A-VARTM TECHNOLOGY APPLICATION FOR JAPAN'S NEW REGIONAL JET AIRCRAFT

Tomoyuki Shinoda*, Hiroshi Odani*, Eisuke Wadahara*, Yasuhiro Komori, Takashi Shono****
***Toray Industries, Inc **Mitsubishi Heavy Industries, Ltd.**
Keywords: *Low Cost Process, VaRTM, Fiber Wrinkle Elimination, MRJ, Vertical Stabilizer, Static test*

Abstract

Advanced Vacuum-assisted Resin Transfer Molding (A-VaRTM) process for Carbon Fiber Reinforced Plastics (CFRP) has been developed for aircraft primary structures application. Newly designed fabric and toughened resin system with efficiently designed resin infusion have been introduced for A-VaRTM, Competitive mechanical properties are realized, compared with a pre-impregnated material for primary aircraft structures.

In order to achieve drastic low cost and good process-ability by use of the advantage of dry fabrics, Toray Industries (Toray) and Mitsubishi Heavy Industries (MHI) have jointly developed new fabrication processes to apply on aircraft structural elements such as a vertical stabilizer of Japan's new regional jet aircraft called as "MRJ".

We have already created Full-scaled Proof-of-Concept Vertical Stabilizer to verify low cost fabrication process and confirmed the great advantage regarding fabrication cost compared with pre-impregnated process.

In addition, the second full-scaled vertical stabilizer is currently under fabrication and assembly to verify structure strength by static test in 2007 with support of Japan Aerospace Exploration Agency (JAXA).

Coupon, element and sub-component tests are being conducted to acquire the basic design data for A-VaRTM MRJ empennage structure design.

This work is partially funded by New Energy Development Organization of Japan.

1 Introduction

1.1 Mitsubishi Regional Jet (MRJ)

MRJ program is a national project in which MHI being its principal corporation to coordinate the program with other companies and research organizations. MRJ program originally started in 2003 focusing on the 30 – 50 seat RJ. However, after a few years of market research, more demands for larger RJ are predicted. Thus MHI changed its target market segment from 30-50 to 70-90 seat size. Currently MHI is finalizing the conceptual design (Fig. 1). Program-launch and entry into service (EIS) are expected in early 2008 and 2012 respectively.

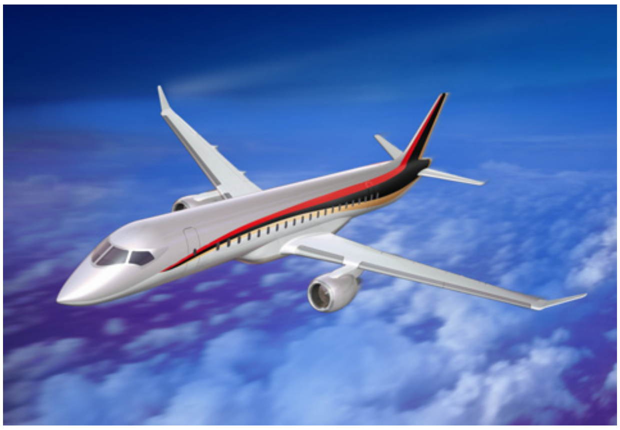


Fig.1. Mitsubishi Regional Jet (MRJ)

In order to be successfully accepted in the worldwide market, MRJ is designing to achieve lowest operating cost in the class and equivalent cabin comfort to mainline jet.

MRJ's development goal is to provide 15% lower operating cost. In order to achieve this goal, new technologies will be applied (Fig. 2). The main technology targets are reduction of the aerodynamic drag, weight saving, increase in engine efficiency, reduction of the noise, and lowering the pilot workload. In order to achieve such targets, aero-structure multidisciplinary design optimization tool, composite structures, next generation engine, advanced cockpit/flight control systems have been developed.

MRJ cabin cross section is optimized to combine high cabin comfort with less fuel consumption (Fig. 3). Large head clearance and foot clearance are equivalent to the mainline jets. Bins can accommodate large roll-on bags.

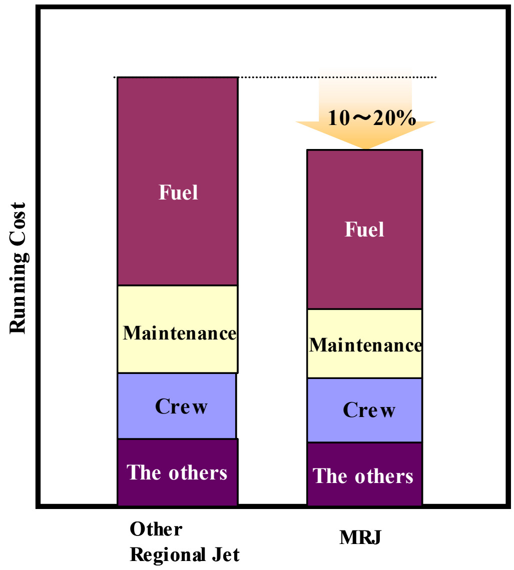


Fig.2. Mitsubishi Regional Jet (MRJ)

