the manufacturing process in order to reduce the MDs, aiming at saving cost by decreasing the rejection rate of composite parts and components.

The formation mechanisms of MDs are very complex involving many factors including product geometry, processing conditions, state of raw material, operation experiences, and so on. Hassan have reviewed the MDs of aircraft composite structures with complex shapes made by the autoclave molding, and found out that the thickness uniformity, resin distribution and fiber wrinkling are the critical MDs,which contribute to the reduced mechanical properties and life span of the structure[1]. Wang have found a strong relationship between the MDs and the composite laminates complex shapes including non-uniform thickness, L-shape, U-shape, I-shape, or Box-shape, and they discovered that delamination, void, pore and resin-richness are four main defects in autoclave molding, mainly induced by geometric factors such as too thick or too thin, too small radius and abrupt change in thickness and so on[2]. Gaydachuk made investigate into the MDs of composite materials sandwich structure (CMSS), and divided them into four main categories: honeycomb core defects, defects of out layers, CMSS joint defects and CMSS components interface defects. [3]. Paney have analyzed the mechanisms of wrinkle formation during the processing of continuous fiber polymeric composites from the perspective of the mechanics[4].

Tremendous researches have been carried out on the negative impact of MDs on the performances of composite parts and components. Nelson and Riddle studied three common MDs of composite wind turbine blades: in-plane and out-of-plane fiber waviness and porosity/voids. Their effect on the macroscopic tensile and compressive properties were quantitively evaluated by building analytical geometry models discretizing the wave forms[5,6]. Woo K included delamination and voids in the finite element model to evaluate their effect on the ultimate load-bearing capacity and delamination modes of a L-shaped composite beam[7]. In recent years, Zambal have developed a digital twin capable of fast evaluating the effects of process variations and different kinds of defects on the mechanical properties[8].

In the present paper, we focus on the defects and damage appeared during the manufacturing process of composite structures in helicopter fuselages. First, the MDs and damage data were collected and analyzed to discover the ones with most frequencies. Then, primary causes for different MDs and damages are also discussed. At last, composite repair methods corresponding to the MDs and damages are counted and categorized, and the main drawbacks of the current repair methods are also discussed.

2. MDs and damage categorization and analysis

Carbon fiber reinforced plastics (CFRPs) are widely used in helicopter fuselage, their structure types mainly includes: honeycomb or foam sandwich structures and laminates. They have common characteristics:

1) The structure geometry is usually complex, with variational curvatures and complex profile;
2) The structure is usually thin-layered compared to the fixed wing aircraft;
3) The honeycomb sandwich composite structures (CS) are the most common types of them.

In this paper, we selected one type of helicopters using CFRPs in fuselage skin, tail boom and horizontal tails, their composite materials used are T300-grade carbon fiber reinforced medium- and high- temperature epoxy resins. 236 concession sheets in recent 5 years are collected for composites products (not including the rejected ones) and the recorded MDs and damages and their primary causes are statistically analyzed and categorized.

2.1 MDs and damage types

The concession sheets recorded non-conformation descriptions including the MDs and damage types and their characteristic size and positions (see Figure 1) based on the quality detection reports after visual check, knock-down inspection, A-Scan, C-Scan and other non-destructive inspections. The causes and corresponding repair methods proposed by designers are also recorded.

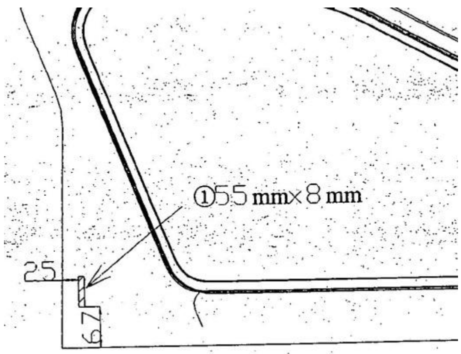


Figure 1 - A typical record of depression area depicted on a concession sheet.

Based on the information extracted from the concession sheets, the MDs and damage types of laminates and honeycomb/foam sandwich structures are collected and counted. It should be noted that there is possibility that more than one type of defect or damage may occurred in the same composite part, so each type of MDs and damage should add it up once. However, if there is repeated record about one type of defect or damage on the concession sheet, we just count it one time.

