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CFRP using braided preforms/RTM process for aircraft applications

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Abstract—Braiding is one of the useful textile techniques for fabricating near-net-shaped fiber preforms. Automated braided preform fabrication process has been improved. Triaxial braiding was evaluated as a means of reducing the cost of producing airplane framesusing automation technology. A new preforming process was proposed to make the near-net-shaped preforms by using the conventional tubular braiding technique and deforming technique to change the configuration into the near-net-shapes. The preforms were fabricated with carbon fibers by using the new performing process and molded using resin transfer molding (RTM) process with epoxy resin into I-beam frames and panels for investigating mechanical testing and production cost. Mechanical testing and cost analysis indicated that the mechanical properties of the braided composites are superior to those of aluminum materials and that the combination of the braiding and the RTM process is less costly than the hand-lay-up and autoclave process.

Keywords: Braiding; performing; RTM; CFRP frames.

1. INTRODUCTION

In the 1990s, textile machine producers, manufacturers of textile fabrics and preforms, and aerospace companies combined forces to further exploit the benefits of textile processes for fabrication of advanced composite materials, and the airplane manufacturers began to show increased interest in textile processes. Textile processes offered potential for major cost reductions and performance gains [1–5].

Braiding is one of the useful textile techniques for fabricating near-net-shaped fiber preform. Fabrication of braided preforms is highly automated and a good balance in off-axis properties can be achieved with braided configurations. The

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braided preforms are well suited for complex shapes and they have good drapability [6]. Braiding technologies have been improved by developments combining robotic mechanism to make complex shaped performs [7]. The automation of complete production systems including a braiding machine has also been improved [8]. The production cost includes the cost of labor, tooling, depreciation, materials, etc. The cost of labor is the biggest individual cost and automation technology of production process is capable of reducing the costs of labor. Therefore, automation technology is the most efficient way to reduce the production costs.

A 3D braiding mechanism that can fabricate braids with complex shaped cross-section such I-beam has been developed [9]. The 3D braiding mechanism can transfer carriers widely along the track arranged according to the shape of the cross-section of the braid. The 3D braid is constructed with multiple braid yarns oriented continuously and intertwined into the near-net-shape automatically. The 3D braided composites indicated superior mechanical properties.

However, production speed of the 3D braids is lower than that of the conventional tubular braids because of complex track configuration. When various types of 3D braids are fabricated, it is necessary to design and arrange the track configuration for each. These processes increase the production cost. Therefore, considering production cost and ability to make various shapes of braids, it is necessary to develop a new preforming process with conventional tubular braiding technique.

The resin transfer molding (RTM) process is well suited for molding the textile-reinforced composites. Recently, low viscosity thermosetting resin systems have

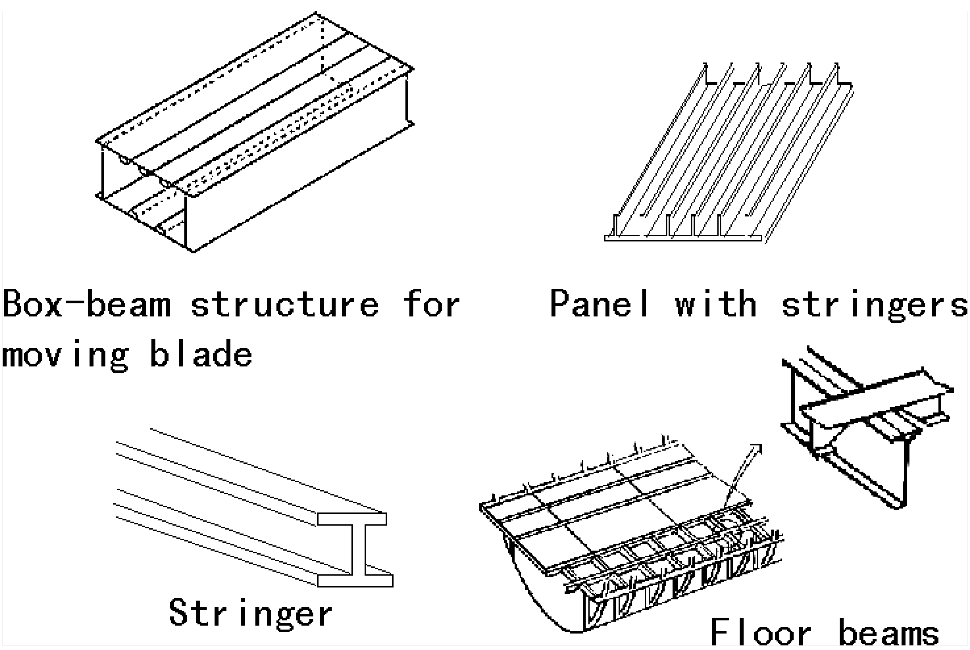


Figure 1. Airplane applications for braid frames or stringers.

been developed, so that they are capable of penetrating near-net-shaped large part cavities. In addition, the RTM process has been well known due to its excellent surface finish and the short cycle times [10].