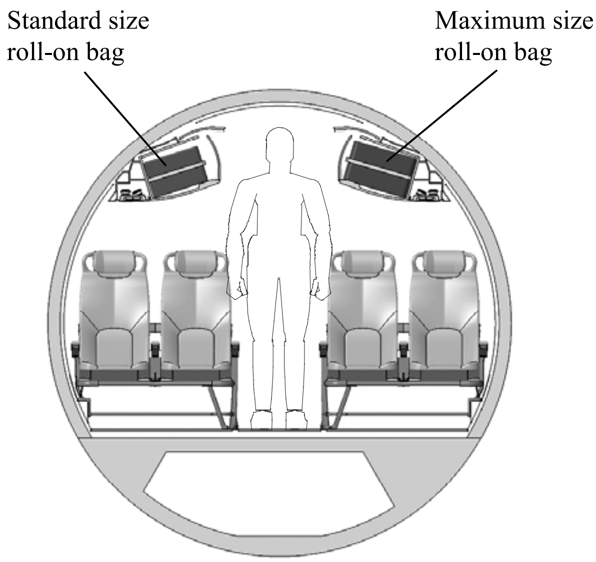


Fig.3. MRJ Cabin Cross Section

1.2 A-VaRTM (Advanced VaRTM)

It is well known that VaRTM is an attractive fabrication process not requiring expensive autoclave for traditional prepreg technology. This fabrication process leads not only contributing low cost production but also relieving product's size limitation due to autoclave. MHI and Toray have been jointly developed a new VaRTM process, or "A-VaRTM" (Advanced VaRTM), aiming for application on aircraft primary structures

The technical approach has been made to harmonize material development, fabrication process development and structural design/manufacturing engineering study. Finally, the competitive material/process can be realized for aircraft primary structures and we step forward to assess risks to apply this technology on an actual structural component such as a vertical stabilizer.

2 Material and Process Development

2.1 Basic Material and Process (A-VaRTM)

A-VaRTM Material contains non-crimp woven fabric (CZ8431DP) including intermediate modulus carbon fiber T800SC-24K-10E as reinforcement, fine wefts and auxiliary warps. Thermoplastic toughening particles are applied onto the fabric in order to improve the inter-laminar toughness of the laminates and the handling properties by stabilizing the fabric structure. A 180 ℃ cure epoxy resin system, TR-A36, a two-part epoxy, is used as a matrix resin because of its low viscosity suitable for resin infusion, which allows the fabrication of a large component by one shot.

A-VaRTM basic process consists of the following 3 processes mainly, preforming, resin infusion, and curing, shown in Fig. 4. On preforming process, fabrics are cut and laid up at first.

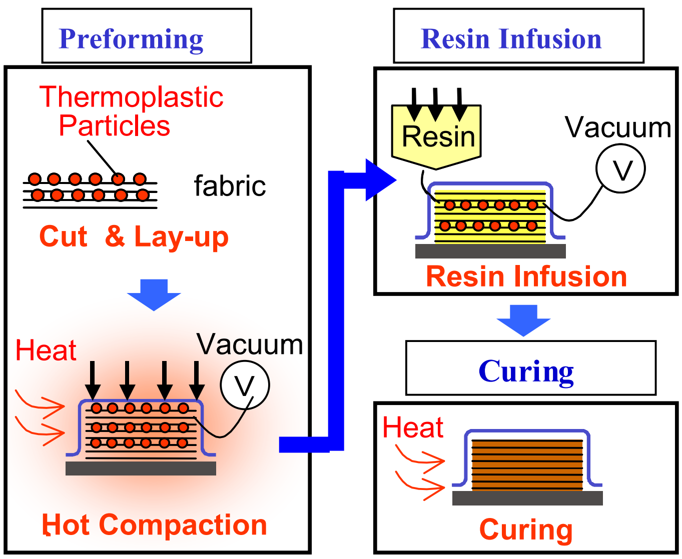


Fig.4. A-VaRTM basic process

In hot compaction process, the stack of fabrics is compacted with vacuum pressure at high temperature. As the stack is compacted, thermoplastic particles applied onto fabrics are deformed and each fabric is bonded together. Hot compaction is a drape forming process developed for our unique A-VaRTM materials to keep dimensional accuracy with the fiber volume control and stabilize preform structure. On resin infusion process, resin is infused on vacuum pressure into the preform. At last, curing process is performed.

Typical mechanical properties of CZ8431DP / TR-A36 system fabricated with A-VaRTM method are shown in Table 1. Competitive mechanical properties are realized, compared with a prepreg material for primary aircraft structures, T800S/3900-2B.

Table 1 Typical Mechanical Properties

Item	Condition	T800S/TR-A36 A-VaRTM	T800S/3900-2B Prepreg
0° Tensile Strength [MPa]	RT	2890	2960
0° Tensile Modulus [GPa]	RT	150	153
0° Compressive Strength [MPa]	RT	1570	1500
	82℃ Wet	1250	1280
Open Hole Tension [MPa]	RT	519	500
	-59℃ Wet	473	448
Open Hole Compression [MPa]	RT	295	298
	82℃ Wet	238	236
CAI (30.5J) [MPa]	RT	277	300
CAI (40.7J) [MPa]	RT	248	272

*) Fiber Volume Fraction 56.0 %. Fiber Areal Weight 190 g/m2.

