DEVELOPMENT OF 3-D WOVEN COMPOSITES TO AIRCRAFT STRUCTURES

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Keywords: *3-D woven composites, Textile composites, Aircraft structures*

Abstract

In order to achieve high performance and low cost manufacturing of composite aircraft structures, we have adopted resin transfer molding (RTM) process and three-dimensional(3-D) textile pre-form which consists of carbon fiber not only in-plane but also through-the-thickness direction.

1 Introduction

A weight reduction has been pursued as an eternal target for the aircraft. The further weight reduction which can achieve the improvement of mobility and increase of pay-load is requested for the small aircraft such as fighters in the future. The increase of the application rate of composite materials to the airframe structures is the effective way for it. Fig. 1 shows the progress of research and development for the composite structures by the Ministry of Defense (MoD). The research and development for the composite material structures by MoD had achieved the application of the composites to the main wing structure of F-2 support fighter of the Japan Air Self-Defense Force. The structures which are difficult parts to apply laminate type composites, such as root fittings and lugs, are selected as one of application parts to increase the composite material application rate in the future aircraft.

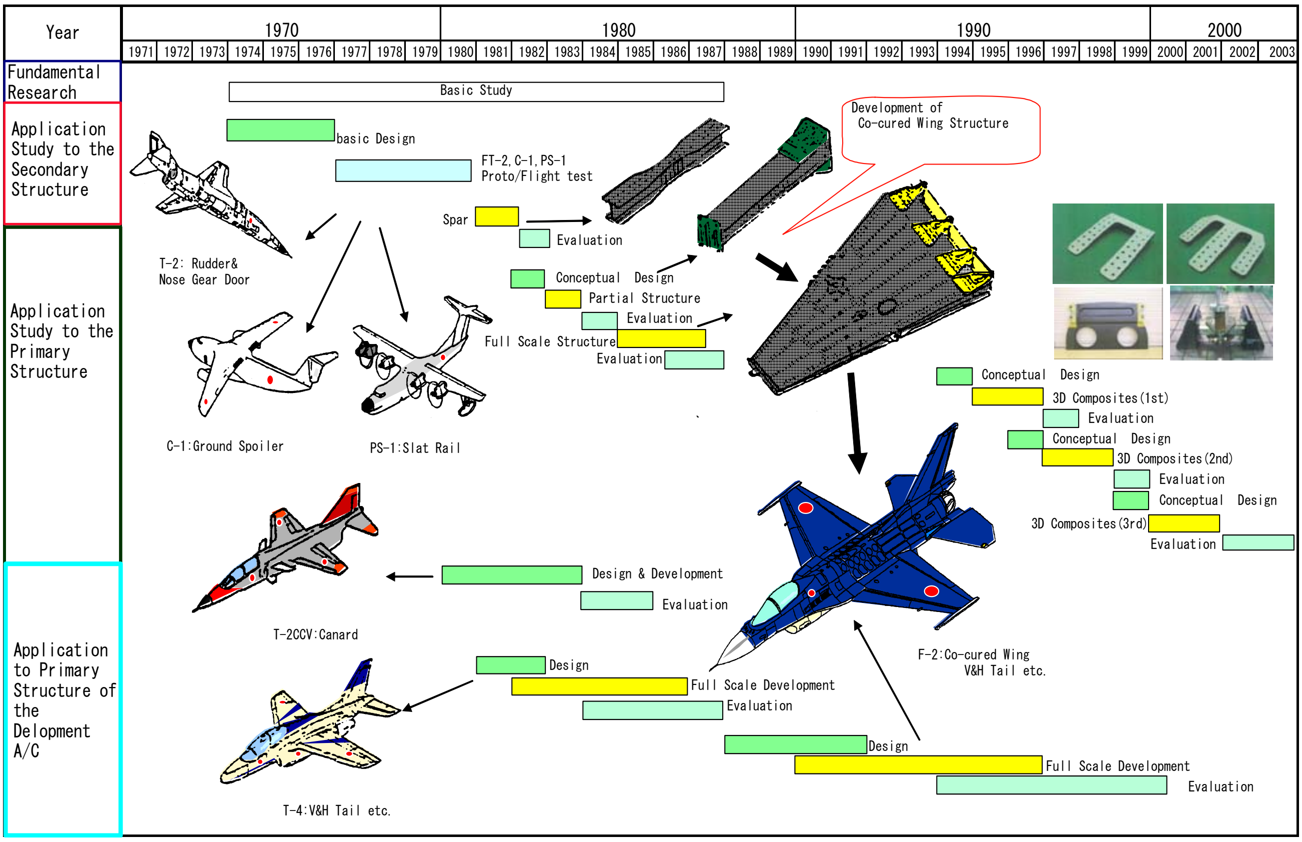


Fig. 1 Progress of composite aircraft structures by MoD

We programmed to apply three-dimensional woven composites material because they have much more strength for out of plane and CAI (Compression After Impact) than pre-preg type composites. The researches were conducted by the Air Systems Research Center, Technical Research and Development Institute, MoD.

2 Development of 3-D Woven Composites

2.1 3-D Composite Model

As an architecture of textile with reinforcements in the through-the-thickness direction, we have developed 3-D woven composites with five directional reinforcement. As shown in Fig.2, yarns go through in the 0/90/±45° directions in plane and in the through-the-thickness direction (z direction).

