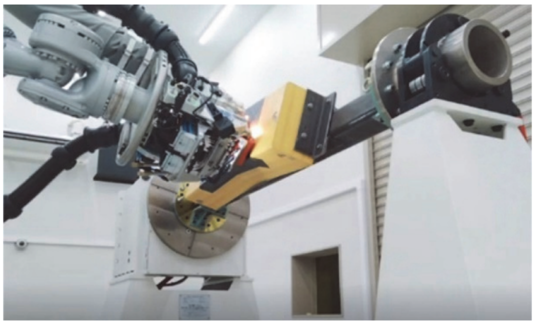
Innovative Carbon Fiber Composite Lamination Technology Using Automated Fiber Placement



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Owing to their significant advantages in reducing structural weight, high specific strength composite materials are widely used in aerospace products. Accordingly, establishing efficient and effective design and manufacturing methods for such parts has become a key challenge. Mitsubishi Heavy Industries, Ltd. has introduced Automated Fiber Placement (AFP) equipment in Japan and has conducted research on lamination optimization design methods and manufacturing processes. As a result, although strength of AFP laminates decreased by up to approximately 18% under certain specific conditions compared to manual laminates, the lamination optimization design implemented in this study could improve the strength of structures by approximately 20%, thus compensating for the decrease in strength. Furthermore, the use of AFP was shown to reduce the number of steps in the manufacturing process required for manual lamination, thereby improving the manufacturing efficiency.

1. Introduction

In order to economize payload transport, aerospace products that are lightweight have always been demanded. Consequently, high specific strength composite materials have long attracted attention as excellent candidate materials for aircraft. Through various improvements in materials, structural design, and manufacturing methods, the application rate of composites in aircraft has continued to increase, and their presence has grown significantly in recent years. For example, Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) was in charge of the development large composite products, such as F-2 support fighters and the wings of Boeing 787 aircraft, in the past and has incorporated the results of continuous research and development in such composite structures since the 1970s. This report describes research activities conducted in conjunction with the domestic introduction of Automated Fiber Placement (hereinafter referred to as AFP) equipment[*], which has been actively introduced in Europe, the United States, and China since the early 2010s. Manufacturing using AFP is described in Chapter 2. The effects of gaps and overlaps, which are inherent in laminates manufactured using AFP, on strength and rigidity are discussed in Chapter 3. An overview of the optimization design and strength test results of the optimization-designed perforated plate are reported in Chapter 4.

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* AFP was introduced in fiscal year 2021 at the Japan Aerospace Exploration Agency (hereinafter referred to as JAXA) Chofu Aerospace Center Aerodrome Branch through a joint collaboration between MHI and JAXA under "Materials Integration for Revolutionary Design System of Structural Materials" (1) of the Cross-ministerial Strategic Innovation Promotion Program (SIP (2nd period)) of the Council for Science, Technology and Innovation in the Cabinet Office. After completion of the program, AFP has been utilized in research and development at JAXA and has also been made available for use outside JAXA through its facility utilization program.

2. Manufacture using AFP

2.1 Specifications of AFP equipment

The installed AFP equipment was models C1 and Csolo manufactured by Coriolis. The main feature of model C1 is the simultaneous lamination of 16 rows of 1/4-inch wide tape. On the other hand, while model Csolo can only laminate one row of tape at a time, it can handle various tape widths, including 1/8-inch, 1/4-inch, 1/2-inch, 1-inch, and 3/2-inch. The equipment can be used for thermoplastic and thermosetting composite materials. Research on thermosetting composite materials using the model C1 is described here.

As shown in **Figure 1**, material tape is wound around a paper tube and supplied to the system by feeding it into the end effector of a manipulator-type robot. The supplied material is heated by a halogen lamp in the process section of the end effector to enhance its adhesive properties, and then pressed by rollers to firmly bond the plies together in the thickness direction. This system can laminate more complex-shaped parts by linking it to a rotating fixture.