2.2 Low Cost Fabrication Process

A-VaRTM low cost fabrication process consists of automated dry preform fabrication and molding process without autoclave.

Low-cost dry preform fabrication process, one of the key technologies in A-VaRTM, is conducted in two stages, fabricating multi-stacked plies of fabric, and 3-D forming with hot compaction process.

Multi-stacked plies as shown in Fig. 5 have high drape-ability and improve handling of preform, with ply-to-ply point linking via thermoplastic powder (TP-powder) by point heating and compression. Multi-stacked plies can be produced automatically by prototype machine shown in Fig.6.

High drape-ability of Multi-stacked plies makes preform fabrication process easier than prepreg. Multi-stacked plies are applicable to various 3-D forming with hot compaction, for example, automatic press forming applied to stringer preform and rubber forming applied to spar and rib preform in Fig. 7.

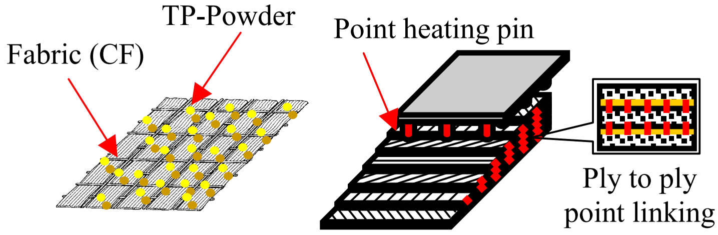


Fig.5. "Multi-stacked plies" of fabric

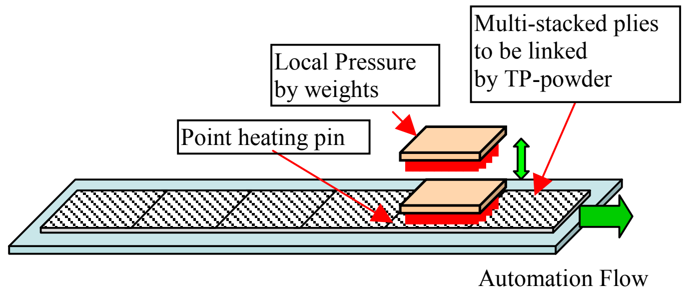


Fig. 6. Automatic Multi-stacking concepts

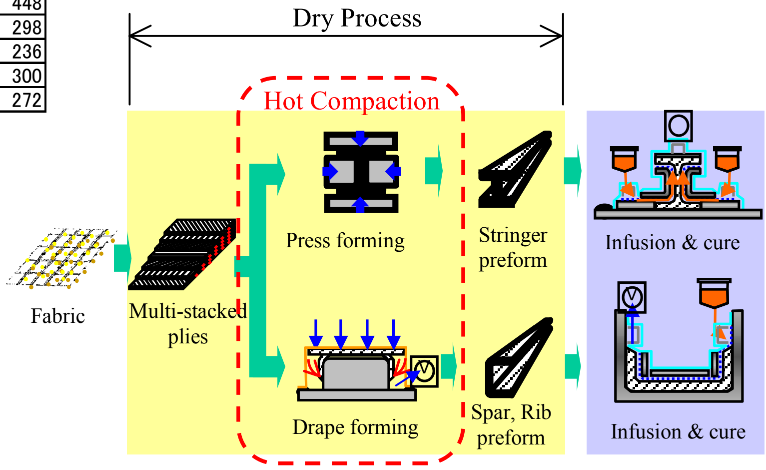


Fig.7. A-VaRTM Fabrication Process

A uniform and straight preformed stringer has been realized with "Multi-Stacked plies" on great advantage of dry process. Fig. 8 shows automatic press forming for T-section stringer preform. This automatic process has following advantages.

- Continuous process with sequential hot press forming
- Fabrication speed : 2m/hr (Prototype)
  (in future : 10m/hr)
- Applicable to pad-up
  (in future : ply-drop and height change)

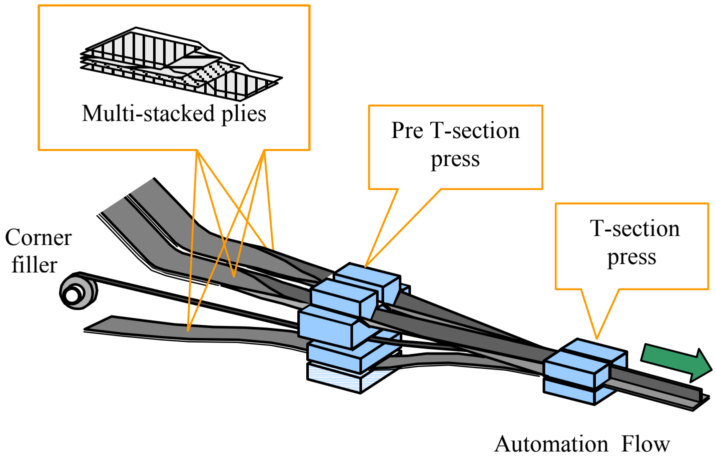


Fig.8. Automatic Press Forming for T-Section Stringer Preform

Aggressive ply-drop-off test (including the ramp ratio 100:1, 50:1 and 25:1) shows great advantage of dry process. Pre-impregnated based process has a limitation with large ramp ratio due to fiber wrinkling. In A-VaRTM process, however, no fiber-wrinkle is observed even with 25:1 ramp ratio shown in Fig. 9, based on Non-destructive inspection(NDI) and destructive inspection(DI) results.