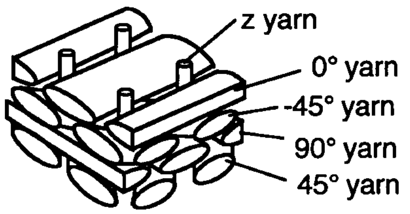


Fig. 2 Five directional 3-D woven composite

2.2 Technical challenges

Because technologies for the 3-D composite materials are much different from those of 2-D composites in the designing and manufacturing, there are several issues to be solved. Table 1 shows the details of the technical challenges.

3 Application of 3-D Woven Composites

3.1 Test Articles

For the structural components to be applied to 3-D woven composites, we selected a wing root fitting, a fuselage carry-through fitting, and a horizontal stabilizer root fitting, and designed and manufactured the full scale components of 3-D woven composites as shown in Fig.3.

Each fitting was designed to satisfy the structural requirements for high maneuver small aircraft with a maximum load factor of 9G to -3G.

Table 1 Technical Challenges

1	Design Analysis	Method of stress analysis for 3-D composites
2	Weaving Technology	Optimum technology for fiber orientation
		Five directional 3-D weaving of complex shape
3	Resin impregnation and Manufacturing	RTM and cure technologies of thick woven 3-D pre-form
		Functionalization of structural composite parts
		Manufacturing process of full-scale structure

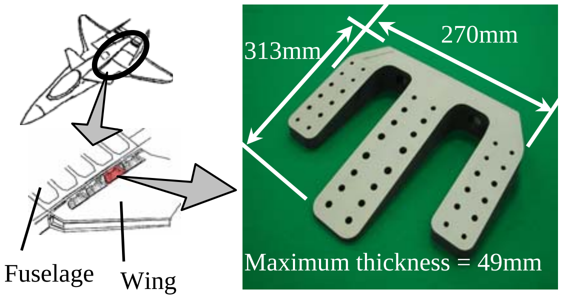
3.2 Comprehensive Design Requirements

The comprehensive design requirements are to acquire the designing and manufacturing technology of full scale structures of 3-D composites which satisfy the static and requirements and achieve the weight reduction of fatigue strength 30% or more compared with the conventional metal material components under high temperature and high humidity condition.

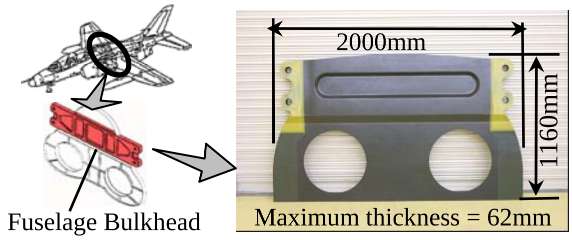
3.3 Building Block Approach

In the development of each test article, the decrease of the risk were attempted respectively by building block approach composed of trial model structure, scaled structure, and full scale structure stage. Fig. 4 shows article of each stage.

