Research in the Application of the VaRTM Technique to the Fabrication of Primary Aircraft Composite Structures

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The VaRTM process is a low cost composite fabrication technique, differing from prepreg laminated composites, the resin is infused into dry fabric formed on a mold near product shape under vacuum pressure and cured in an oven. This process has already been utilized in the manufacture of commercial products such as windmills. This study examined ways to improve existing VaRTM techniques so that they can be applied to the fabrication of aircraft primary structures, and to improve VaRTM materials, processes, and cost. It was verified that the mechanical properties of VaRTM materials are almost equivalent to those of prepreg materials, and that the prospects of applying them to the empennage of the Mitsubishi Jet are feasible. Development work is proceeding with the aim to realize further cost reductions and to obtain conformance to regulatory on the application of this process to the production of civil commercial aircraft in the future.

1. Introduction

Since resin matrix composites are superior in specific strength compared to aluminum alloys and further weight reduction can be expected, efforts are underway to expand the scope of their application to commercial aircraft pursuing reduced operational costs. Since 2003, Mitsubishi Heavy Industries, Ltd. (MHI) has also been examining the expanded application of these materials in its research and development of environmentally friendly, high performance small aircraft known as the Mitsubishi Jet (MJ) in a project conducted with the assistance of the New Energy and Industrial Technology Development Organization (NEDO).

Conventional composite parts for commercial aircraft are fabricated by autoclave process with unidirectional carbon fiber prepreg. However, conventional composite parts are costly, and substantial costs are required to furnish an autoclave to cure the materials, resulting in parts that are more expensive.

Therefore, in order to reduce production costs and weight, research has been conducted in applying the vacuum assisted resin transfer molding or "VaRTM" technique to the fabrication of the primary composite structures of the MJ aircraft. This technique has already been utilized in the production of low cost composite products such as windmills with significant results in the civilian sector. The aim here is to apply the technique to the fabrication of vertical stabilizer, as shown in **Fig. 1**.

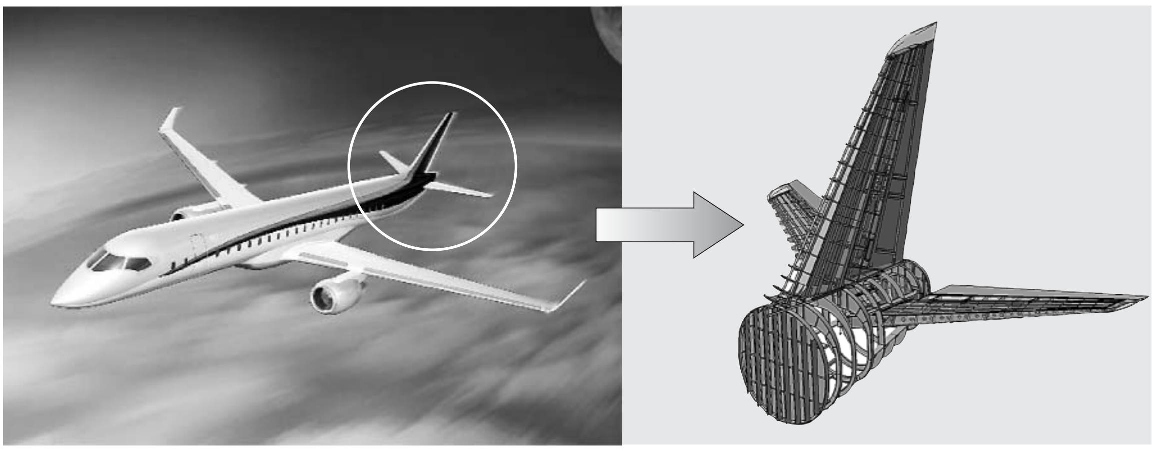

Fig. 1 Empennage structure of Mitsubishi Jet
Research and development on application of VaRTM technique to the vertical stabilizer.

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2. General description of VaRTM

The VaRTM process is a composite fabrication technique by infusing resin into base materials formed with woven fabric or fiber using vacuum pressure. Compared with the conventional composite fabrication methods used in the aeronautical field, this process is an ideal technique using low cost composite materials without prepregs and autoclaves. **Fig. 2** shows the typical differences of the VaRTM process from the conventional technique.