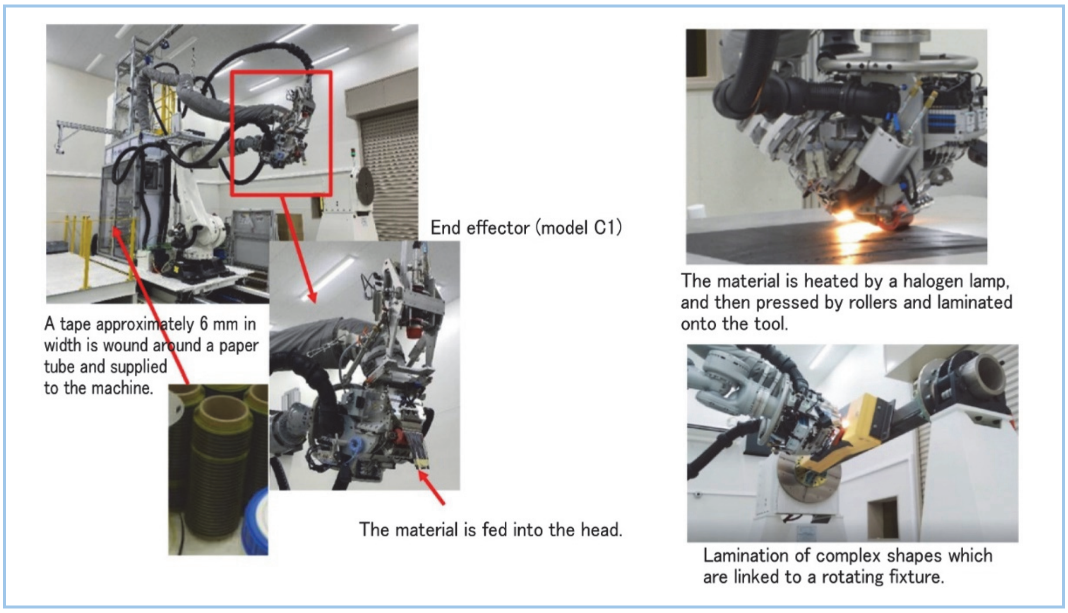


Figure 1 System using AFP

2.2 Manufacturing process using AFP

This section describes changes in the manufacturing process associated with the adoption of AFP. The AFP manufacturing process flow is shown in **Figure 2**: a lamination path and program are created using the design data prepared by the designer. These are loaded into the AFP, and the lamination process is started. This process enables the elimination or reduction of steps previously required for manual lamination operation, such as writing lamination information on 2D drawings, planar development of 3D shape data, and material cutting. In this study, improvement in the efficiency of the overall manufacturing process could be confirmed through prototyping.

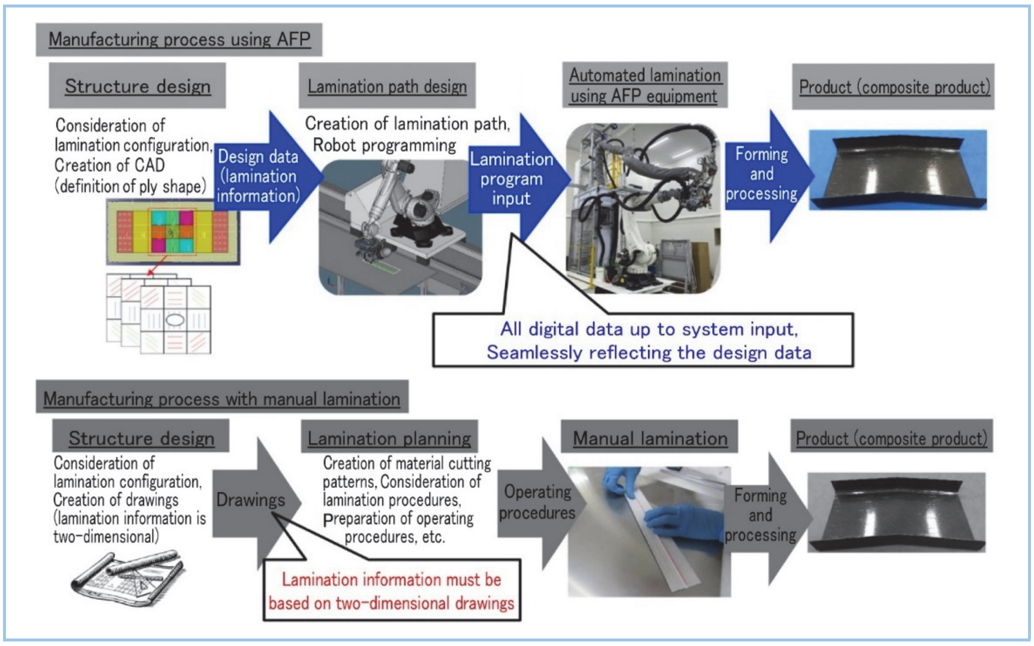


Figure 2 Manufacturing processes using AFP and manual lamination

2.3 Defects in laminates manufactured using AFP

In this section, an example of defects in AFP laminates is discussed. While AFP exhibits high lamination capability for complex shapes, uneven roller pressure, wrinkles caused by perimeter differences because the tape does not stretch in the fiber direction, or delamination may occur in areas with extreme curvature conditions (**Figure 3**). As MHI advanced to prototype development, test samples with relatively complex shapes were manufactured using specialized software to identify areas with extreme curvature conditions with respect to tape application direction, and the lamination paths were modified as needed.