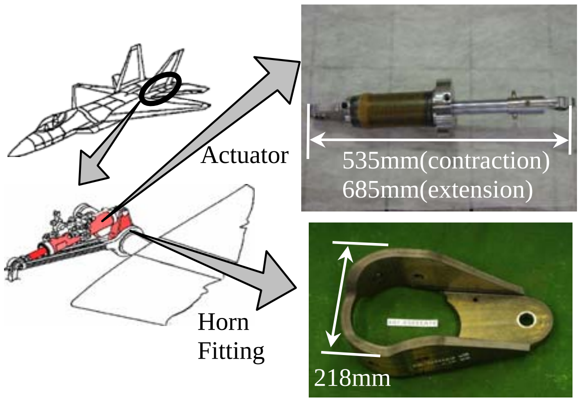
In the design and manufacture of each structure article in the building block approach, the basic property tests and structural element tests were conducted first. Many specimens were prepared for not only the basic characteristics as the tensile, compression, and shear strength, but also the through-the-thickness properties as ILSS, CAI, DCB, ENF, and tested for static and fatigue strength under environments. The design rigidity value and the design strength allowance value were set based on the tests as a design basis.



Wing Root Fitting



Fuselage Carry-Through Fitting



Horizontal Stabilizer Root Fitting

Fig. 3 Full scale components

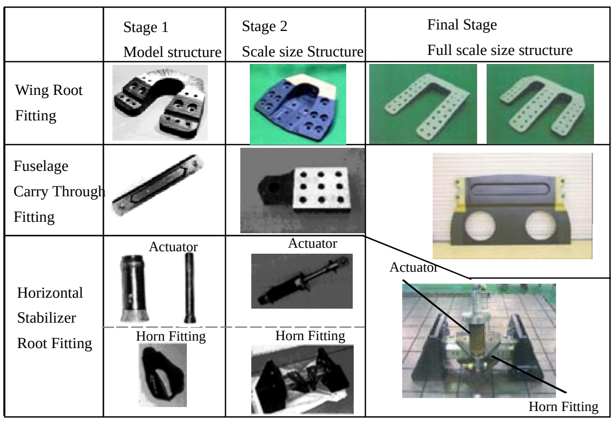


Fig. 4 Articles in each stage of building block approach

3.4 Analytical Model

Analytical designs of these fittings are conducted by using the finite element analysis with unit cells. The example of analytical model for the wing root fitting is shown in Fig. 5 One of the advantages for 3-D woven composites is the increased freedom to orient the yarns in plane. Besides the 0/90/±45 directional yarns in plane, the round yarns were added in the part where the hoop tension is dominant.

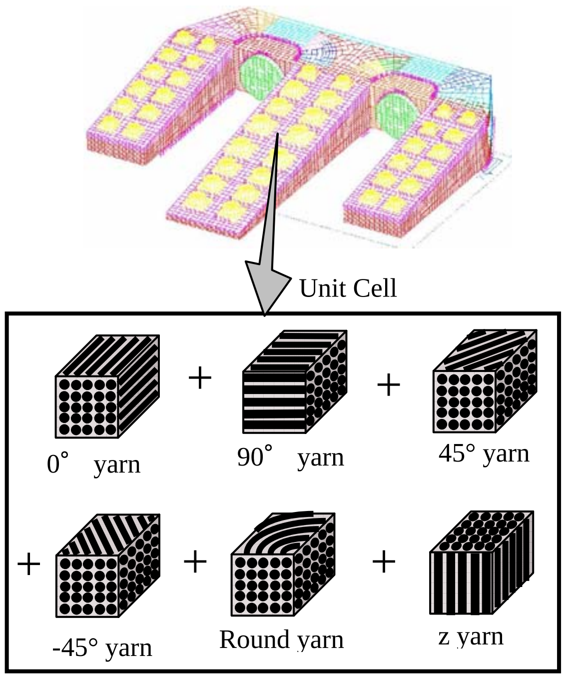


Fig. 5 Analytical model of wing root fitting

3.5 Process of Manufacturing

The process of manufacturing concept of the wing root fitting is also shown in Fig. 6 The validity of how to weave was made in the following procedure. First, making the FEM model after necessary strength and rigidity of the basic property data were obtained by the material testing for design, second, deciding the shape size and the orientation of the fiber for the assumed load, and. finally we compromised the best fiber orientations. Table 2 shows the designing and manufacturing companies and pre-form manufacturer of each test article.

