Development of Advanced Vacuum-assisted Resin Transfer Molding Technology for Use in an MRJ Empennage Box Structure

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Vacuum-assisted resin transfer molding (VaRTM) is a high-efficiency composite fabricating process. However, materials made using VaRTM have difficulty meeting the performance and quality requirements for applications on primary aircraft structures. Mitsubishi Heavy Industries, Ltd. (MHI), has been developing with Toray advanced vacuum-assisted resin transfer molding (A-VaRTM) technology to overcome the performance and quality shortcomings of VaRTM. MHI demonstrated the feasibility, quality, and consistency of A-VaRTM through trial fabrications and strength tests in 2007. This included the fabrication and structural analysis of a full-scale vertical stabilizer box structure. The results of these tests demonstrated that A-VaRTM technology could be used to make parts for primary aircraft structures. MHI intends to use A-VaRTM technology on the Mitsubishi Regional Jet empennage box structure, and will work toward expanding the application of this technology after the aircraft Type Certificate (TC) is acquired.

1. Introduction

Reducing the weight of airframes lowers their operational costs. Therefore, a growing number of carbon fiber-reinforced plastics (CFRP) with higher specific strengths than aluminum alloy are being used in commercial aircraft. However, there are concerns about the cost of using such materials. The cost of prepreg, which has conventionally been used as a composite material for commercial aircraft, is high. The autoclave equipment used to fabricate composite material is also expensive. Although the range of applications of composite materials expands every year, further advanced and more efficient technology is required to enhance the manufacturing processes.

The New Energy and Industrial Technology Development Organization (NEDO), an independent government corporation, started the government-subsidized Research and Development of Environment-friendly, High-performance Small Aircraft project in 2003. As part of this project MHI developed advanced vacuum-assisted resin transfer molding (A-VaRTM) technology for application on primary aircraft structures. A-VaRTM is able to provide the necessary productivity improvements to composite fabricating processes while simultaneously reducing the weight of the final product.

2. Outline of A-VaRTM technology

Vacuum-assisted resin transfer molding (VaRTM) is an advanced fabricating process for composite materials. The process is performed by infusing liquid resin, which is sucked up by utilizing the differential pressure between the

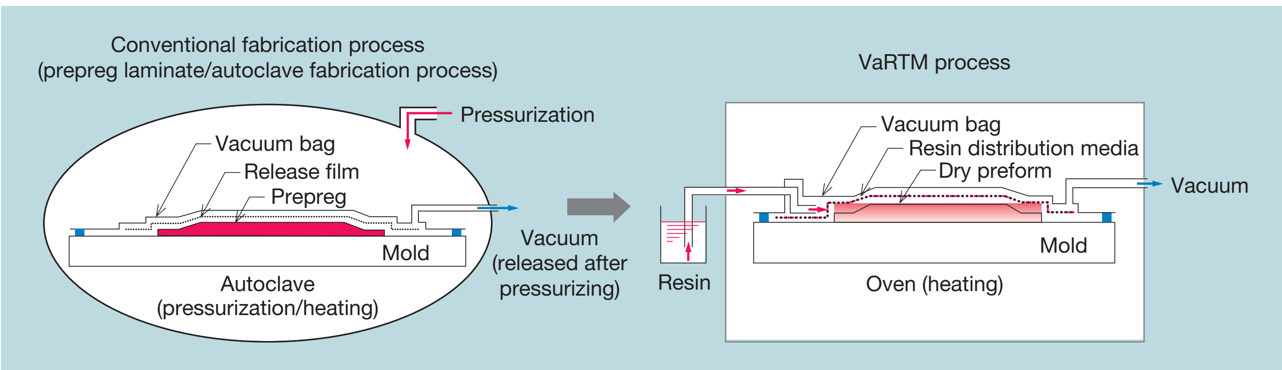

Fig. 1 Differences between composite fabrication processes
An expensive autoclave is not required for the VaRTM process.

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atmosphere and a vacuum, into laminated fibers or woven fabric, followed by heat hardening. Since this method does not use prepreg or an autoclave, feasibility of highly efficient fabrication of composites is expected. The difference between the conventional fabricating process and VaRTM is illustrated in **Fig. 1**.