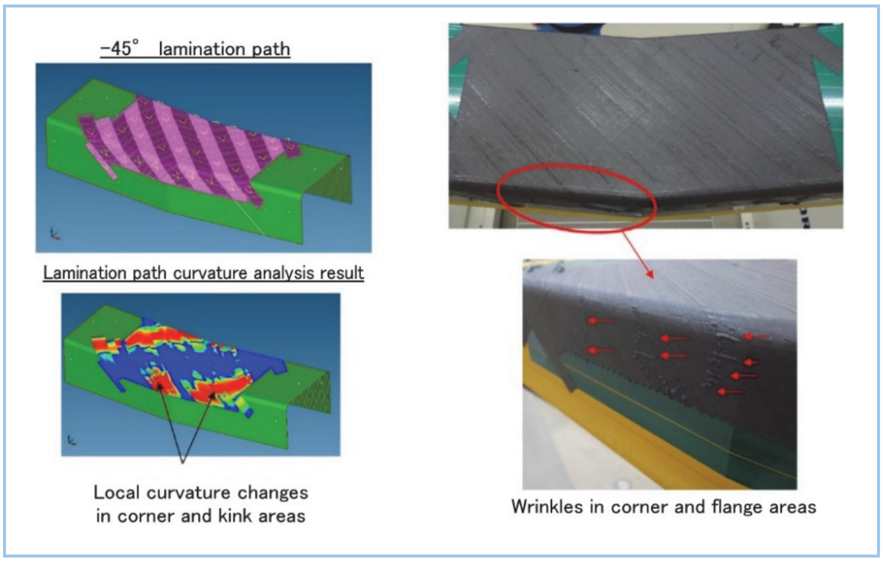


Figure 3 Quality of laminates manufactured using AFP

3. Strength and rigidity characteristics of AFP laminates

As shown in **Figure 4**, tapes which are applied at the same time are collectively referred to as a "course." The space between adjacent tapes is referred to as a "lane gap," and the space between courses is referred to as a "course gap." While the lane gap is nearly constant and does not change, the course gap can be set to any value on the system side. A negative course gap is called an "overlap," whereas a positive course gap is called a "gap." An AFP laminate has either an overlap or a gap. In order to consider the effects of these overlaps and gaps on the strength and rigidity of the laminate, MHI conducted strength tests on test samples with overlaps and gaps (material: Toray T800S/3900-2B, lamination configuration: [45/0/-45/90] 3s, simulated gaps and overlaps in the 90° layer at the coupon center) prepared by manual lamination. The cross-sectional condition of the sample after curing is shown in **Figure 5**. From this cross-section, fiber waviness caused by gaps and overlaps was found to decrease when a cowl plate (a tool placed on the side opposite the tool surface during curing to keep the sample in place) was used when curing the sample, compared to when a cowl plate was not used. Next, MHI conducted tensile and compression tests using these samples. Results are shown in **Figure 6**. The vertical axis is normalized to the strength and rigidity of samples without gaps or overlaps and that were cured using a cowl plate. From this figure, laminates with overlaps cured without using a cowl plate are shown to exhibit a maximum reduction in strength of 18%. In this case, rigidity increased while strength decreased. The increase in rigidity was due to the increase in the cross-sectional area caused by the overlap. On the other hand, FEM analysis revealed that the decrease in strength was caused by resin failure occurring in the overlap area of the 90° layer at the center of the plate thickness, which led to stress concentration near the 0° layer, which then initiated early breaking. Gaps and overlaps act as internal defects, reducing strength and rigidity in principle. However, when a cowl plate is used, fiber undulation is suppressed and decrease in strength and rigidity is attenuated compared to when a cowl plate is not used.