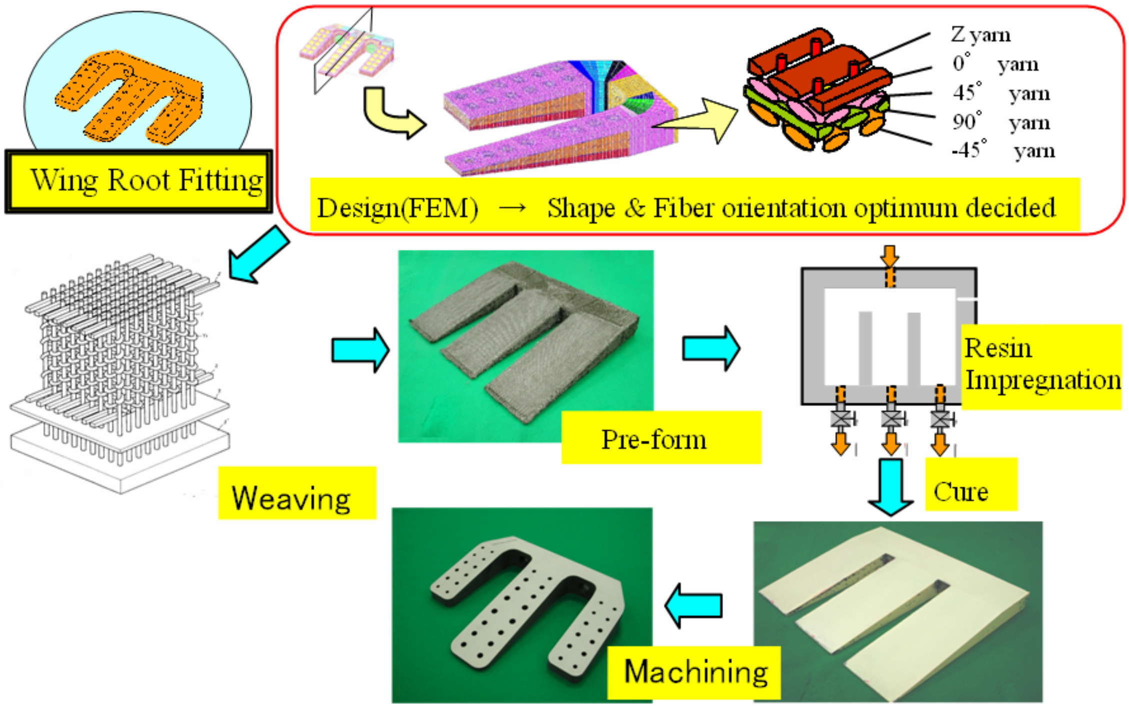


Fig. 6 Process of manufacturing concept

Table 2 Designing and manufacturing companies and pre-form manufacturers

Test Ariticles	Design and Manufacture	Pre-form manufacurer
Wing Root Fitting	Mitsubisi Heavy Industries, Ltd	Shikibo Ltd
Fuselage carry through fitting	Kawasaki Heavy Industries, Ltd	Toyota Industries Corporation
Horizontal stabilizer root fitting	Fuji Heavy Industries, Ltd	

3.6 Weight Reduction

As the results of design and manufacture of the fittings, the effective weight reductions in comparison with those made of conventional metals were achieved (Table 3).

Table 3 Weight reductions in comparison with those made of conventional metals

Components	Ratio of weight reductions
Wing Root Fitting	30.2%
Fuselage Carry-Through Fitting	38.8%
Horn Fitting	31.1%
Actuator	31.1%

4 Evaluation Tests

4.1 Test Requirements for Articles

Table 4 shows test requirements for each test articles. Table 5 shows loading forces and Table 6 shows loading cycles for fatigue tests in each test article. It was confirmed that each test article satisfied the requirement of Table 5 and 6 for those forces and cycles by tests.