In this paper, a new preforming process with conventional tubular braiding techniqueand RTM technique was proposed. The new preforming process involves the use of the conventional tubular braiding technique and deforming technique to change the configuration into the near-net-shapes. The frames or stringers for airplane shown in Fig. 1 were manufactured using the new preforming process and RTM technique for appraising the effectiveness of the process.

CFRP braided composite flat panels were fabricated using the RTM process, and their tensile property was evaluated in order to obtain the basic mechanical properties. The frames and a box beam were made using braiding/RTM process. The stiffness of the box beam was predicted by using a finite element method to examine the mechanical properties of the CFRP box beam and comparison with a box beam made of aluminum.The production cost of the braiding/RTM process was also compared to that of the conventional process, prepreg hand-lay-up/autoclave process.

2. BRAIDING/RTM PROCESS

2.1. Braiding

2.1.1. Braiding construction. Figure 2 shows a schematic of a triaxial braided structure. Multiple yarns are intertwined on a mandrel to form tubular shape. Triaxial braid consists of three types of fiber orientation, $0° + \theta°$ and $-\theta°$.

The braid has axial yarns in the axial direction, labeled as middle-end-fibers, in addition to the braid yarns with braiding angle of $+\theta/-\theta°$. The braiding angle can be varied in each layer to meet the design requirements. If a preform design must be formed with a thickness requiring more than one layer, several layers can be braided over each other to achieve the required thickness.

2.1.2. Preform deforming process. As the conventional tubular braiding technique cannot directly fabricate the near-net-shaped preforms of the frame configurations such as an I-beam, the preform deforming process was used after the braiding process. First, tubular braid is fabricated on a mandrel; the dimension and fiber orientation angle are calculated by considering the required configuration and mechanical properties of final products. Next, the mandrel is removed from the tubular braid. Then, in the preform deforming process, the tubular braid is deformed and flattened to make shape of final products with jigs as shown in Fig. 3a. The preform deforming process can realize the fabrication of various frame configurations such as the 'I', 'J', 'T' and 'Z' cross-sectional shapes shown in Fig. 3b. The fiber architectures of the braid after deforming process are still the same as that of the original tubular braid. The braid is not cut out but folded up, so that braiding yarns are oriented continuously at the edges.