MHI has researched and developed a VaRTM process jointly with Toray Industries, Inc. as an advanced-VaRTM (A-VaRTM) technique in order to apply it in the fabrication of principal structural elements (PSE). The A-VaRTM technique is based on the traditional VaRTM technique and is characterized by the hot compaction of the base material prior to resin infusion, the bleeding off of excess resin after resin infusion , and other steps that are taken in order to obtain high volume fiber content (Vf: 55 to 60% targeted value) composites that can be used in the fabrication of primary structural parts members for aircraft.

The mechanical characteristics of the VaRTM material determined by the coupon test are equivalent to the prepreg materials for aircraft primary composite structural parts[1] as shown in **Table 1**. However, the following technical issues need to be resolved before practical use are there. at present:

- confirmation of feasibility as a structural element,
- stabilization of quality,
- realization of low cost, and
- compliance to the applicable airworthiness regulation.

3. Basic A-VaRTM fabrication process

Fig. 3 shows an outline of the basic A-VaRTM fabrication process.

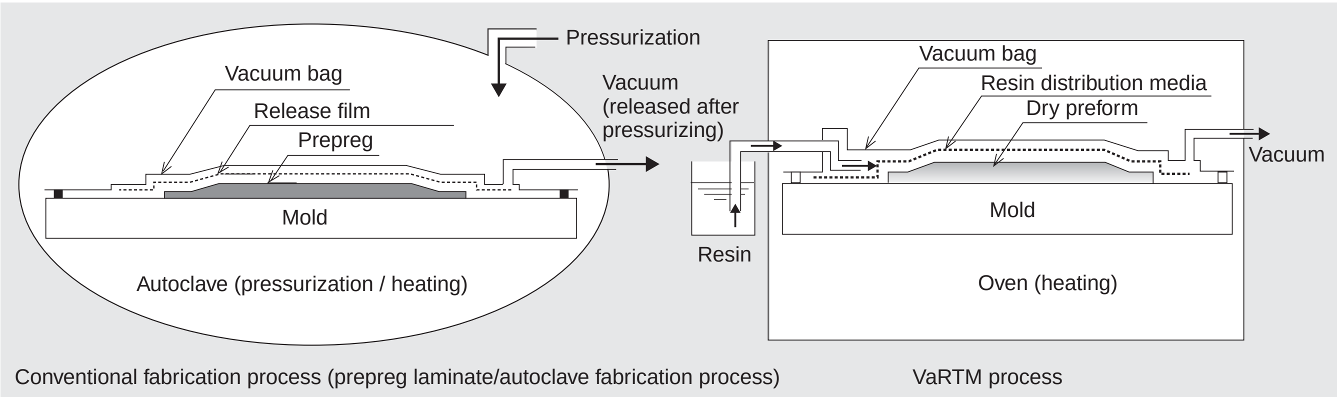

Fig. 2 Difference in composite forming methods Expensive autoclave is unnecessary for VaRTM.

Table 1 Mechanical Properties for A-VARTM and Prepreg Materials for Primary Structures

Test item	Testing environment	A-VaRTM composite (T800S/ TR-A36)	Prepreg composite (T800S/ 3900-2B)
0° Tensile strength (MPa)	RT	2 890	2 960
0° Tensile modulus (GPa)	RT	150	153
0° Compression strength (MPa)	RT	1 570	1 500
	82 C° Wet	1 250	1 280
Open Hole Tensile strength (MPa)	RT	519	500
	−59 C°	473	448
Open Hole Compression strength (MPa)	RT	295	298
	82 C° Wet	238	236
Compression strength after-impact (30.5J*) (MPa)	RT	277	300
Compression strength after-impact (40.5J*) (MPa)	RT	248	272