Table 4 Test requirements for each test articles

Test Articles		Requirement: Static	Requirement: Fatigue	Requirement: Function
	Wing root fitting	under HTW ①There shall be a harmful neither deformation nor residual deformation for the limit load ② There shall not be failure for the ultimate load	under HTW ①There is no harmful deformation , and endures a spectrum load for 2 lifes.	
	Fuselage carry through fitting			
	Horizontal Stabilizer root fitting (Horn fitting)			
	Horizontal Stabilizer root fitting (Actuator)		Complay with SAE ARP1281	Operate Smoothly

Table 5 Loading forces for each test article

Test Articles	Direction of load	Limit loadF(kN)	Ultimate Load F (kN)	Bolt load for limit load Q (kN)	Bolt load for Ultimate load Q (kN)
Wing root fitting	Upper bending	85	127.5	653.8	980.7
	Down bending	28.3	42.5	217.9	326.9
Fuselage carry through fitting	Upper bending	85	127.5	653.8	980.7
	Down bending	28.3	42.5	217.9	326.9
Horizontal Stabilizer root fitting (Horn fitting)	Upper bending	71.9	107.8		
Horizontal Stabilizer root fitting (Actuator)	Tension	71.9	142.7		
	Compression	143.8	215.5		

Table 6 Loading cycles for fatigue tests

	Wing root fitting		Fuselage carry through fitting		Horizontal Stabilizer root fitting (Horn fitting)		Horizontal Stabilizer root fitting (Actuator)	
Load condition	Load (%LMT)	Cycles	Load (%LMT)	Cycles	Load (%LMT)	Cycles	Load (%LMT)	Cycles
a	55	48000	55	48000	12.69	27000	10	1000000
b	65	18000	65	18000	14.93	15000	50	250000
c	75	7200	75	7200	17.16	9000	100	50000
d	85	3600	85	3600	19.40	1800	−10	1000000
e	95	1104	95	1104	21.64	900	−50	250000
f	105	96	105	96	26.38	275	−100	50000
g	11	96000	11	96000	33.50	54	10	50000
h	−6.2	7200	−6.2	7200	37.00	7	75	550190
i	−16	3600	−16	3600	−12.69	27000	−75	550190
j	−34.4	1104	−34.4	1104	−14.93	15000		
k	−62.3	90	−62.3	90	−17.16	9000		
l	−80	6	−80	6	−20.14	2044		
m					−26.00	816		
n					−33.50	164		
o					−37.00	12		

4.2 Setting of moisture absorption rate

Before starting of the static and fatigue tests, we conducted the preparation tests for moisture absorption to compare the moisture absorption rate of the test articles with the moisture absorption rate of the test requirements. The test pieces for the monitor which consist of the same fiber and resin system as those of test articles were used to manage absorption rate. Absorption rate were obtained by the tests and analysis , and both absorption rate of static test (Maximum absorption rate during 20 years by 85℃) and fatigue test (Average rate during 20 years by 60℃) was set.

4.3 Detail of Tests

Fig. 7 through 10 show dimensions such as distance between the loading point from reaction point for each test article.

Gray areas in each figure are 3-D composite test articles. As an example, the loading force of 980.7kN is applied to the lower side tension bolts for wing root fitting at ultimate load test. For fatigue test, the occurrence load frequency of the fatigue test in table 6 that corresponded to twice of 6000 flights/life. The LO-Hi-LO loading sequence and the flight by flight loading method were applied.