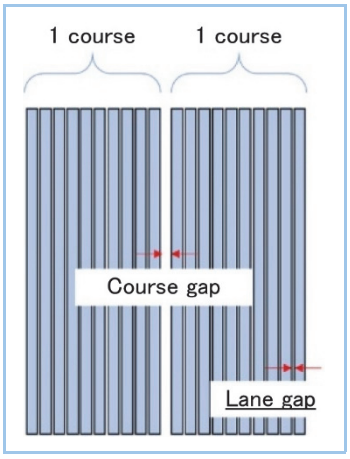


Figure 4　Definition of gaps

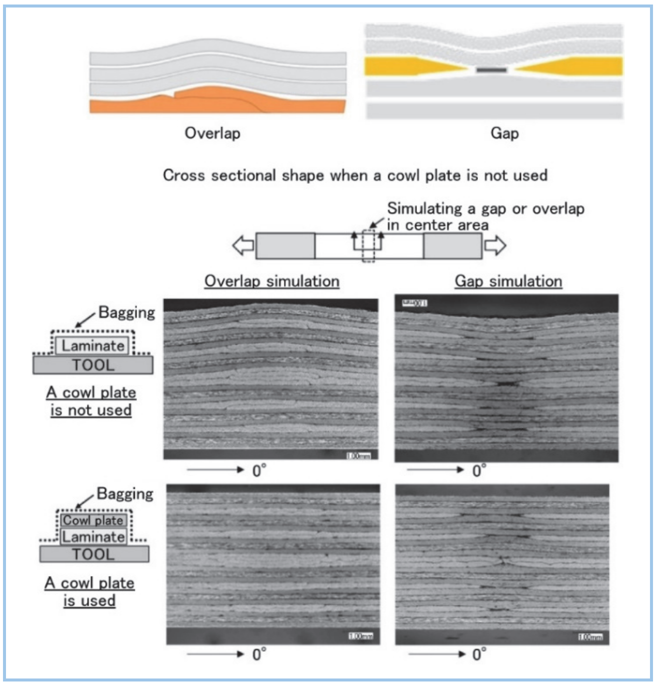
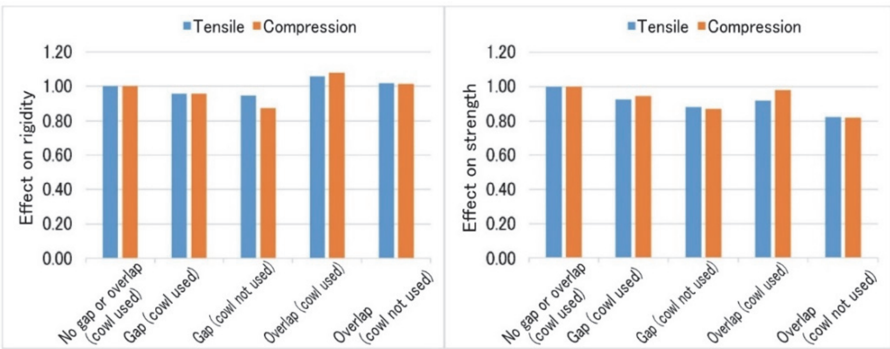


Figure 5　Cross-section of AFP laminate after curing



[%]

	Rigidity		Strength	
	Tensile	Compression	Tensile	Compression
Gap (cowl used)	−4.3	−4.4	−7.5	−5.4
Gap (cowl not used)	−5.1	−12.8	−11.9	−12.9
Overlap (cowl used)	+5.9	+8.0	−8.1	+2.1
Overlap (cowl not used)	+1.9	+1.5	−17.7	−18.2

Figure 6　Strength and rigidity of laminates with gap and overlap

4. Multi-objective optimization design and strength evaluation test

As mentioned in Chapter 3, laminates with gaps and overlaps exhibit a decrease in strength up to 18% under specific conditions compared to conventional manual laminates. On the other hand, AFP offers accurate and rapid lamination of even laminates with complex lamination patterns. As a result, lamination optimization designs with complex patterns that were not considered in manual lamination due to manufacturing efficiency concerns can be adopted and compensate for the decrease in strength caused by the gaps and overlaps. This chapter presents an overview of the lamination optimization design process and an outline of the manufacturing process of test samples along with an example of their test results. As shown in **Figure 7**, in the lamination optimization design process, boundary conditions and domain partitioning of perforated plates are set first. Next, multiple lamination optimization design plans are obtained using multi-objective optimization analysis, and then a design plan is selected from the plans [(2)]. In this phase, layup configuration, plate thickness distribution, and rigidity distribution could be obtained for each area of the perforated plate. Based on these, MHI determined the ply shape in consideration of manufacturability during automated lamination, then carried out lamination design of the perforated plates, manufacturing using AFP equipment, and tensile tests using the test samples. As confirmed in **Figure 8**, initial failure load could be improved by approximately 16% compared to that of standard samples made with manual lamination. Furthermore, lamination optimization for thickness transition zones in the pad-up area around the holes could achieve approximately 5% strength improvement, leading to a possible overall strength enhancement of approximately 20%. This demonstrates the effectiveness of an approach where the disadvantages of strength reduction due to gaps and laps are compensated by lamination design modifications.