To apply VaRTM technology to primary aircraft structures, A-VaRTM has been jointly developed with Toray Industries, Inc. MHI has made efforts to improve VaRTM technology as follows:

- adoption of a fiber-reinforced base material with high quality and strength,
- application of thermoplastic particles designed to toughen the composite materials, and
- optimization of the forming process to obtain a high volume fraction of fiber (Vf = volume of fiber/volume of object × 100).

With such improvements, the mechanical properties obtained by coupon tests have improved to a level comparable to that of prepreg, which is often applied on primary aircraft structures.[1] The mechanical properties of A-VaRTM and prepreg materials are compared in **Table 1**.

Based on the result of various structural element tests conducted in parallel with the coupon tests, MHI is now confident about using A-VaRTM material on actual aircraft.[2] Thus, MHI planned and conducted strength tests using a full-scale test specimen.

Table 1 Mechanical properties of A-VaRTM and prepreg material

Test item	Test environment	Material fabricated using A-VaRTM	Prepreg material
0° Tensile strength (MPa)	RT	2890	2960
0° Tensile modulus (GPa)	RT	150	153
0° Compressive strength (MPa)	RT	1570	1500
	82°C Wet	1250	1280
Open-hole tension (MPa)	RT	519	500
	–59°C	473	448
Open-hole compression (MPa)	RT	295	298
	82°C Wet	238	236

With improvements of the materials and the fabricating process, the mechanical properties of A-VaRTM have improved to a level comparable to that of prepreg.

3. Fabrication of a full-scale vertical stabilizer test specimen

As part of the evaluation of using A-VaRTM-fabricated parts in primary aircraft structures, MHI and Toray jointly fabricated a full-scale vertical stabilizer test specimen to demonstrate the feasibility of the process. We set the specifications for the test specimen using the profile and loads taken from an assumed vertical stabilizer box structure. The test specimen consisted of co-bonded panels of skins and stringers, spars, and ribs, and it was assembled with fasteners.

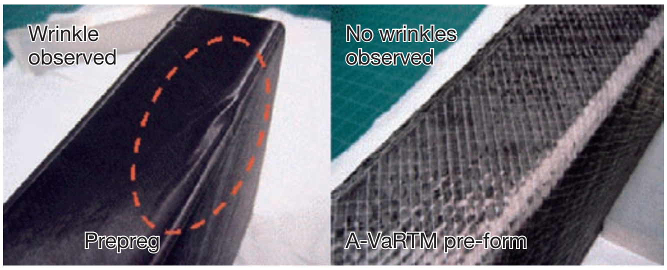

Fig. 2 Comparison between A-VaRTM pre-form and prepreg
Wrinkles are not likely to be generated in A-VaRTM material because of the good following response to profile transition.

The quality of the ply-drop-off areas was evaluated after fabricating the full-scale structure. A ply-drop-off area consists of a thickness transition in composite parts where steps are generated because the number of laminated plies is reduced to decrease the thickness of the part. In traditional prepreg fabrication, the base material is impregnated with semi-hardened resin. Therefore, when prepreg is used to fit a three-dimensional geometry with a ply-drop-off area, there is a high possibility of generating wrinkles, as shown in **Fig. 2**. Thus, restrictions are required in these areas. But since VaRTM uses dry fabric that is not impregnated with resin, the material is easier to fit around three-dimensional geometry, reducing the possibility of generating wrinkles. No quality degradations such as wrinkles were found in the ply-drop-off areas of the full-scale test specimen.

We have worked on improving the handling of dry VaRTM pre-form during the fabrication process. We would also like to increase the Vf by applying a hot compaction process. A hot compaction process densifies dry pre-form while maintaining its shape by using thermoplastic toughening particles, allowing us to achieve the desired Vf.

We have also developed a new multi-stacking process and a new automatic press forming process. In the multi-stacking process, the basic layer constitution is patterned in advance, as shown in **Fig. 3**, and combined so as to

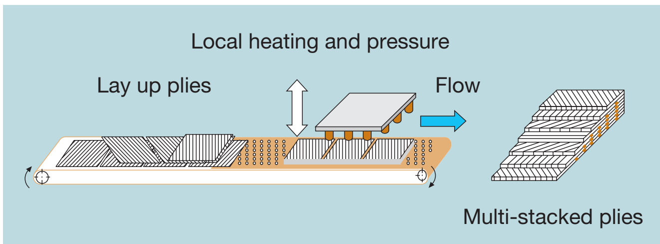

Fig. 3 Schematic diagram of automatic multi-stacking
The concept of a basic layer-constitution kit makes effective lay-up operations possible.