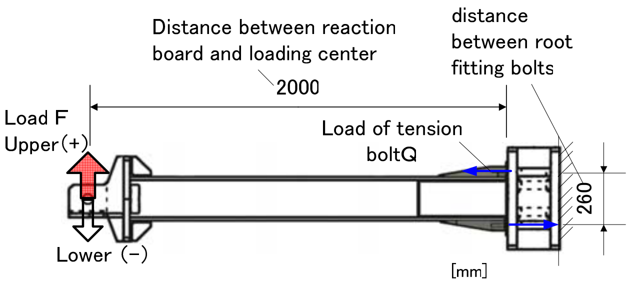


Fig. 7 Test description of Wing root fitting

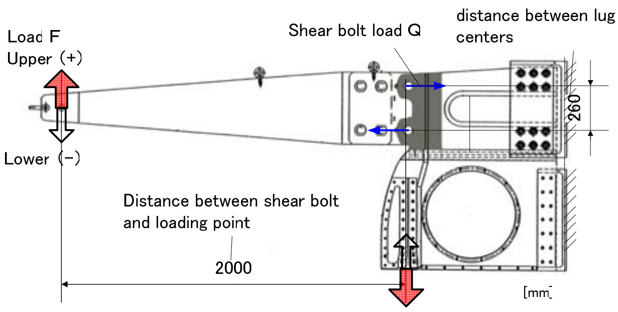


Fig. 8 Test Description of Fuselage carry through fitting

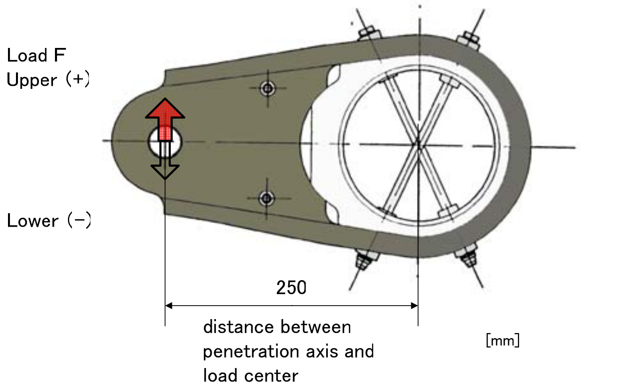


Fig. 9 Test description of Horn fitting

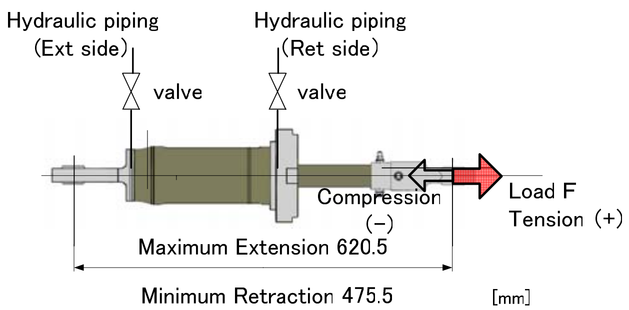


Fig. 10 Test description of Actuator

5 Test Results

Table 7 shows the result of static, fatigue and function tests of each test article. All test articles are satisfied test requirements. Fig. 11 shows an example of strain distribution as the test result. The test results and the analyses show good correspondence. Fig. 12 shows an example of the observation result in the failure area of wing root fitting.

Table 7 Test Results

Test item		Wing root fitting	Fuselage carry through fitting	Horizontal Stabilizer root fitting (Horn fitting)	Horizontal Stabilizer root fitting (Actuator)
Static test	Limit Load test	Satisfied requirement(under HTW For Limit load , test articles were not harmful deformation and not residual deformation)			
	Ultimate load test	Satisfied requirement(under HTW, For Ultimate load , test articles are endured			
	Failure test	209%LMT Fail	204%LMT Fail	250%LMT endured	178%LMTfail
Fatigue test	Durability Test	Satisfied requirement(under HTW, test articles were endured 2life spectrum load)			Satisfied requirement (SAE ARP 1281)
	Residual strength test	209%LMT Fail	198%LMT Fail	270%LMT endured	-
Functional test		-			confirmed to operate smoothly