The statistic data show that there is up to 27 types of MDs in the helicopter composite products, as shown in Table 1, in which resin richness, delamination, thickness out-of-tolerance (OOT), ply wrinkle, plate-core disbond, honeycomb depression, resin starvation, joggle depth OOT, ply slipping, layer stack are top 9 types with most frequencies. The MD types of resin richness, delamination and thickness OOT show apparent higher frequency of occurrences than other defects. This result is similar to the statistical outcome carried by Wang[2]. concerning the defects in complex composite structures. Moreover, the MD problems emerged during the assembly process are also not neglectable. 5 types of assembly MDs are found, as listed in Table 2, where excessive assembly tolerance and bondline de-adhesion are two main defects frequently detected.

As the composite parts and components of helicopter structures investigated in this paper are mostly made by hand, human operation errors are inevitable during the manufacturing process. Although the frequencies are relatively low, up to 11 types of MDs and damage are caused by human operation errors. In which, the position deviation of connecting hole (such as 8-style hole), ply stacking sequence error, improper cutting, impact damage are randomly occurred during the manufacturing process. These MDs and damage usually impose serious influence on the mechanical performance of the products and should be carefully repaired.

Table 1 - Counting results of different manufacturing defects in composite parts.

Types	Honeycomb sandwich CS	Foam sandwich CS	Laminated CS	Total counts
Resin richness	49	3	1	53
Delamination	24	24		48
Thickness OOT	46		1	47
Ply wrinkle	16	1	1	18
Plate/honeycomb disbond	12	5		17
Honeycomb depression	14			14
Resin starvation	6	8		14
Joggle depth OOT	12			12
Ply slipping	10			10
Layer stack	1			7
Fabric clamping	6			6
Steps in part surface	6			6
Fiber distortion	6			6
Surface dents	2	1	3	6
Honeycomb sliding	4			4
Layer bulge	2		1	3
Voids	1	2		3
Hole damage	2			2
Local fabric missing	2			2
R-corner size OOT		2		2
Film property unqualified		1	1	2
plate-honeycomb weak bond	1			1
Honeycomb flaw	1			1
Ply bridging at R-corner	1			1
Ply loose	1			1
Foam size OOT				1
Fabric/filling agent disbond				1

Table 2 - Counting results of manufacturing defects during assembly.

Types	Honeycomb sandwich CS	Foam sandwich CS	laminated CS	Total counts
Excessive assembly tolerance	24	2	3	29
Bondline de-adhesion	7	4		11
Joggle in butt-joint surface			3	3
Bondline sliding	1	1	1	3
Bondline over thickness	1			1

Table 3 - Counting results of composite damage caused by human operation errors.

Types	Honeycomb sandwich CS	Foam sandwich CS	laminated CS	Total counts
Position deviation of connecting hole (CH)	10	5		15
Ply stacking sequence error	6			6
Improper cutting	2	3		5
Impact damage	2	2		4
Redundant hole	1	1		2
Displacement of iron belt	1			1
Fiber damage by improper grinding	1			1
Scratch on fabric surface			1	1
Reverse riveting	1			1
Riveting failure	2			2
Filling agent misplaced by fabrics		1		1

By horizontal comparison from Table 1 to 3, the top 10 MDs and damages with the most frequencies of occurrences (see Figure 2) can be easily identified: resin richness, delamination, thickness OOT, excessive assembly tolerance, ply wrinkle, plate/honeycomb disbond, position deviation of connecting hole, honeycomb depression, resin starvation and joggle depth OOT. Most of them belong to MDs of composite structures. Besides, the occurrence of top 6 MDs account for over 56% of total counts, which reveals that they are the most common MDs of helicopter composite structure studied in this paper. Their typical photos except the excessive assembly tolerance and plate/honeycomb disbond can be seen in Figure 3.