*Impact energy applied to test specimens

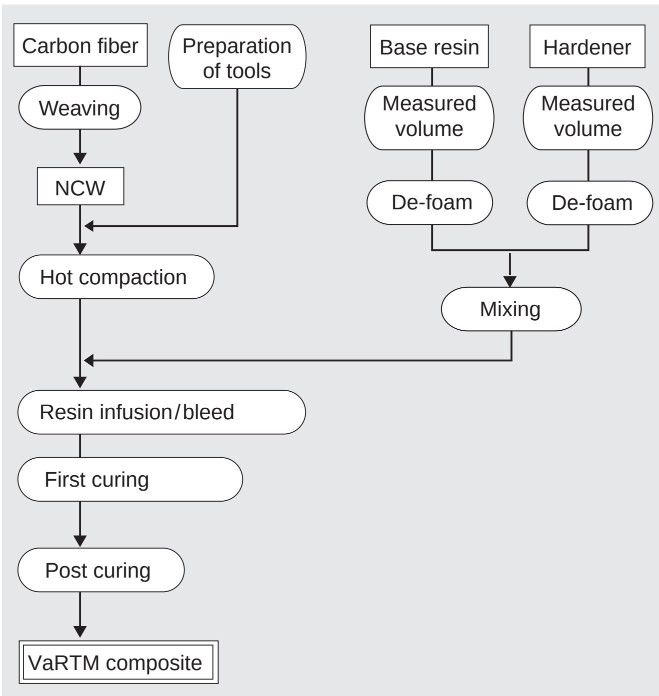

Fig. 3 Composite fabrication flow with A-VaRTM

A special woven fabric (NCW: Non Crimp Woven) that improves the unidirectional properties of A-VaRTM reinforced fiber base material by removing crimps, as shown in **Fig. 4**, has been developed so as to efficiently enhance fiber strength[2]. Further, a two component epoxy resin system with low viscosity, which is superior in infusion into perform (laminated NCW), has been developed for the matrix fiber[1].

In the A-VaRTM technique, the densification of the preform was accomplished by subjecting the NCW fabric to hot compaction after lamination in order to obtain high Vf structural parts. Vacuum bagging was applied to the preform with arranging the resin distribution media (RDM) that will keep resin path on the NCW fabric after hot compaction. The resin is distributed on the surface of the NCW fabric through the RDM and is vertically infused in the thickness direction. Excessive resin is bleed off from an vacuuming port. Since the thickness of the NCW fabric becomes thicker as it becomes infused with resin and the Vf becomes lower, excess resin is bleed off after infiltrated in order to obtain a high Vf.

Once the excessive resin has been bleed off, the resin infused NCW fabric is first cured. In the A-VaRTM technique, a resin is used which, compared with the prepreg resin, can be cured at temperatures that are lower than those of the prepreg resin used for aircraft primary structures. In addition, post curing is carried out to ensure sufficient heat resistance and strength of the resin in the now completed composite.

4. Evaluation of strength and rigidity

As a part of the evaluation of the A-VaRTM material to determine its suitability in the fabrication of aircraft primary composite structure, a structural element test was conducted with a three-stringer panel[3].

4.1 Test specimen

The test specimen used to evaluate strength and rigidity was fabricated in accordance with the basic forming process of the A-VaRTM. The bonding of the skin with the stringer was accomplished by setting three sets of stringer base materials of 1000mm in size individually formed on the I-shaped cross section on the pre-cured skin fabricated to the size of W850 x L1050 mm with a film adhesive. The "co-bonding" technique was then applied in which the resin is infused into the stringers and cured, while it bonds with the film adhesive.

Fig. 5 shows the fabrication process for the test specimen.

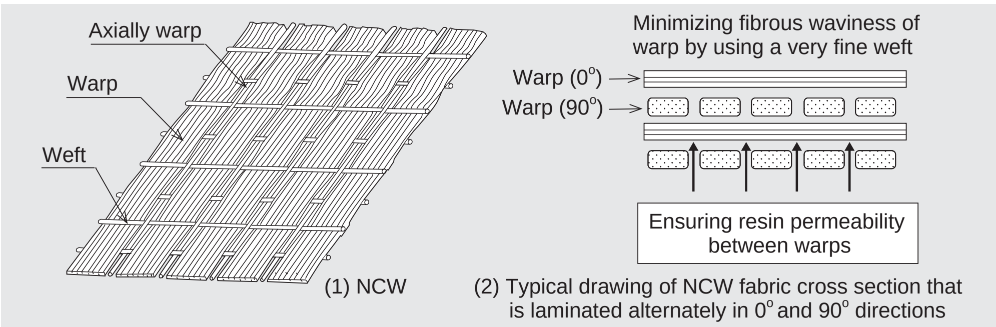

Fig. 4 Outline of NCW fabric The flow of resin is ensured by arranging carbon fiber bundles (warp) in one direction, and arranging glass fiber between the airborn fiber bundles.