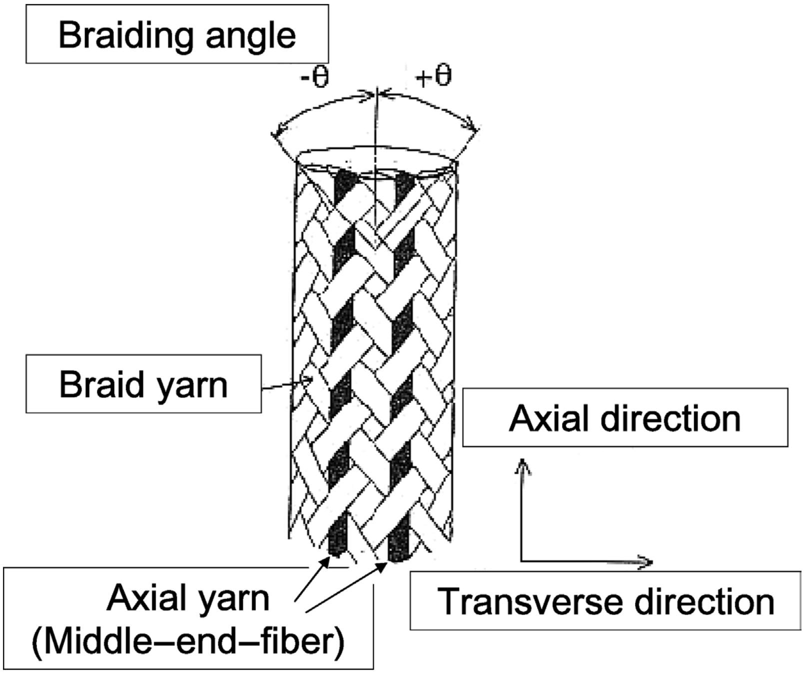
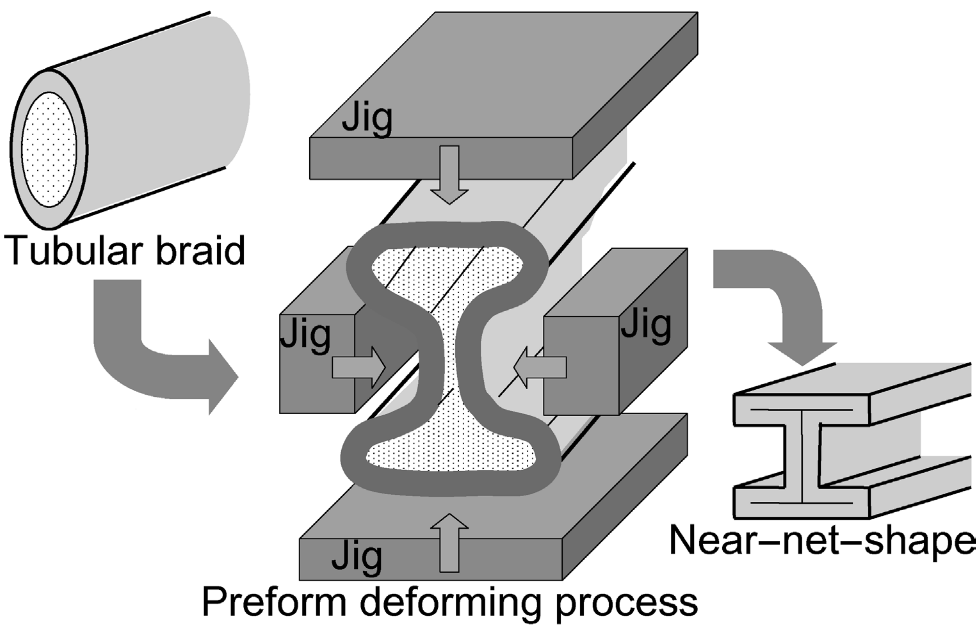
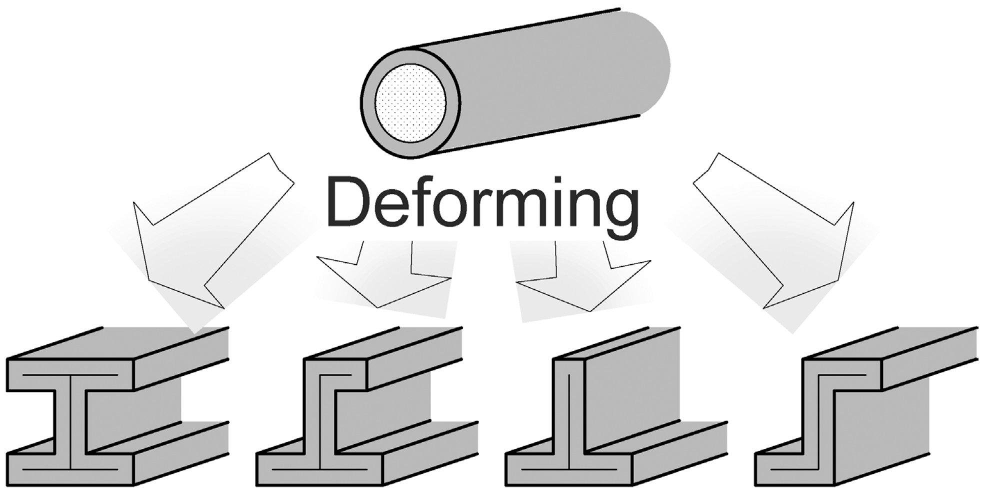


Figure 2. Triaxial braid.



(a)

Figure 3. (a) Preform deforming process. (b) Frame configurations using deforming process.



(b)

Figure 3. (Continued).

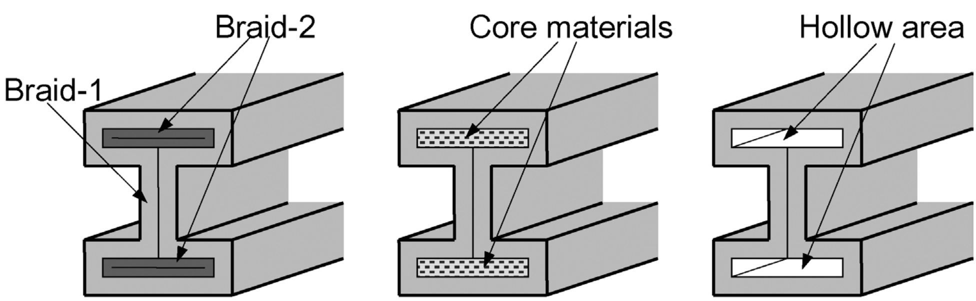


Figure 4. Variations of braid frame construction.

Figure 4 shows variations of braid frame construction to make thick flange parts of an I-frame, using other smaller braids, core materials or mandrels. Tapered I-shaped frame can be also fabricated as shown in Fig. 5.

2.2. RTM Process

The RTM system used in this study is shown in Fig. 6 and consists of four units, pumping unit, heating unit, mold unit and vacuum unit. The RTM process is simple and consists of only a few steps:

(1) prepare the mold tooling,

(2) place the preform into the mold, and close the mold,

(3) force or draw the resin into the mold and saturate the preform,

(4) cure the resin, and demold the parts.