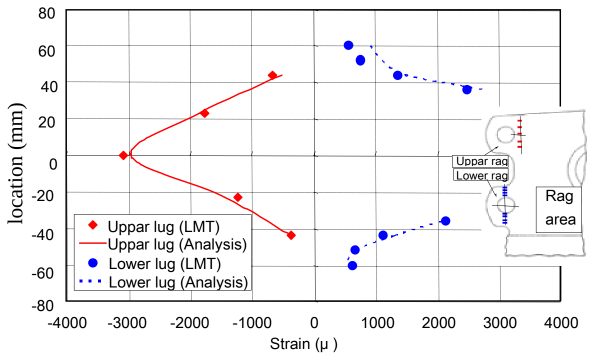


Fig. 11 Strain distribution of lug area for fuselage carry through fitting

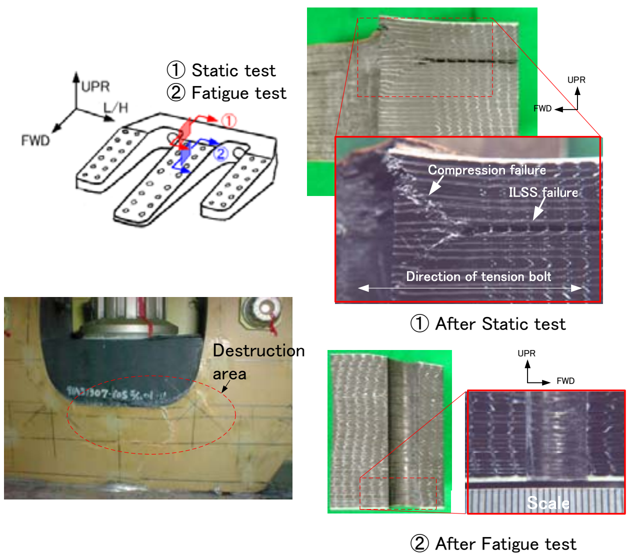


Fig. 12 Failure area of wing root fitting

The failure of wing root fitting in both static and fatigue test generated near the tension fitting bolts of lower side, and the compression failure occurred at the interface between the barrel nut and test articles. ① shows, the failure advanced toward the direction at about 45°, and followed the inter laminar shear failure to the direction of the tension bolt. ② shows , no damages by the fatigue test loading was seen in the section.

6 Technology achievements

Table 8 shows the achievements of technical challenges and Fig. 13 and Fig. 14 shows the examples of the details of the achievements.

Table 8 Achievement of technical challenges

Technical challenges		Achievements
Design analysis	Method of stress analysis for 3-D composites	Stress and rigidity design
	Optimum technology for fiber orientation	FEM Unit cell method
Weaving technology		Adapted fiber orientaion to complex shape
		Five directions (Fig. 13)
	Five directional 3-D weaving of complex shape	High volume fraction
		Reduce fiber undulation of in-plane
		Tension of fiber for through-the-thickness direction
		Automatic weaving
Resin impregnation and Manufacturing	RTM and cure technologies of thick woven 3-D preform	Tool technology (near net shape)
		Thermal process, Pressure keeping Technology
		Low viscosity resin (for RTM)
		Measures of resin flowing (for resin rich and void)
	Functionalization of structural comosites parts	Application to hydraulic component
		Round rod, Cylindrical shape manufacturing
	Manufacturing process of full-scale structure	Full scale Aricraft structure manufactured
		Joining of 3-D and 2-D composites by scarf joint (Fig. 14)
		Wedge effect joint

7 Conclusions

3-D composite materials for aircraft structures were developed, and the weight reduction rate of 30% or more was achieved. Moreover, the test articles of 3-D composites were manufactured and tested, and it was confirmed that they satisfy the requirements for the static and fatigue strength. The results show that the application of the 3-D composite to the aircraft structures is valid.

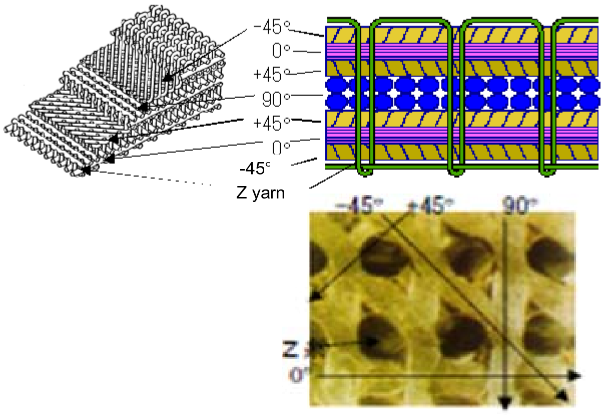


Fig. 13 Five directional weaving technology

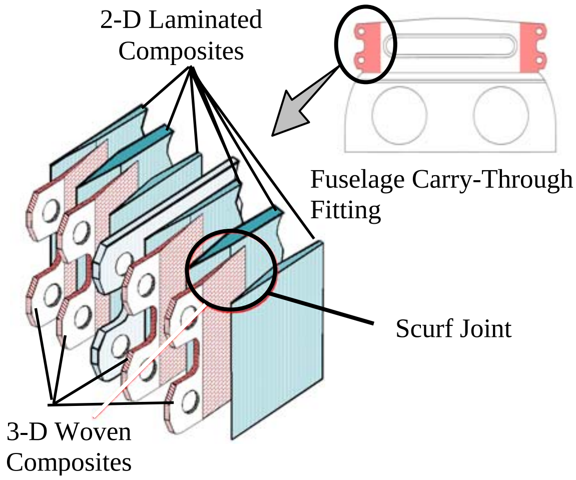


Fig. 14 Jointing of 3-D and 2-D composites

Reference

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