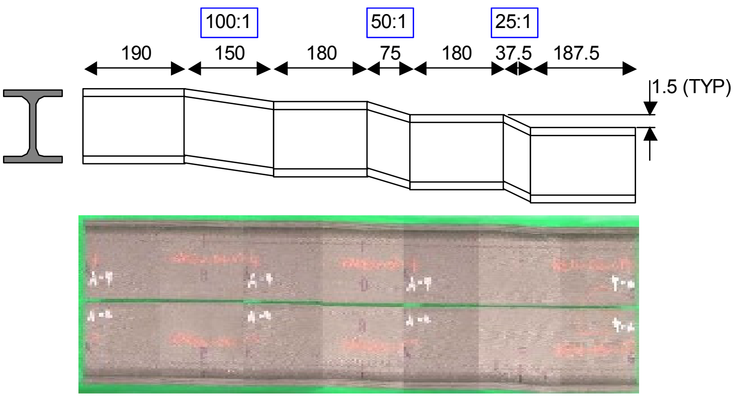


Fig.9. Aggressive ply-drop-off test

"Multi-Stacked plies" can be formed with rubber bag in condition of room temperature and atmospheric pressure. Then multi-stacked plies are bonded in hot compaction process with heated mold as shown in Fig.10.

Fig.11 shows C-shaped joggled spar in comparison between multi-stacked A-VaRTM plies and prepreg charged. Prepreg spar using "hot drape " has a big risk to induce wrinkle and should be fabricated quite carefully. As a result, cost reduction level is lower than expected. A-VaRTM spar has no wrinkle observed.

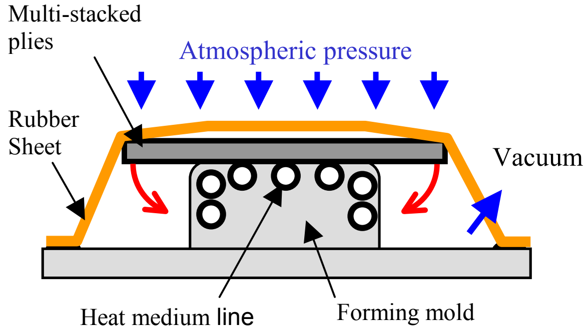


Fig.10. Drape Forming for Multi-Stacked Plies

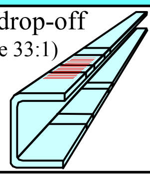
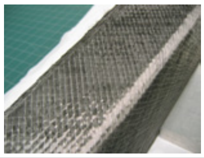
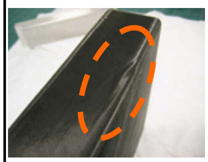
	Multi-stacked plies	Prepreg lay-up
Ply-drop-off (Slope 33:1) 		
Wrinkle	None	Heavy
Forming conditions	Drape forming at room temperature	Drape forming at 63°C

Fig.11. Comparison of Drape forming with Pre-impregnated process

A-VaRTM low-cost infusion and curing process is conducted without autoclave, and an oven is conventionally used as heating device. On the other hand, with conventional oven-used process, handling time of the mold and very long heating-up time causes the higher cost.

We have developed the new process, named "Desktop manufacturing process", that cured parts can be produced without moving the mold for all the A-VaRTM processes (from preforming to curing). As shown in Fig.12, the mold for preforming, resin infusion and curing process is heated directly by heating medium in the mold without the oven. Now it has been realized in pre-cured process (130°C), however, it will be applicable to postcured process (180°C) in future. This process can realize drastic high produce-ability for CFRP.

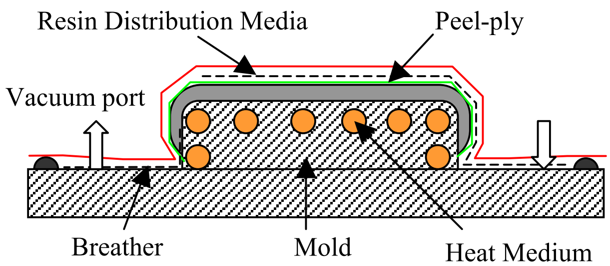


Fig.12. Desktop manufacturing process

2.3 Fabrication Trial of #1 Proof-of-Concept Vertical Stabilizer

We have created Full-scaled Proof-of-Concept Vertical Stabilizer to verify A-VaRTM fabrication process and evaluate low cost concepts shown in Fig.13.