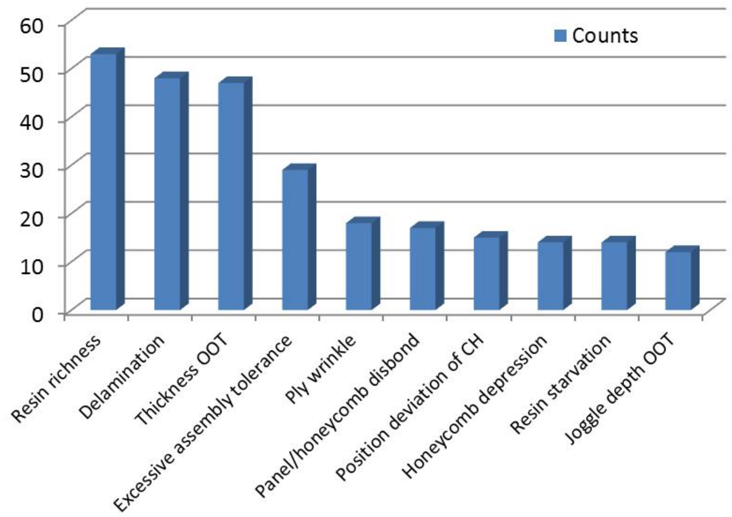


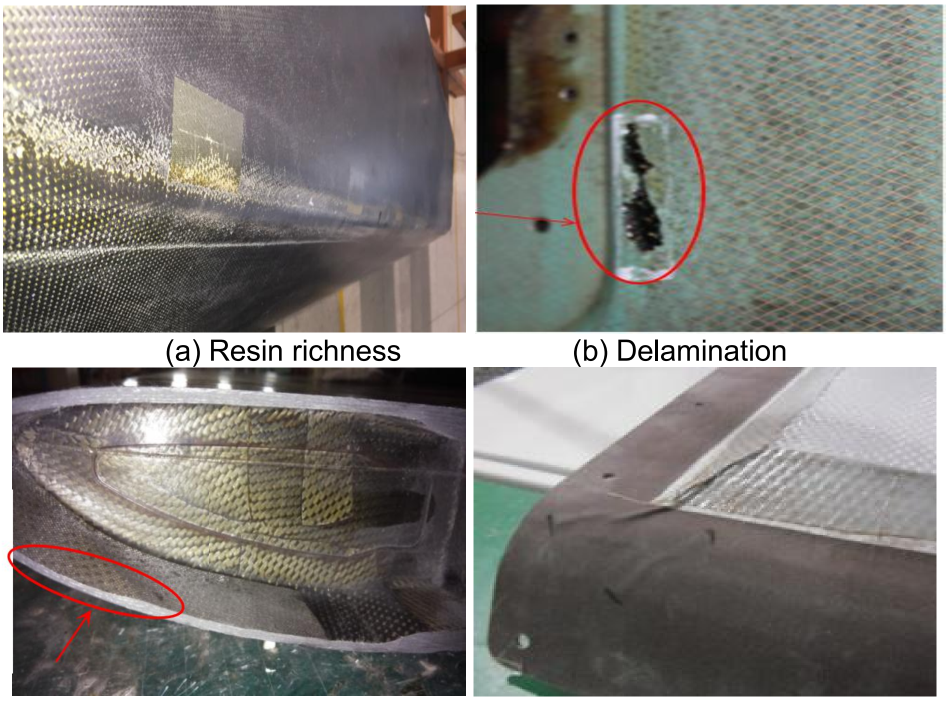
Figure 2 - Top ten manufacture defect types of helicopter composite structures with the most counts.

2.2 Statistic analysis on delamination/disbond area

Compared to other MDs and damages, delamination and disbond (including plate/core disbond or weak bond, bondline disbond) are usually not visible but lead to reduced load-bearing capacity of composite structures, so they are of great concern to designers and maintenance man. In this section, these two defects are specially studied by performing statistic on their characteristic size, which is commonly expressed by delamination or disbond rectangle area (multiply length by width). The statistic results are depicted in Figure 4 and 5, which summarized the delamination and disbond areas and their stochastic distribution of all the recorded defects.