The near-net-shaped preform is put into the mold, and the mold with the preform is placed into the heater unit. The pump push and the vacuum pull within the mold are

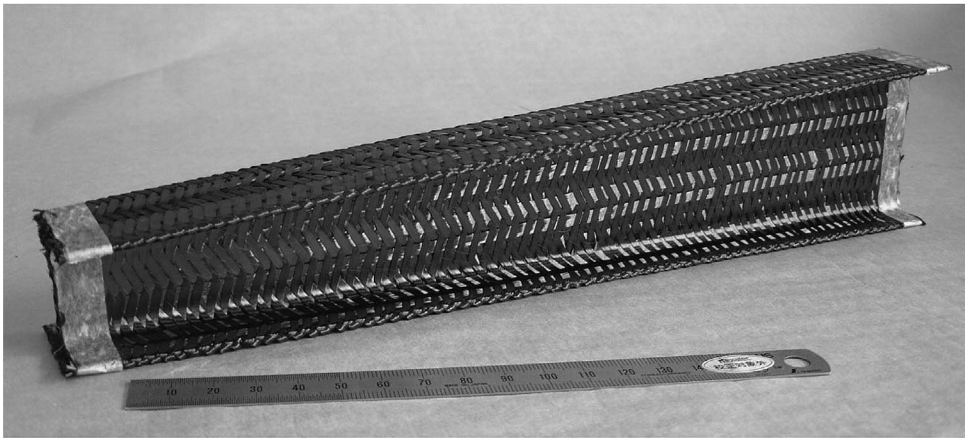


Figure 5. Braided preform of tapered I-shaped frame.

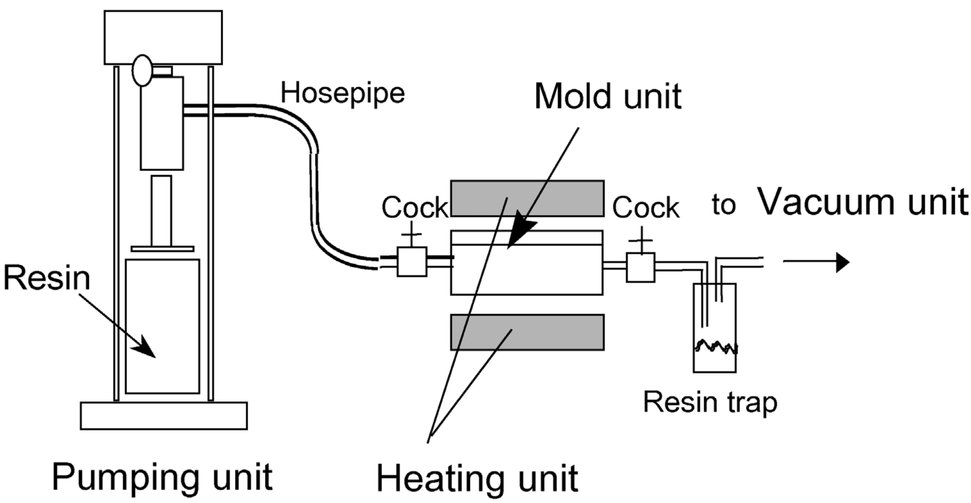


Figure 6. Schematic of RTM system.

the driving force for bringing the resin into the preform. The required temperature can be controlled to keep lower viscosity and to cure the resin during the RTM process.

The RTM process conditions in this study are as follows. The temperature was controlled during the RTM process with the PR-500 (3M) epoxy resin system. The temperature of the mold for filling the mold with the resin was 160°C. The temperature of mold for curing was 180°C for two hours.

3. TENSILE PROPERTIES OF CFRP FLAT PLATES

Two types of CFRP braided composite flat panels were fabricated using the RTM process in order to obtain the basic mechanical properties. Tensile test was performed and the effects of braiding angle on the mechanical properties were evaluated. The mechanical properties were compared with those of aluminum materials used in aircrafts currently, in order to evaluate the adaptabilities of the CFRP braided composites for aircraft parts.

Tubular braids were fabricated with carbon fiber bundles (Torayca T300, Toray). Then, the tubular braids were flattened and laminated to fabricate the preforms of flat plates. CFRP flat plates were obtained through the RTM process with the epoxy resin. The flat plate specimens were cut out from the CFRP flat plates.

Tensile testing was carried out using two types of CFRP flat plate specimens, 'P-60' and 'P-45'. The fiber architectures of braided preform are shown in Table 1. 'P-60' has a 0°/±60° braid construction with 12K carbon fiber bundles for axial yarns and 6K carbon fiber bundles for braid yarns, respectively. 'P-45' has a 0°/±45° braid construction with 12K carbon fiber bundles for axial yarns and 6K carbon fiber bundles for braid yarns, respectively. Those specimens have fiber volume of 55%–59%.