Skin panels, stringers, spars and ribs have been fabricated with A-VaRTM process. Stringers are co-bonded on a pre-cured flat skin panel. The approximate max. length of the structure is 5000mm, and the approximate max. thickness is 6mm. NDI has been conducted to check the quality of composite parts. The results of fabrication trial are shown below.

・Our fabrication process is able to fabricate the box structure represents full-scale MRJ vertical stabilizer without any large defects.

・Our fabrication process is able to decrease the fabrication time related to cost comparing with conventional fabrication process. Especially, our evaluation shows about 40% reduction of stringer fabrication cost including material cost.

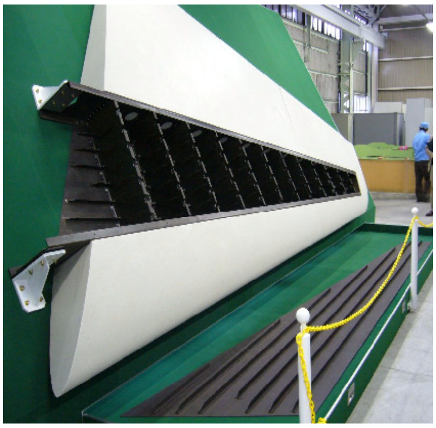


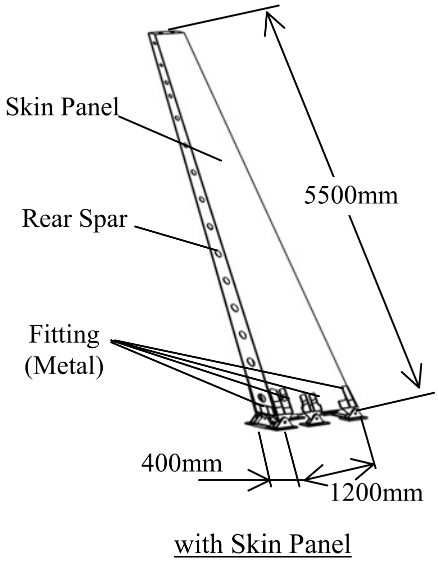
Fig.13. #1 Proof-of-Concept Vertical Stabilizer

3 Full-Scale #2 Proof-of-Concept Vertical Stabilizer Design and Fabrication

3.1 The Design of #2 Proof-of-Concept Vertical Stabilizer

Currently, we are fabricating #2 Proof-of-Concept Vertical Stabilizer shown in Fig.14 for a strength test specimen with improved / low-cost process found in #1 Proof-of-Concept Vertical Stabilizer fabrication. The test specimen incorporates fuselage interfaces and is more accurate structure than #1 Proof-of-Concept Vertical Stabilizer.

Test specimen represents the vertical stabilizer of MRJ. The approximate max. length, width and height are 5500mm, 1200mm and 400mm. Test specimen will be built with two(2) skin panels, fourteen(14) stringers, two(2) spars, fifteen(13) typical ribs, One(1) wing-to-body rib, One(1) tip rib and eight(8) fittings. Those fittings are dummy parts in this test. This test specimen has been designed to sustain with estimated design load.



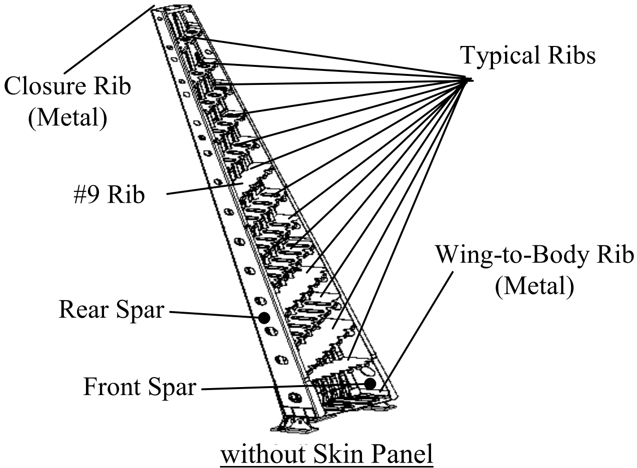
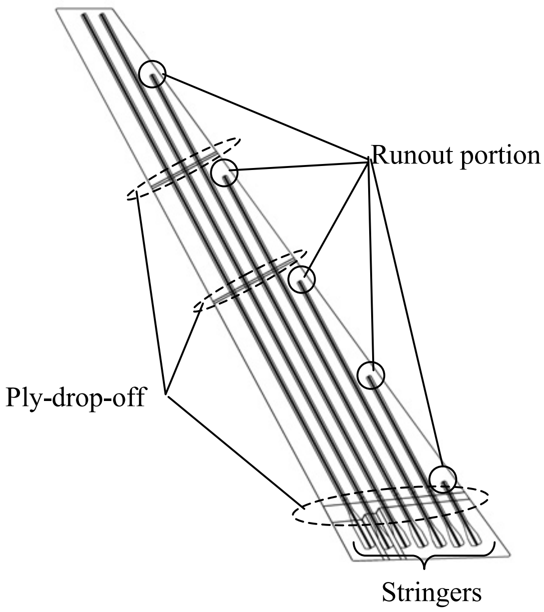


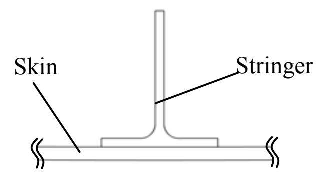
Fig.14. Full-Scale Vertical Stabilizer Test specimen

All Parts except for dummy fittings, wing-to-body rib and closure rib will be fabricated with A-VaRTM. Seven(7) stringers will be co-bonded on one(1) pre-cured skin panel as well as Full-scaled Proof-of-Concept Vertical Stabilizer (Fig. 15). Blade type stringer was applied to this Test specimen.