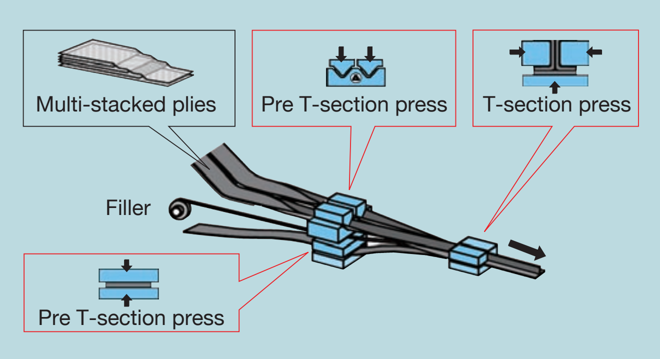

Fig. 4 Automatic press forming for a T-section stringer pre-form
Using A-VaRTM, effective pre-form automation is possible in combination with multi-stacking.

obtain the required lamination ratio. The high-efficiency fabrication process takes into account the automatic press forming, and can be used to manufacture T-section stringers automatically, as shown in **Fig. 4**.

The fabricated components were assembled with fasteners. No problems were identified with the quality of the parts, demonstrating that it is feasible to fabricate primary aircraft structures using A-VaRTM technology. Photographs of the complete test specimen are shown in **Fig. 5**.

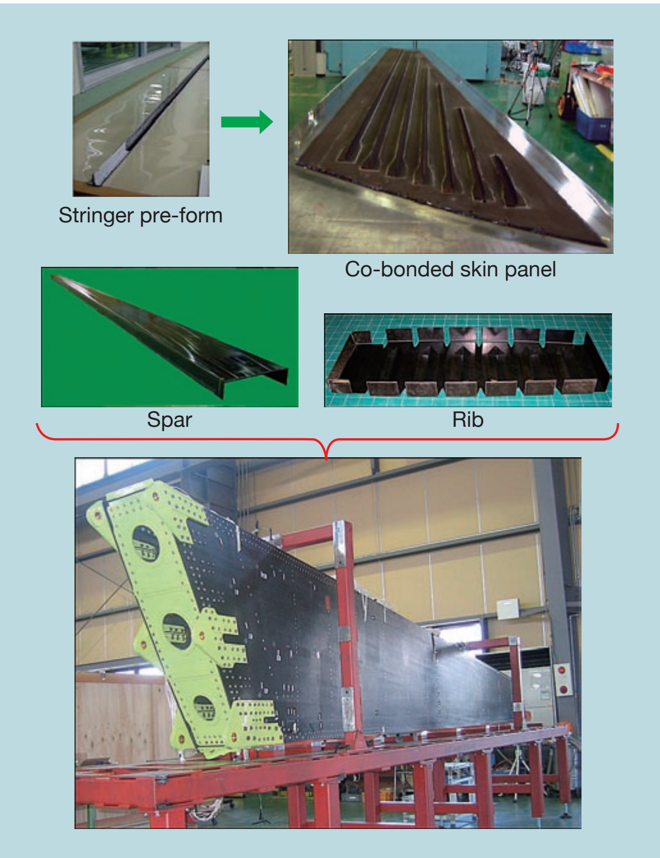

Fig. 5 Full-scale vertical stabilizer test specimen
Fabrication of the test specimen was accomplished without major problems, even using a high-efficiency fabrication method.

Fig. 6 Full-scale test set-up
The test was conducted as part of a joint research project with JAXA.

4. Strength tests of the full-scale vertical stabilizer test specimen

To verify the strength of the full-scale test specimen made using A-VaRTM technology, MHI conducted static tests as part of a joint research program with the Japan Aerospace Exploration Agency (JAXA), an independent government corporation. The tests were conducted by applying estimated loads for the actual model to the full-scale vertical stabilizer test specimen. The purpose of these tests was to verify the design concept of the actual aircraft and to examine the good correlation between the test result and the analysis.

The tests were conducted in the Chofu Aerospace Center Aerodrome Branch of JAXA. The data were measured by applying the sum of the maximum bending and shear force, which is the critical case for the vertical stabilizer. The set-up conditions for the test specimen are shown in **Fig. 6**.