Table 2 shows the results of tensile tests in 0° and 90° direction, with aluminum materials, Al-7075 and Al-2024, as a comparison.Tensile modulus in the 0° direction of P-60 was close to that in the 90° direction of P-60. The P-45 specimen showed the highest value of tensile modulus in the 0° direction and the lowest value of tensile modulus in the 90° direction. Arranging the braiding angle can control the mechanical properties to meet the design requirements. P-60 and P-45 indicated

Table 1.
Braided preform fiber architecture

Type	P-60	P-45
Axial yarn	Torayca T300-12K	Torayca T300-12K
Braid yarn	Torayca T300-6K	Torayca T300-6K
Braid angle (θ)	60°	45°
0°, ±θ°	33.3%, 66.6%	41.4%, 58.6%

Table 2.
Tensile properties of CFRP flat specimens

Test direction		P-60		P-45		Al-7075*	Al-2024**
		0	90	0	90		
V_f	%	57	57	58	58	—	—
Density	g/cm^3	1.51	1.51	1.51	1.51	2.80	2.77
Tensile modulus	GPa	49	46	60	20	72	74
Tensile strength	MPa	427	357	593	183	538	393
Specific tensile modulus	GPa/(g/cm^3)	32	30	40	13	26	27
Specific tensile strength	MPa/(g/cm^3)	283	236	393	121	192	142

* Aluminum 7075-T6 Extrusion.
** Aluminum 2024-T4 Extrusion.

higher specific moduli and strengths than the aluminum materials. It is expected that weight of aircraft parts can be decreased by using the CFRP braided composite in which the braiding angles are arranged according to the load condition of the parts. The test results make it clear that braided composite frames are qualified to be use in aircraft applications.

4. FABRICATION OF CFRP FRAME, STRINGER PANEL AND BOX BEAM USING BRAIDING/RTM PROCESS

4.1. I-shaped frame

An I-shaped frame is described as an example of frames for aircraft. Figure 7 shows a photograph of a CFRP braided composite and braided preforms of I-shaped frames. The dimensions of small ones are 40 mm width, 40 mm height and 2 mm thickness. The dimensions of the large one are 100 mm width, 100 mm height and 2 mm thickness. The braiding machine with larger number of carriers can make larger braids with the same fiber architecture as the small one. The I-shaped braided preforms were placed into the mold, and the mold was closed. The epoxy resin, PR-500, was drawn into the mold. After saturating the preform with the resin, the temperature of the mold was turned up to cure. The CFRP I-shaped frame was obtained after demolding. Figure 8 shows a photomicrograph of the cross section. The photomicrograph investigation did not show any signs of the large voids.

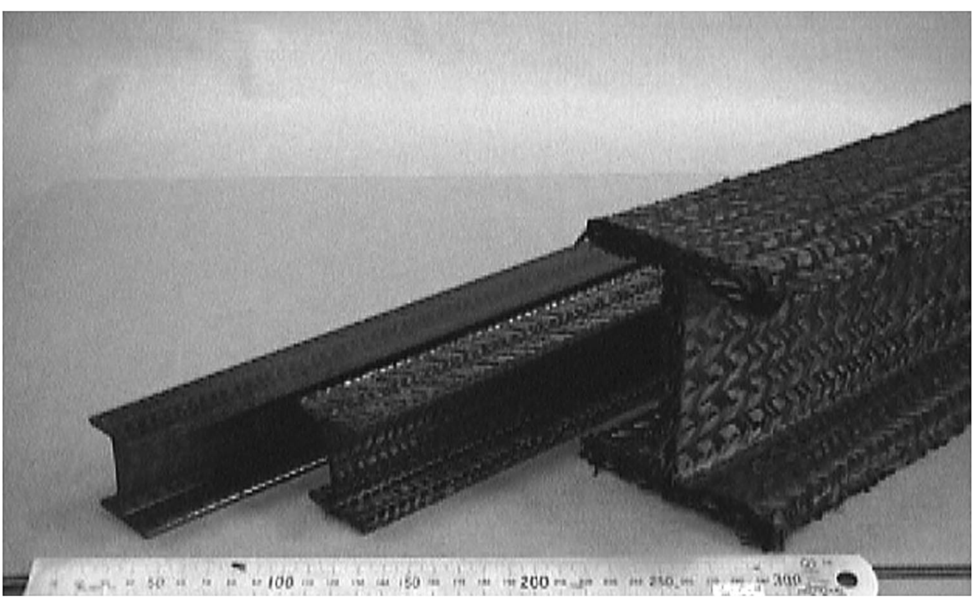


Figure 7. Photograph of I-shaped frame composite and preforms.