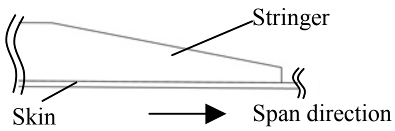
Five(5) stringer runouts are in one skin panel. Skin panel has single contour to chord direction and aggressive ply-drop-off with 25:1 ramp ratio. Maximum thickness in skin panel is approximately 10mm at root portion.



Skin



Stringer Section (Typical)



Ruinout (Typical), side view

Fig.15. Co-bonded Skin

Two(2) spars represents front and rear spar. Both of spars are continuous from the root to wing tip. The section of spar is c-channel and constant thickness. Spar web has large open holes that represent access holes for inspection in service. Approximate dimensions of rear spar is shown in Fig. 16. Thirteen(13) composite ribs and two(2) metal ribs will be assembled to test specimen. Nine(9) of thirteen(13) composite ribs are thinner than other composite ribs. These thinner ribs have beads in web to improve the stability of them. Metal ribs at root and wing tip portion are wing-to-body rib and closure rib. Approximate dimensions and geometry of composite and metal ribs are shown in Fig. 17.

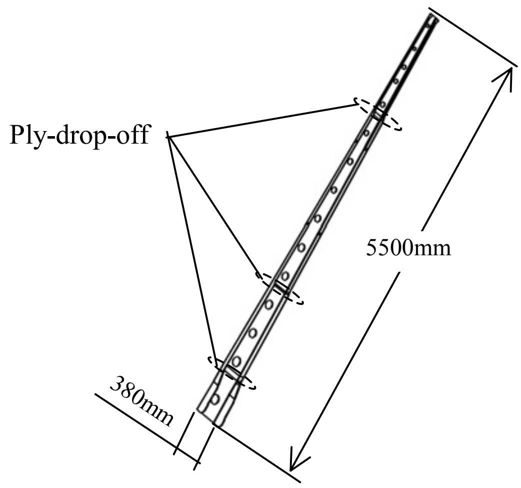
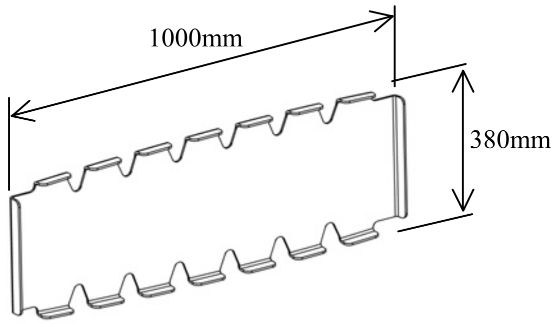
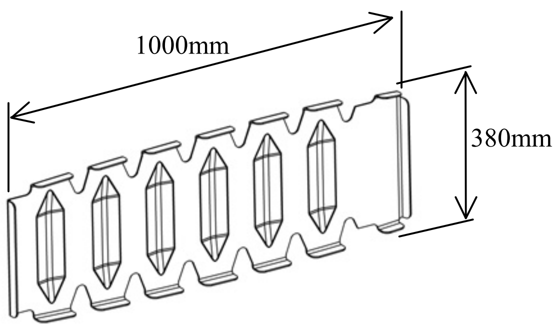


Fig.16 Composite Spar



Composite Rib (Typical)



Composite Rib with Bead (Typical)

Fig.17 Composite Ribs

The design concept of the test specimen is non-buckle with 150% limit load. The stacking sequence of all composite parts are symmetric, and target layup percentages of composite parts are shown below.

- Skin: $(0^\circ/\pm45^\circ/90^\circ)$=(40% / 50% / 10%)
- Stringer: $(0^\circ/\pm45^\circ/90^\circ)$=(40% / 50% / 10%)
- Spar: $(0^\circ/\pm45^\circ/90^\circ)$=(25% / 50% / 25%)
- Rib: $(0^\circ/\pm45^\circ/90^\circ)$=(15% / 60% / 25%)

Finite element model of the specimen was prepared for study of the critical area. The joining concept of the model simulates the joints between the vertical stabilizer and the fuselage of MRJ. But they were designed without consideration of the fuselage flexibility, because the installation of the test specimen to the test frame is on fixed condition.