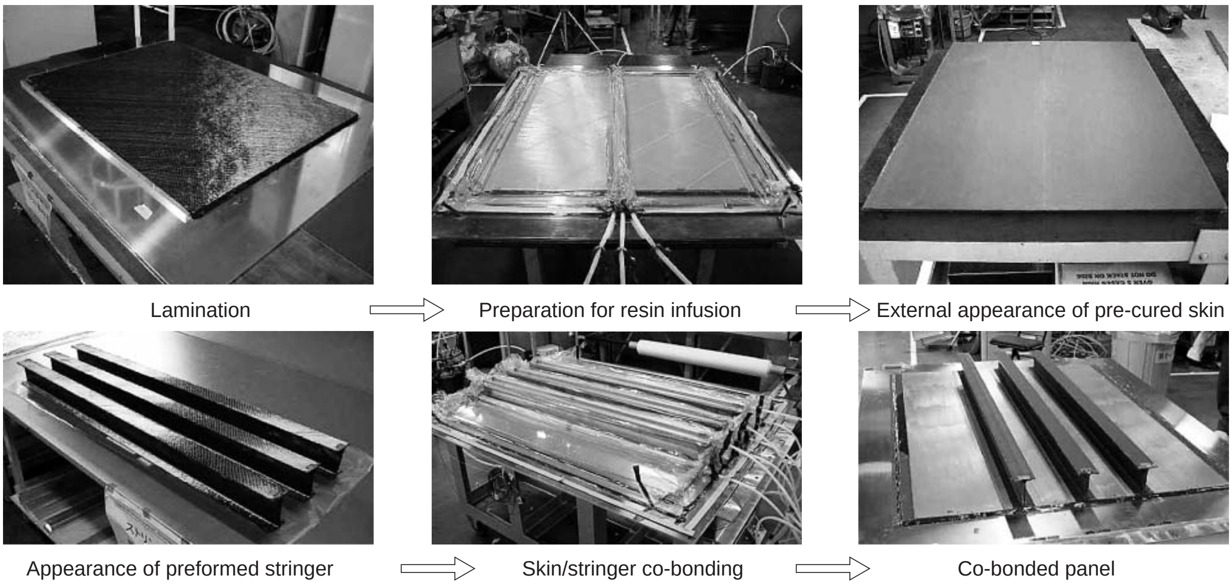

Fig. 5 Fabrication process of three stringers panel

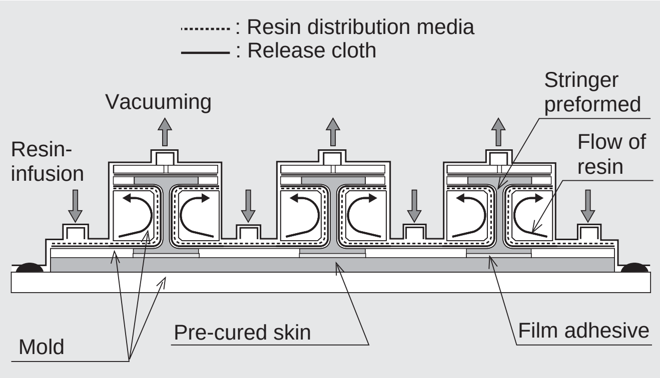

Fig. 6 Set up of skin/stringer co-bonding process
Setting up for co-bonding of dried stringer on pre-cured skin with adhesive, then they are resin infused and cured.