As can be seen in Figure 4, the delamination defect shows large dispersion with regard to its area. The minimum delamination area is 36mm^2 (namely 6mm×mm), which is close to the detection limit of nondestructive detection, and the maximum one approaches 2875mm^2 (namely 115mm×25mm), which is almost 80 times of the minimum delamination area. The distribution of delamination area is not confirmed with normal distribution, where within the scope of 150±40mm^2 it has the highest probability of occurrence, and as much as 80% occurred delamination area is less than 1100mm^2.

Similarly, the disbond defect area also shows great dispersion (see Figure 5) and its distribution doesn't comply with normal distribution. Compared with the delamination defect, the absolute value of disbond area is much larger, and the disbond area of 750±200mm^2 shows the maximum occurrence probability. Disbond defects with area under 4700mm^2 account for 80% of all the disbond defects.



(a) Resin richness (b) Delamination

(c) thickness OOT (d) ply wrinkle

Figure 3 - Typical photos of common manufacturing defects.

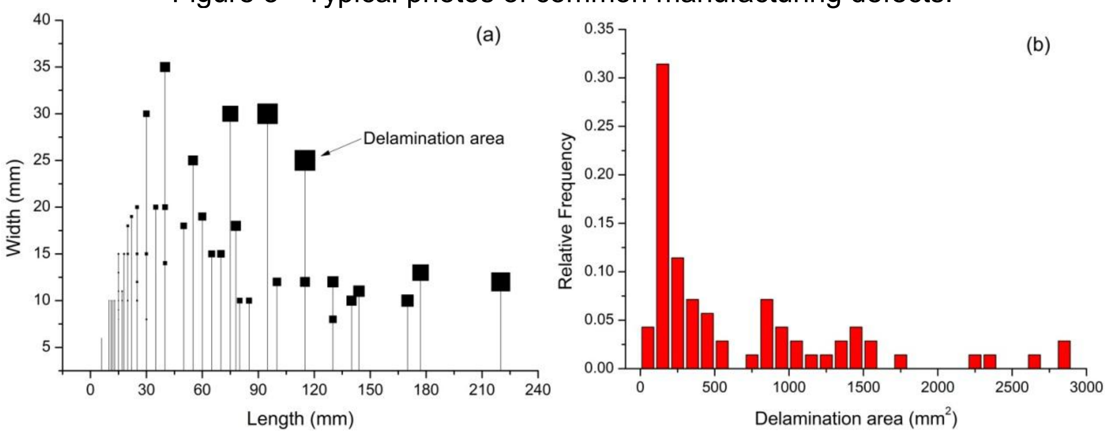


Figure 4 - Dimension record (a) and the distribution (b) of delamination area.

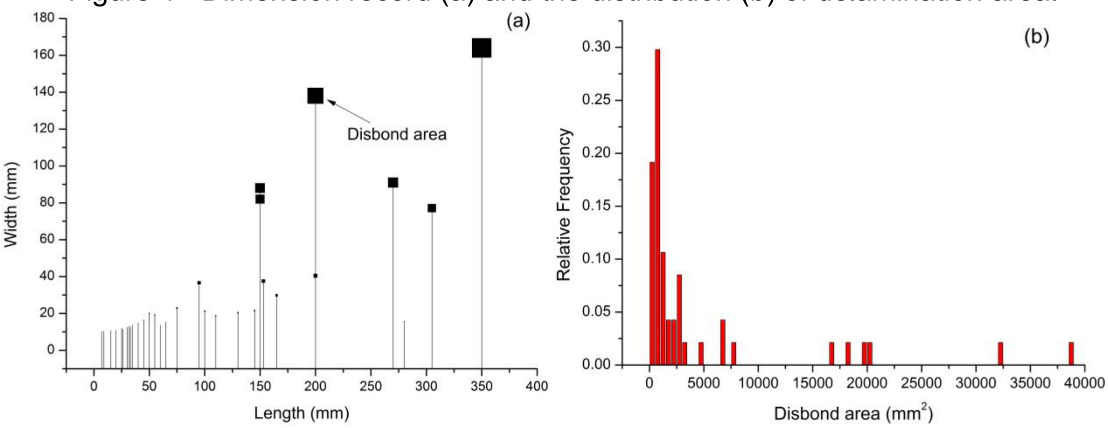


Figure 5 - Dimension record (a) and the distribution (b) of disbond area.