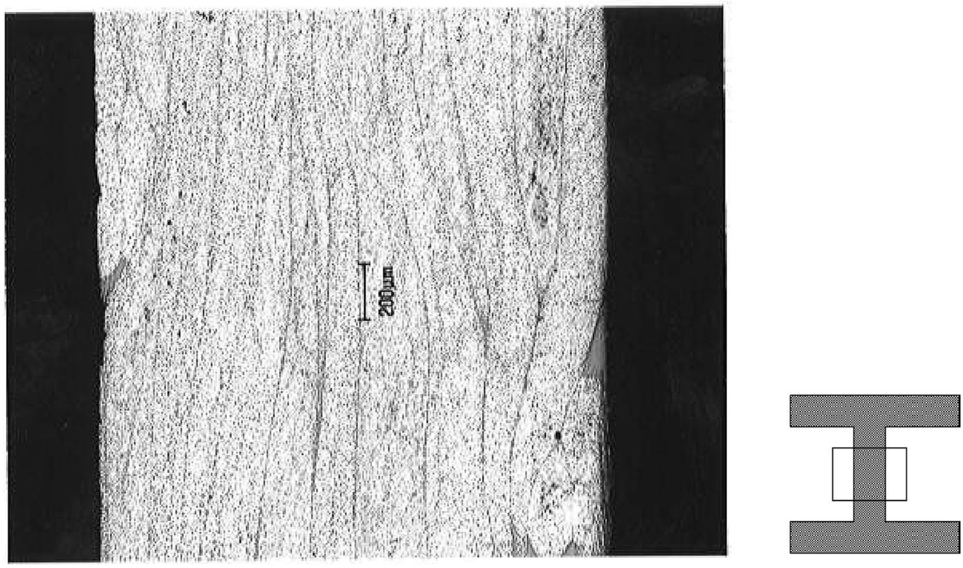


Figure 8. Photomicrograph investigation of cross section.

4.2. Stringer panel

A stringer panel was fabricated to consider the capability of applying the braiding/RTM process to other parts of aircraft. The stringer panel consists of some flat thin panel parts and some hat-shaped-stringers. The near-net-shaped preform was obtained by inserting some tubular braids for the stringer parts into large sized tubular braid in deforming the large tubular braid into the final shape. Figure 9 shows a process flow for fabricating a preform of the stringer panel.

(1) Three braids for stringer parts were fabricated on the mandrels with trapezoidal sectional shape as shown in Fig. 10. The braids ware fabricated by 48-carrier-braider with 48 braid yarns and 24 axial yarns.

(2) A large tubular braid for the panel was fabricated by 144-carrier-braider with 144 braid yarns and 72 axial yarns.

(3) When the large braid was deformed into the near-net-shape, the three trapezoidal braids were put onto the proper potion inside the large braid as shown in Fig. 11. The preform with the trapezoidal braids was obtained.

(4) The near-net-shaped preform was stitched along the stringer parts to keep the shape. Twisted yarn that consisted of three carbon fiber bundles (Torayca T300-1K, TORAY) was used as stitching yarn.

The preform had the same fiber architecture of the braid as the flat plate P-60 described in Section 3. A CFRP hat-shaped stringer panel shown in Fig. 12 was obtained as a single-piece after RTM process.

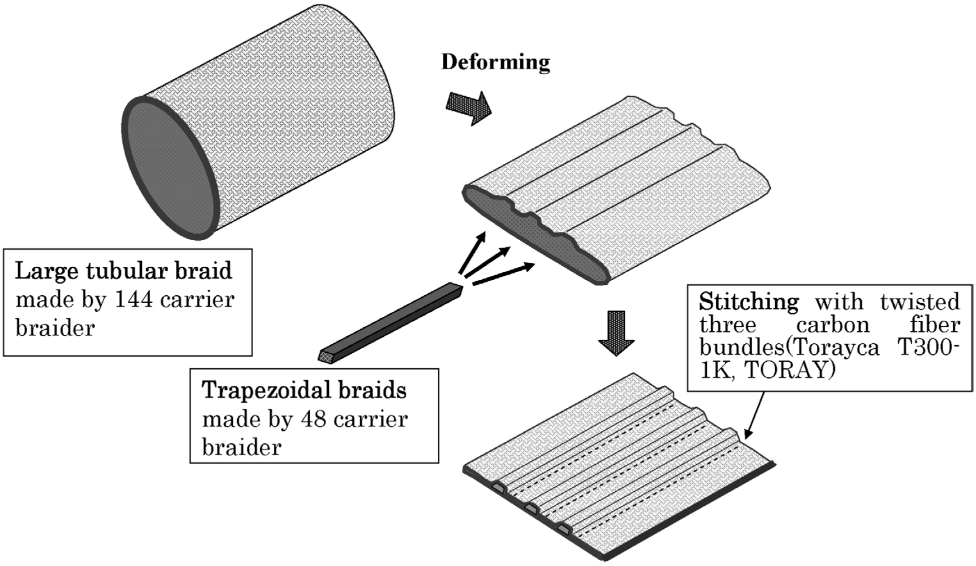


Figure 9. Fabrication flow of integral stringer panel preform.