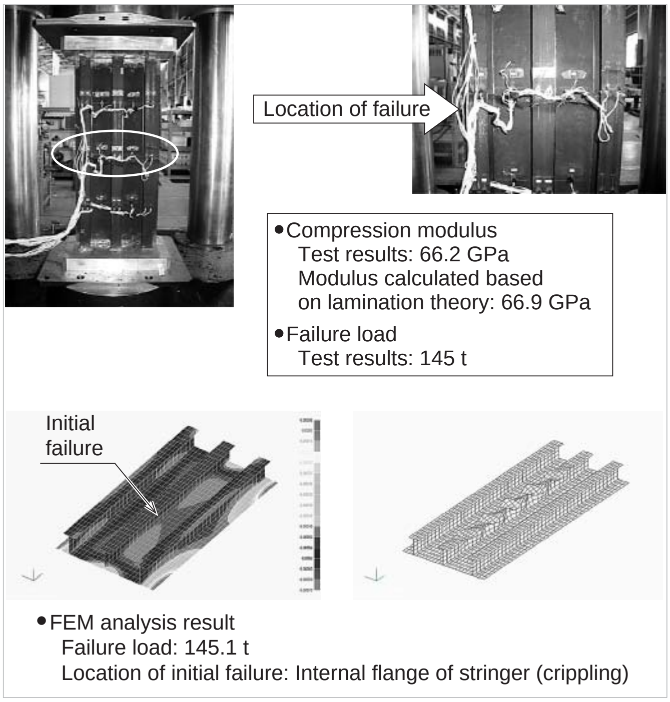

Fig. 7 Compression test for three-stringer panel
Failure state of test specimen and analytical results are corresponding.

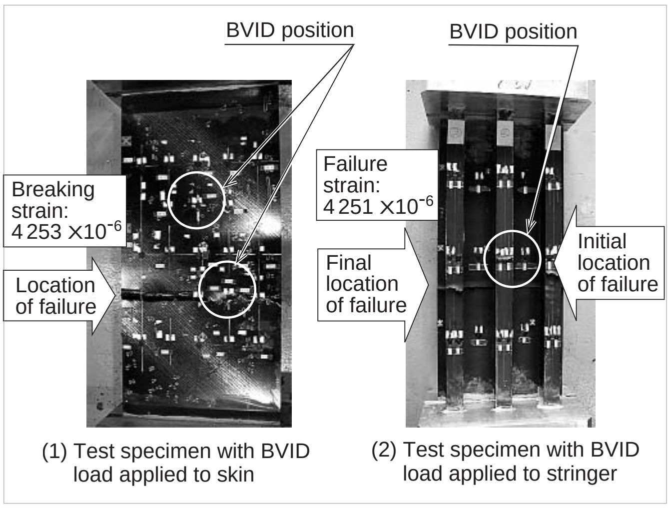

Fig. 8 Compression test result of test specimen applied BVID
Even if a high level damage is applied, failure strain of the test specimen achieved the level of 4 000 $\times 10^{-6}$.

Fig. 6 shows a cross-sectional view of the arrangement of the materials and molds.

Structural members showing good external and cross sectional appearances that were acceptable in the strength test could be fabricated as the test specimen. Hence, prospects for applying the fabrication process in mass production could be confirmed. The test specimen were prepared for the strength test by trimming to W415 x L1000 mm in size and attaching aluminum blocks to the end of the test specimen.

In addition residual strength tests for BVID (Barely Visible Impact Damage) were conducted on the specimen by applying impact energies, taking the cut off energy (136J) specified in MIL-HDBK-17 as the upper limit, as the assumed damage that would occur during actual service.

4.2 Evaluation for compression characteristics

Fig. 7 shows the results of compression test obtained using the test specimen without BVID. The analysis results obtained based on classical lamination theory and the compression test results showed very good correlation. **Fig. 8** shows the respective compression test results for the skin BVID specimen and the stringer BVID specimen.

Although very large impact damage was applied to the test specimen, the failure strain was found to be beyond the desired value of 4 000 x 10^{-6}, and it was confirmed that performance was of sufficiently high tolerance for practical use in the members of the empennage structure.

5. Evaluation of stability in quality

From the results of the structural element test with the three stringer, it was verified that the strength and elastic modulus properties of the composite materials fabricated with the VaRTM technique are acceptable for application to the empennage.

However, composite materials, even those fabricated with the conventional prepreg, may sometimes reveal instability in strength properties (especially strength after suffering damage) depending on the process. In the case of the A-VaRTM technique, the process dependency of strength of which is considered to be qualitatively higher, it is necessary to confirm the variability of the strength properties of the material fabricated under combining the process windows that affect the strength properties.

Hence, the variability level was compared with that of prepreg used for PSE by obtaining the CAI (Compression strength After Impact) representing the strength properties with a coupon test piece.

The public standard SACMA (Suppliers of Advanced Composite Materials Association) SRM 2R-94 was selected as the CAI test specification, and 6.7J/mm (1500 in-lb/in) was taken as the compacting energy.

The resin infusion temperature, temperature ramp rate and resin bleeding quantity were selected in the A-VaRTM as the processing parameters with large potential for being relied upon on for strength after suffering damage, while the other process parameters were made to correspond.