2.3 Primay causes of defects and damage

After performing statistical analysis, the primary causes of composite defects and damage can be summarized into 5 types, which are sequentially listed: fixture problems, process control deficiencies, human operation errors, raw material quality problems and design issues. Their counts are showed in Figure 6. One can easily determine that the former three types are the most frequently occurred problems arising the MDs and damages in the products, and so manufactures should pay special attentions to them.

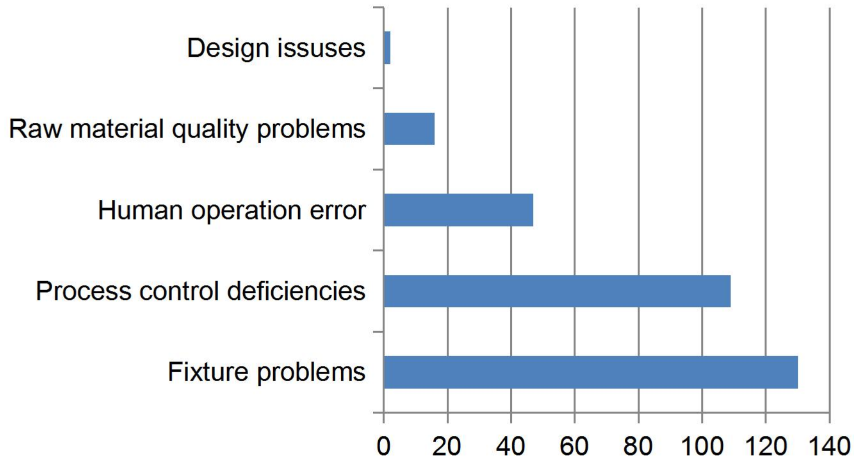


Figure 6 - Main reasons causing manufacturing defects and damage.

The fixture problems includes:

1) Aging and/or unwanted deformation of fixtures;
2) Clearance between the silica gel and mould is out-of-tolerance;
3) Cover mould clearance leakage;
4) Lack of cutting and drilling mold;
5) Mismatch between fixture and parts;
6) Lack of pressure tooling;
7) Mismatch between assembling die.

The process control problems mainly lie in the following issues:

1) The pressure control when using the soft silica gel to implement pressure on composite parts;
2) Soft mold plus vacuum bag method easily leading to ply wrinkle or dents;
3) Resin flow control for thick layered or complex shaped structures;
4) Uniform pressure control on the bondline, especially for parts with large curvature;
5) Honeycomb sliding control;
6) Sliding control of twisted carbon fiber filament;
7) The forming deformation control of parts with large scale.

Moreover, the human operation errors includes:

1) Contamination on the bond surface between honeycomb and prepreg layers;
2) Inaccurate lining, cutting, drilling and riveting due to careless operations;
3) Inaccurate placement of honeycomb or foam;
4) Composite products suffered impact damages due to insufficient protection.

As mentioned before, the composite structures of the studied helicopters still depend on the hand-made methods, MDs and damage seem to be inevitable. Manufacturers should pay more attention to improve the training level and increase management refinement at this stage. In the long term, the modern production technologies such as automatic tape layering or fiber placement, automatic rivet installation should be introduced n order to deliver more reliable and even flawless composite products.

3. Categorization of repair methods

3.1 Repair method selections

The repair processes implemented for the flawed composite structures following the quality inspection were also studied. Statistical data (see Figure 7) shows that the frequency of utilization of wet layup and prepreg layup methods accounts for over 60% of all the selected repair methods, which may attribute to the distribution of MDs and damage types. The main defects such as delamination, thickness OOT, excessive assembly tolerance, ply wrinkle, and plate-core disbond probably need patch reinforcement, of which wet layup is usually used for minor defects, and gap-filling or strengthening the too-thin local areas. However, the prepreg layup reinforcement methods are main options for the repair of delamination, ply wrinkle and plate-core disbond defects.