The strains were measured by strain gages attached to the skins, stringers, spars, and ribs. The displacements were measured by displacement gages installed on the spars. We designated the estimated maximum load to be applied on the actual model as 100%, and increased the test load by 5 to 20 % step-by-step up to 100 % without causing any detrimental permanent deformations. Thus, the design concept was verified.

We compared the test results with finite element model (FEM) analysis using lamination theory. The strain distribution was close to the FEM results, as shown in **Fig. 7**. The strain values were within a 5% allowance, showing an excellent correlation. These results also verified the strength of the full-scale structure created using A-VaRTM technology. However, the FEM estimates for the load distribution at the stabilizer root joints were inadequate. The FEM therefore requires additional work and verification.

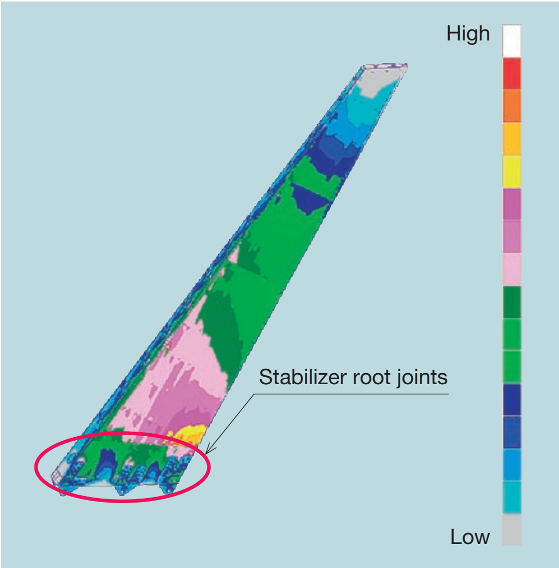

Fig. 7 Strain distribution of strains determined by FEM analysis
The test and analysis results were in reasonable agreement, but the analysis method at the stabilizer root joint requires further work.

5. Quality evaluation

To evaluate the quality of the full-scale vertical stabilizer structure, the test specimen was cut after the strength tests were finished, as shown in **Fig. 8**, and static compression tests were performed. The Vf values of the formed parts were verified, and the cut surfaces were observed.

A total of 35 pieces were cut, covering a wide range of parts from the skin panel. The Vf variation was small, which was initially a concern. The coefficient of variation (CV = standard deviation/average × 100) was only 2%. There was also a concern about possible Vf degradations in thick areas, but this was not evident in the results, even at the maximum 52-ply thickness and the minimum 16-ply thickness. Thus, the quality of the full-scale structure was verified. The compression tests did not show a large variation in the elastic modulus. Although a partial wrinkle was observed on the cut surface of the test specimen, its elastic modulus and strength were equivalent to those of the intact test specimen. These results suggest that the largest possible wrinkle produced using the present forming process will not degrade the stiffness and strength of the composite significantly

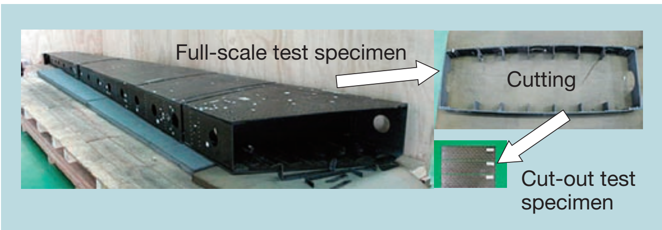

Fig. 8 Cutting the full-scale test specimen
Strength tests and quality analyses were performed on pieces cut from the full-scale test specimen.

6. Conclusion

We fabricated a full-scale vertical stabilizer test specimen and conducted strength tests to verify that A-VaRTM technology has adequate characteristics for use on primary aircraft structures in terms of ease of fabrication, strength, and quality. Based on these results, MHI will step up efforts to apply this technology to actual aircraft, and will focus on further quality and efficiency improvements. We plan to conduct a TC acquisition test using the MRJ Empennage box structure, in cooperation with outside personnel, for example JAXA. MHI also plans to expand the application of this technology to other of its products in the future.

References

1. Toshio Abe, et al., A-VaRTM Process for primary aircraft structures, Proc. 25th Int. Conf. SAMPE Europe, Paris, April (2004)
2. Takeda, F. et al., Research in the Application of the VaRTM Technique to the Fabrication of Primary Aircraft Composite Structures, Mitsubishi Heavy Industries Technical Review Vol.42 No.5 (2005)


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