Table 2 shows the results of the quantitative evaluation by CV (Coefficient of Variation) value for the variability levels of the CAI results obtained by combining the parameters of the A-VaRTM material based on the design of experiment. As a result, it was confirmed that the CV values of the A-VaRTM material were equivalent to or higher than for the prepreg materials for the primary structures, and stable strength properties based on sound quality without being affected by variations in the process was realized. The absolute value of CAI is lower than that of the prepreg for primary structures; however, the performance shows sufficient level against structures to be used the vertical stabilizer box considered at this stage. In addition, it is necessary to specify all process windows for future mass production based on these results.

6. Preforming technique

The most big issue concerning the application of composites to commercial aircraft is production cost. As noted above, it has been verified that A-VaRTM materials are equivalent to prepreg for primary structures in terms of material characteristics, and have performance suitable for aircraft empennage, while production costs are lower than those for prepreg but higher than those for aluminum structures. Accordingly, with the aim of reducing costs even further, an examination has been made of applying the preforming technique used in the three-dimensional fabric weaving process to the A-VaRTM base materials.

Since the preforming method is a technique for directly forming fiber bundles, it may be considered that the technique is more effective in reducing production cost by eliminating secondary workings compared with other methods, including cutting sheet-form base materials such as NCF and laminating them to a mold. Therefore, I-shaped stringers were preformed as a prototype as the first step in the study of the preforming technique.

In the A-VaRTM process of the stringer preform, the same method used to flat panel was applied in the fabrication process except for the use of a mandrel to maintain the I-shape. Although it was confirmed that some voids and fiber bending were observed in cross-sections of the prototype I-shaped stringer, it was determined to be have acceptable compressive strength and that the desired properties were obtained(3).

The stringer test specimen was affixed with aluminum end blocks, and was subjected to compression testing. For comparison purposes, tests were also performed at the same time on test specimen formed with the A-VaRTM process using NCW fabric.

Fig. 9 shows the test results. From the test results, it was clarified that the properties of the preformed stringer were somewhat less (5.5% on average) than those determined by classic lamination theory. It was also confirmed that the delaminating level of the test specimen was a little large in terms of failure properties.

Table 2 CAI test result of A-VARTM material and prepreg material for primary structure

Test specimen	Numbers of specimens	CAI maximum value (MPa)	CAI minimum value (MPa)	CAI average (MPa)	CV value (%)
A-VaRTM material	64	270	207	237	5.5
Prepreg materials for primary structure	70	348	236	295	7.1

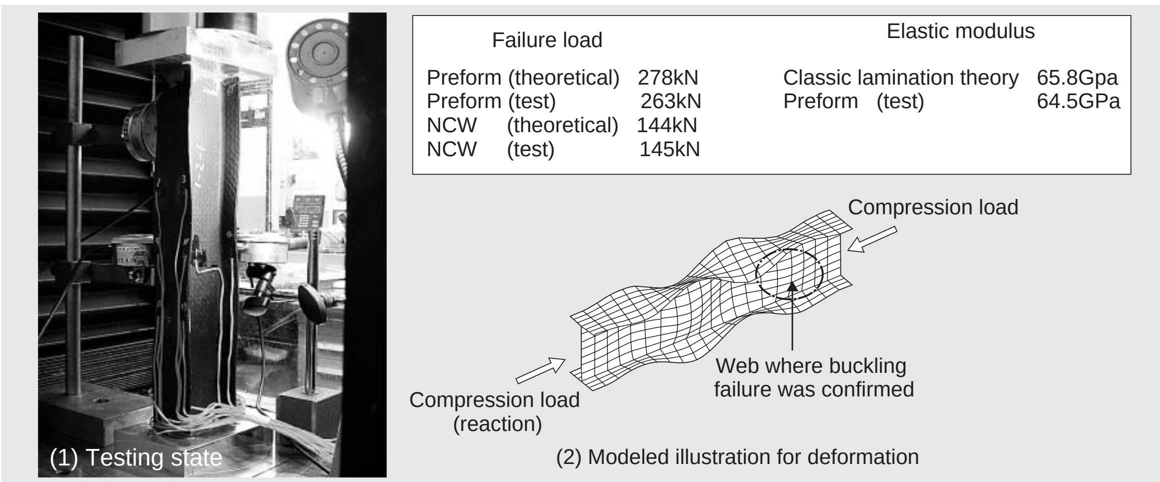

Fig. 9 Compression test for stringer unit The test values and theoretical values for the NCW fabric were in agreement, but in the case of the preform, both of strength and elastic modulus were lower than the tested value.