For some composite structures with MDs or damage, such as miscut, shortage of edge distance or excessive assembly tolerance, they have to be strengthened by riveting/bonding new-made metal parts. The room-temperature curing resin is widely used to repair the disbonded honeycomb sandwich CS by filling the area of removed honeycomb, or make a supplement to the resin starvation area by frictioning. The delaminated or disbond area can also be strengthened by making extra riveting or resin injection or both of them, sometimes following by wet layup reinforcement. Surface grinding, however, is mainly used to clean the resin-rich area for the purpose of decorative repair.

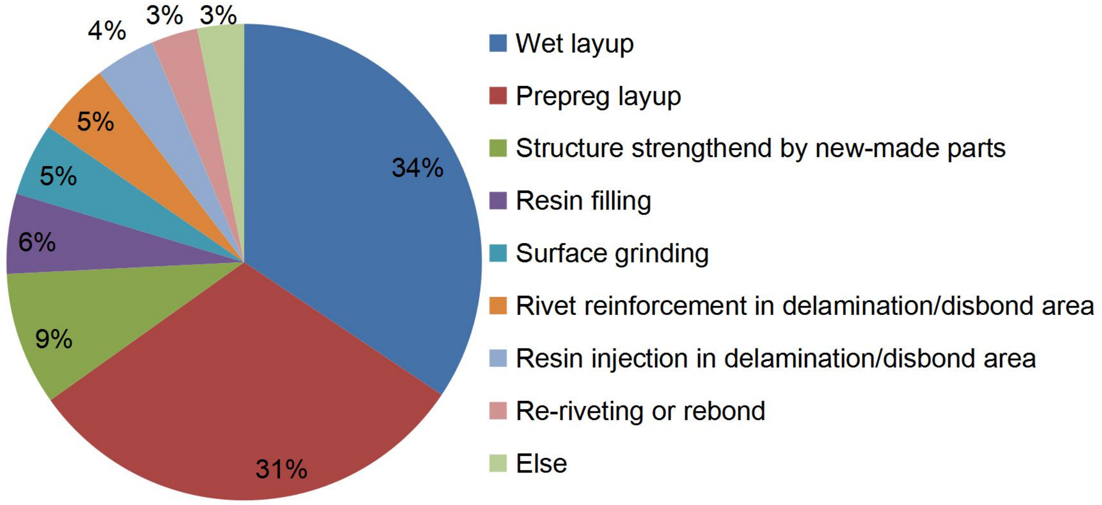


Figure 7 - Proportions of different methods chosen for composite repair.

3.2 Problems to be solved

By analyzing the details and selection preference of conventional repair methods in the composite repair process, we can find that some problems are still need to be solved:

1) The choose of wet layup or prepeg layup mostly relies on the experience or knowledge level of designers due to the lack of support based on experiment data or referable regulations;

2) Repair specification for helicopter composite structures needs to be built urgently, in order to regularize the frequently-used repair methods, such as to standardize the overlapping length during the wet and prepreg layup reinforcement, or specify the methods of how to impose pressure and heat on reinforcing layers in the wet layup repair method. These details are important but usually neglected in the concession sheets.

3) Monitoring the long-term effect of repair is another concern to designers and users. At present manufacturers focus on the real-time repair effect on the products. Actually, the repair result have to be followed continuously to determine its validity to composite structures, for example by rechecking the repaired area after multiple fly hours. This is important for the repaired structures recovered from manufacturing delamination and/or plate-core disbond.

4. Conclusions

In this work, a systematic survey and statistical analysis has been performed to investigate the defects and damage of helicopter composite structures during the manufacturing process. 27 types of manufacturing defects, 5 types of assembly problems, and 11 types of damage and defects induced by human operation errors are identified. Among them, resin richness, delamination, thickness out-of-tolerance, ply wrinkle and plate/honeycomb disbond are the main manufacturing defects according to their frequencies of occurrences. The causes of the manufacturing defects and damage were categorized into 5 groups, in which fixture problems, process control deficiencies and human operation errors are the primary sources resulting in over 90% of the defects and damage.

The corresponding repair methods were also analyzed. Statistical results show that wet layup and prepreg layup are the most commonly selected repair methods in the manufactory. These two repair methods account for over 60% of all the recorded ones according to the frequency of utilization. As the selections of the repair methods overly depend on experiences, it is recommended that repair specifications for helicopter composite structures be established to settle this problem.

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