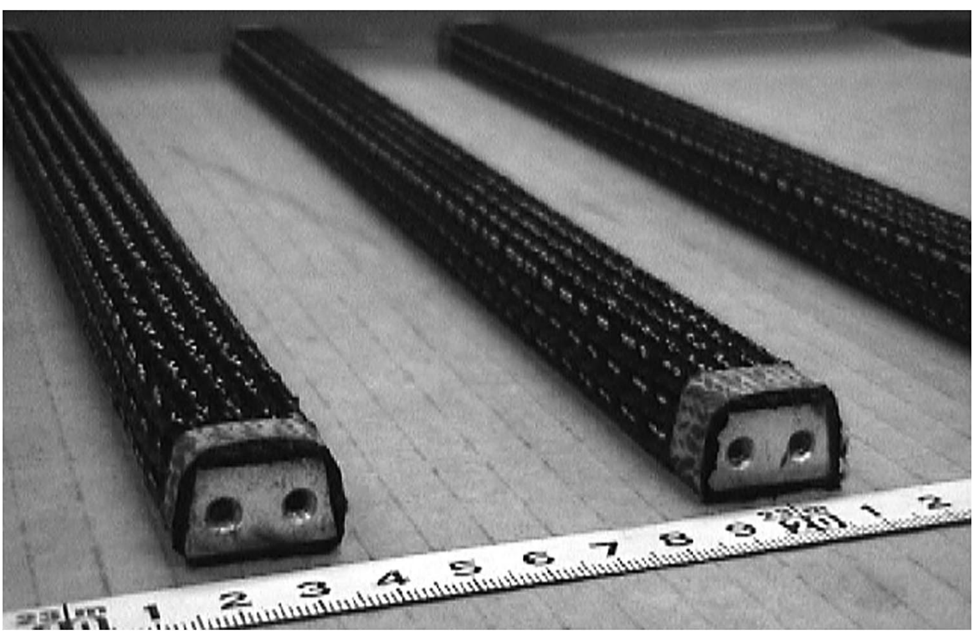


Figure 10. Photograph of trapezoidal braided preforms.

4.3. Box beam

A box beam was also fabricated to consider the possibility of applying the braiding/RTM process to aircraft element structures. The box beam is used as one of the structural members in wing parts. The box beam consists of a bottom panel

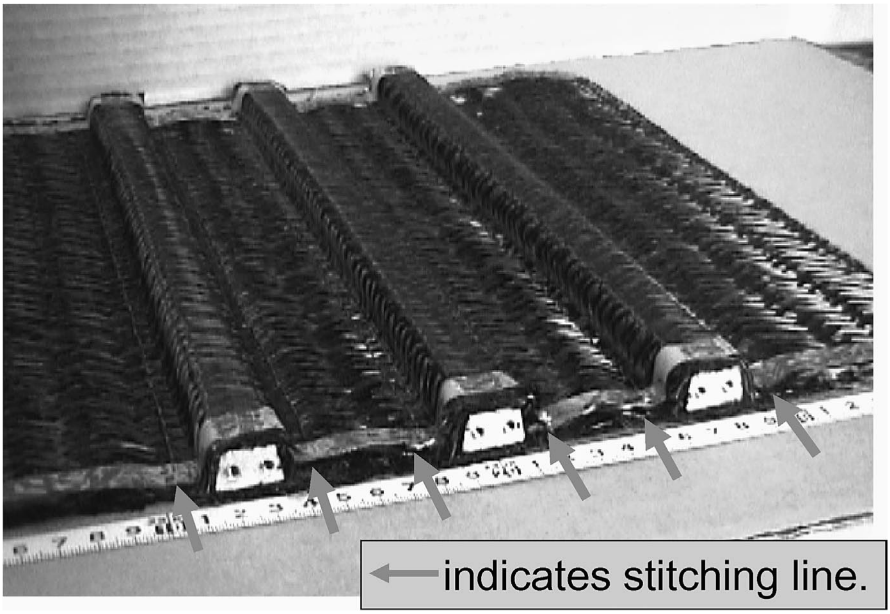


Figure 11. Integral hat-shaped stringer panel preform.