As an evaluation of the simplification of the forming process using preforms, conformability during the setting process was also confirmed through the use of a forming jig that simulated changes in skin thickness.

Since sufficient formability could not be achieved with the prepreg, thickness change rates as large as 100:1 were necessary at the skin-ply drop off area. However, for the preform with superior drape-ability, any fiber wrinkle, resin rich, resin starve or similar conditions were not observed at the web surface or corners, even at a thickness change rate of 25:1. Hence, it was possible to ensure excellent quality(3).

In addition, observations of cross sections of the center of the web and flange were conducted, in which conditions were found to be excellent without any disorders in the fibers, voids or the like at ramp areas.

It is thought that by establishing the preforming technique, the fabrication of parts with a certain suitable shape with a continuous performing that have a definite cross section becomes possible, and the technique may contribute to a reduction in cost and weight.

As above-mentioned, introducing the preforming technique makes it possible to realize a reduction in mass production costs to about 1.2 times as much as those of empennage structures fabricated with aluminum materials, as shown in **Fig. 10**. Finding suitable ways of reducing the costs of producing composites and A-VaRTM including structural design optimization, and demonstrating further reductions in costs with structural elements in actual airframes are major themes of further study to be pursued in the future.

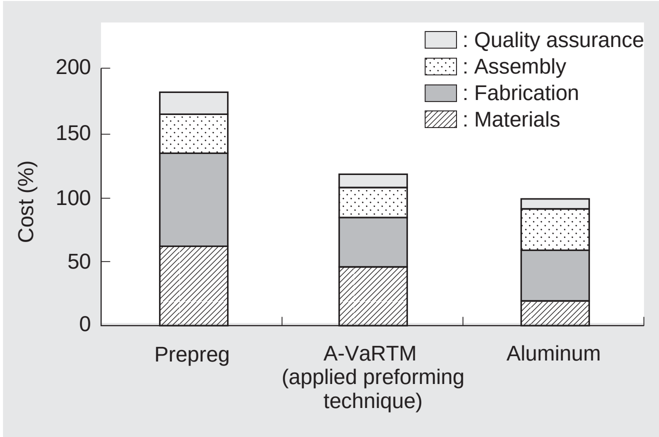

Fig. 10 Comparison of costs for empennage box structure
By incorporating a preforming process, an outlook of cost reduction of 1.2 times as much as aluminum structure could be obtained.

7. Conclusion

7.1 Material development

The aim of ensuring the stability in quality and strength of the structural members such as structural box and control surface of the empennage have been realized with the present A-VaRTM technique. Issues awaiting solution in the future include evaluating processability and strength with sub component and full-scale component.

7.2 Reduction of production costs

Existing preforming techniques that can be expected to lower costs are insufficient in terms of the straightness and toughness of the fibers compared with NCW. An optimal application method is due to be established in cooperation with weaving and materials manufacturers from now on.

Establishment of the manufacturing process, verification of strength, and evaluation of the costs are to be achieved by means of full-scale structural elements from now on.

7.3 Schedule for acquisition of compliance methodology to the airworthiness regulations

Consideration is being given to acquiring compatibility in obtaining certification for A-VaRTM materials with advice on how to do so from the Designated Engineering Representative (DER: Attorney who examines certification designated by the FAA (Federal Aviation Administration)).

This involves clarifying the risks involved based on the building block approach in the same manner as that with conventional composite materials, and validation of analysis methods, material design values and manufacturing processes.

References

(1) Toshio Abe, et.al., A-VaRTM Process for primary aircraft structures", Proc. 25th Int. Conf. SAMPE Europe, Paris, April (2004)

(2) Toshio Abe, et.al., A-VaRTM Process and Z-Anchor Technology for Primary Aircraft Structure", Proc. 24th Int. Conf. SAMPE Europe•C Paris, April (2003)

(3) Toshio Abe, et.al., A- VaRTM for primary aircraft structures", Proc. 26th Int. Conf. SAMPE Europe, Paris, April (2005)


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