The critical load cases were selected to determine the design load of the box, such as the continuous gust load for the maximum bending moment and shear force, and the yaw maneuver load for the maximum torque. The box was designed with the design load, which is composed of the highest values among the critical loads at each rib station.

The analysis was carried out with applying the design load above on the model, resulting that the most critical areas are the spar flanges near the root of the stabilizer. Fig.18 shows the strain contours of the skin panel.

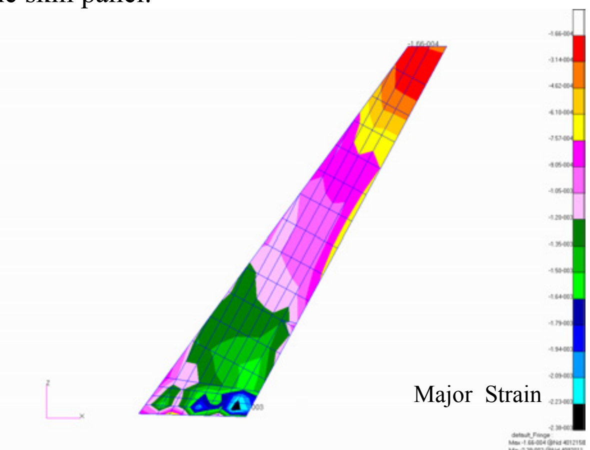


Fig. 18. Strain Contours of Whole Test Specimen

3.2 The Fabrication of #2 Proof-of-Concept Vertical Stabilizer

All of composite parts of test specimen has been fabricated with our low cost process. The flow of test specimen fabrication is shown in Fig.19.

The max. thickness of the skin panel is approximately 10mm as described. This skin panel can be produced with the preform fiber volume fraction control technique in hot compaction process.

The seven stringers are co-bonded on a pre-cured skin panel. In A-VaRTM process, however, no stringers' fiber-wrinkle is observed even with 25:1 ply-drop-off as shown in Fig.20.

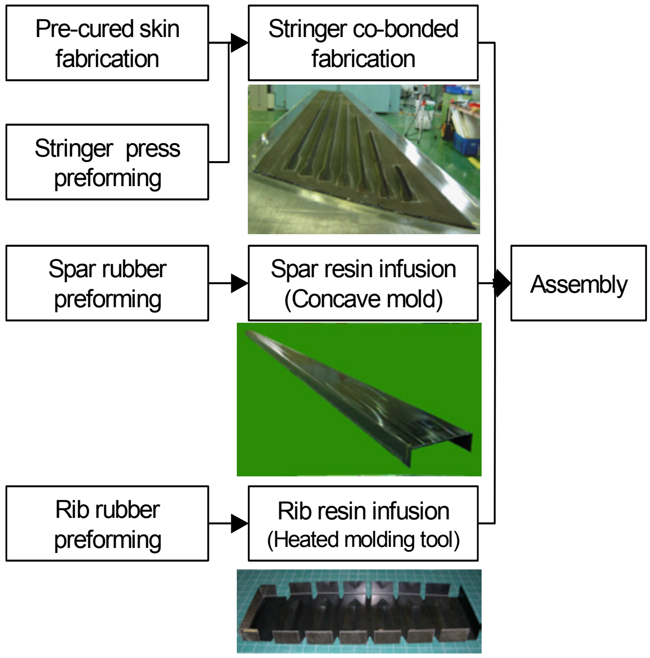


Fig.19. Flow of Test specimen Fabrication

Spars and ribs with unique rubber forming process have achieved consistent quality and shorter production time. #9 Rib in Fig.14 was produced with "Desktop Manufacturing Process" and it is verified that production time become very shorter than conventional method with no quality changes.

NDI and Three-dimensional measurement have been conducted to composite parts. NDI shows a few of small indications in some parts. The effects of small indications will be evaluated with static test as mentioned in next section. And three-dimensional measurement shows geometries of composite parts are controlled in acceptable level as the static test specimen.

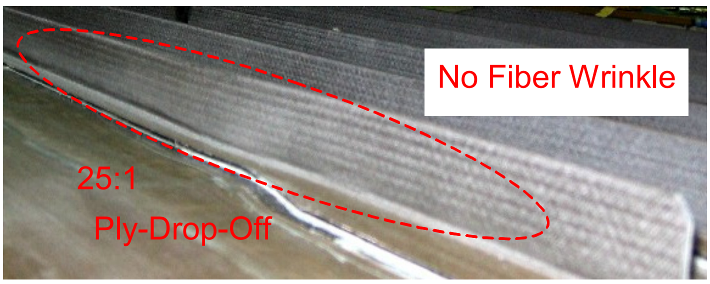


Fig. 20. Stringer on 25:1 Ply-Drop-Off

4 Static Test

4.1 Test Purpose

The purpose of the full-scale static test is to mitigate the development risk of MRJ Empennage structure fabricated with A-VaRTM. The design concept and analysis method will be verified by confirming the correlation between analytical and practical strain and the behavior of specimen failure.

4.2 Test Load

The static test will be conducted with the test load case shown in Table 2. The maximum root bending case was selected as the test load because of the most critical condition for the specimen, which is severe on the wing-to-body joint.