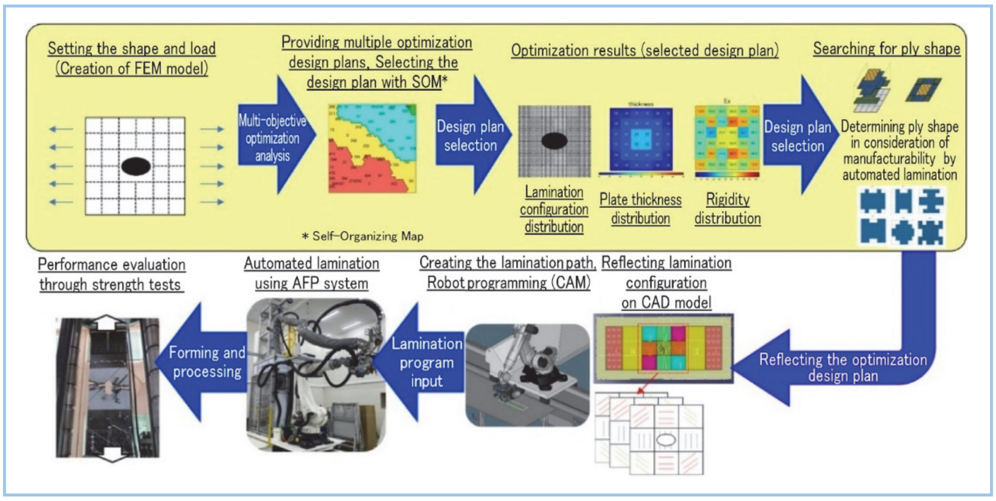


Figure 7 Lamination optimization design for automated lamination using AFP, test sample manufacturing, and strength testing

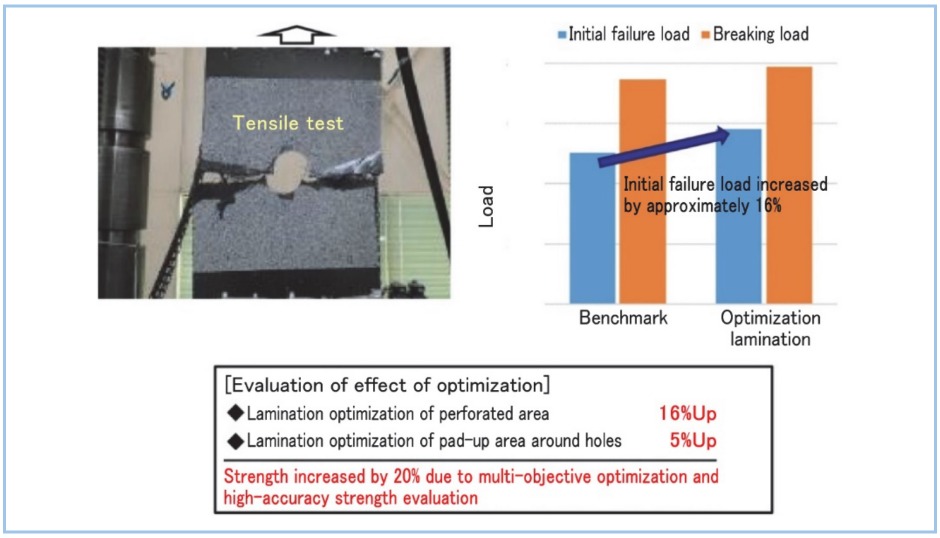


Figure 8 Tensile test results for perforated plates

5. Conclusion

This report describes efforts by MHI to establish efficient and effective design and manufacturing methods for parts after switching the manufacturing method from conventional manual lamination to automated lamination using AFP. By utilizing AFP, automated lamination even for parts with complex lamination patterns or multi-curved surfaces is possible, and design information can be transferred directly to the manufacturing process as digital data. At the same time, processes associated with manual lamination can be eliminated, thereby improving manufacturing efficiency. A decrease in the strength of AFP laminates up to approximately 18% under specific conditions compared to manual laminates due to the effects of tape gaps and overlaps inherent in AFP laminates could be confirmed. On the other hand, the results also showed that this decrease in strength can be compensated by applying the lamination optimization design, thus increasing the strength of the structure by approximately 20%. MHI plans to continue advanding its research on lamination optimization design and manufacturing automation, aiming for further improvements in the performance, cost, and manufacturing speed of composite parts.

Part of this research was conducted under "Materials Integration for Revolutionary Design System of Structural Materials" (managed by Japan Science and Technology Agency), the Cross-ministerial Strategic Innovation Promotion Program (SIP (2nd period)) of the Council for Science, Technology and Innovation, Cabinet Office.

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