Table 2 Approximate Test Load at Root (LMT)

Shear Force	13000 kgf
Bending Moment	36000 kgf･m
Torque	4000 kgf･m

4.3 Test Set Up

The concept of test set-up is shown in Fig. 21. The load of the test will be applied to the test specimen with the tournaments and wing clips. The mass balances are used for canceling the original mass of the specimen itself.

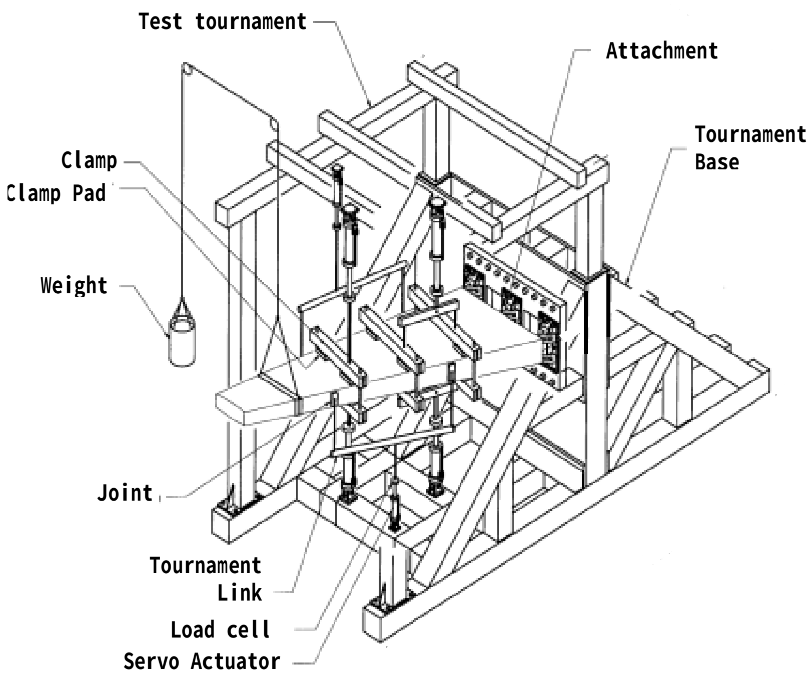


Fig. 21. Test Set-Up (concept)

4.4 Test Schedule

The fabrication of test specimen will be completed by the end of June. The test set-up will be completed by the end of August. The test will be conducted in this September with support of JAXA.

5 Basic Design Data for A-VaRTM MRJ Empennage Structure

Coupon, element and sub-component tests are being conducted to acquire the basic design data for A-VaRTM MRJ empennage structure with support of JAXA. Test items are summarized in Table 3. These tests will be completed by the end of July.

Development test for MRJ will be continued to obtain type certification in 2012.

Table 3 Test Items for Basic Design Data

Test Item
・Open Hole Tension / Compression Test ・Fastener Joint Test ・Compression After Impact Test ・Bondline Strength Test ・Configured Panel Test

6 Conclusion

We have reached the following conclusions.

1) A-VaRTM material and process development have been successfully conducted.
2) Low cost part preparation has been successfully conducted.
3) The #1 Proof-of-Concept Vertical Stabilizer has been successfully fabricated and assembled with competitive estimated cost in comparison .
4) The #2 Proof-of-Concept Vertical Stabilizer is currently under preparation for strength test in 2007.
5) Development tests for MRJ program will be continued to obtain type certificate in 2012.

7 Acknowledgement

This work represents the collaboration of MHI and Toray for A-VaRTM. Tests for verification and basic design data are supported by JAXA. Authors wish to thank allconcerned in related affiliations. This work is partially funded by New Energy Development Organization of Japan. Authors also wish to acknowledge their support.

8 References

[1] T. Abe, K. Hayashi, T. Satoh, S. Yamane and T. Hirokawa, "A-VaRTM Process and Z-Anchor Technology for Primary Aircraft Structure", Proc. 24th Int. Conf. SAMPE Europe, Paris, April, 2003

[2] T. Abe, K. Hayashi, Y.Komori, A.Okuda, Y.Suga, K.Yoshioka, E.Wadahara "A-VaRTM Process for primary aircraft structures", Proc. 25th Int. Conf. SAMPE Europe, Paris, April, 2004

[3] T. Abe, K. Hayashi, F.Takeda, Y.Komori, A.Okuda, Y.Suga, K.Yoshioka, E.Wadahara "A-VaRTM Process for primary aircraft structures", Proc. 26th Int. Conf. SAMPE Europe, Paris, April, 2005

[4] T. Abe, K. Hayashi, F.Takeda, Y.Komori, Y.Suga, N.Asahara, K.Yoshioka, "A-VaRTM Process for primary aircraft structures", Proc. 27th Int. Conf. SAMPE Europe, Paris, March, 2006

[5] T. Abe, K. Hayashi, F.Takeda, Y.Komori, Y.Suga, N.Asahara, K.Yoshioka, "A-VaRTM Process for primary aircraft structures", Proc. 28th Int. Conf. SAMPE Europe, Paris, April, 2007