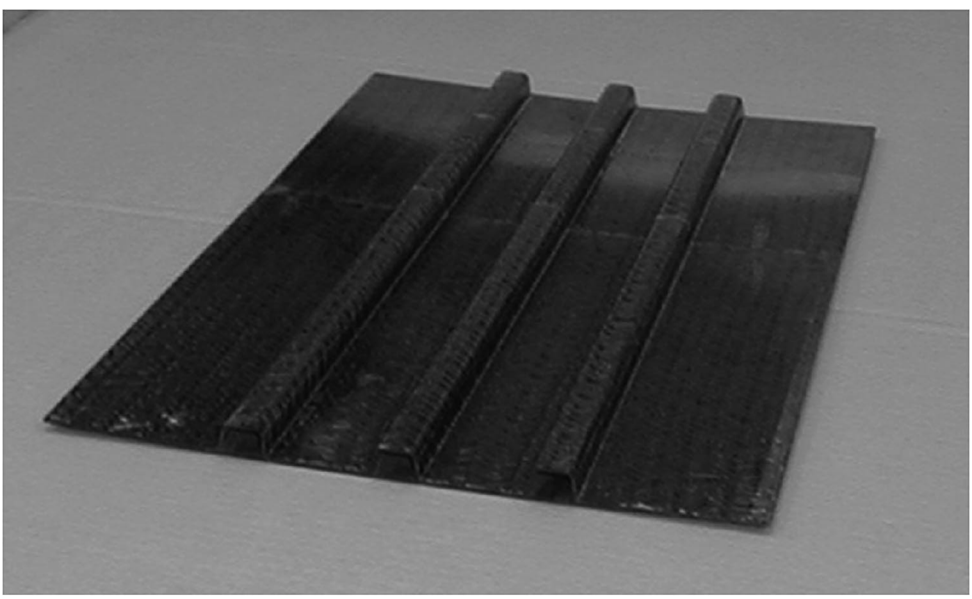


Figure 12. CFRP hat-shaped stringer panel.

and side panels. The bottom panel was same configuration as the stringer panel. The side panels have C-shaped cross-section.

The near-net-shaped preform was obtained by connecting side panel preforms to a bottom panel by using stitching process. Figure 13 shows a process flow for fabricating the preform of the box beam.

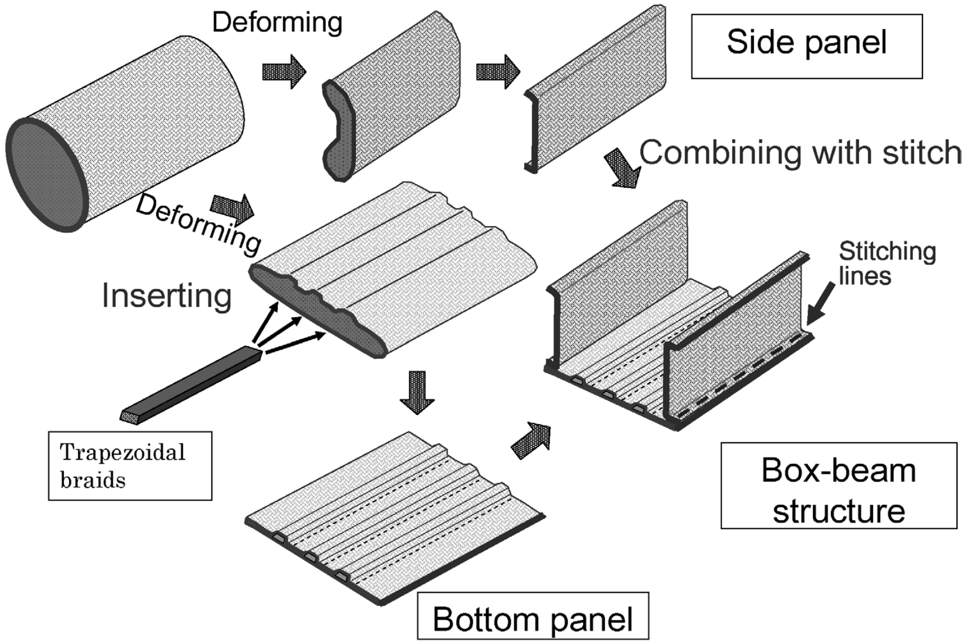


Figure 13. Fabrication flow of integral box beam preform.

(1) A preform for the bottom plate was fabricated by using the same process in the case of stringer panel.
(2) Two large tubular braids were fabricated for side panels and they were deformed into C-shaped panels respectively.
(3) The side panel preforms and the bottom panel preform were stitched.

Figure 14 shows a photograph of a box-beam preform. The preform had the same braided preform fiber architecture as P-60 in Section 3. The CFRP box beam shown in Fig. 15 was obtained as a single-peace after RTM process.

5. MECHANICAL PROPERTIES OF BOX BEAM

The stiffness of the box beam was predicted by using finite element method in order to compare with the box beam made from aluminum.The configuration of the CFRP box beam is shown in Fig. 16, and the configuration of the aluminum box beam is shown in Fig. 17. As the aluminum box beam was designed based on a conventional design manual that has been used already for parts of aircraft, configurations of stringer parts and corner parts were different between CFRP and aluminum box beam. For the CFRP box beam, hat-shaped stringer parts were installed into the panel, while Z-shaped stringer parts were installed for the aluminum box beam. It is recognized that CFRP box beam has an advantage of configuration of the stringer that cannot be produced using aluminum. For CFRP box beam, the thickness of the

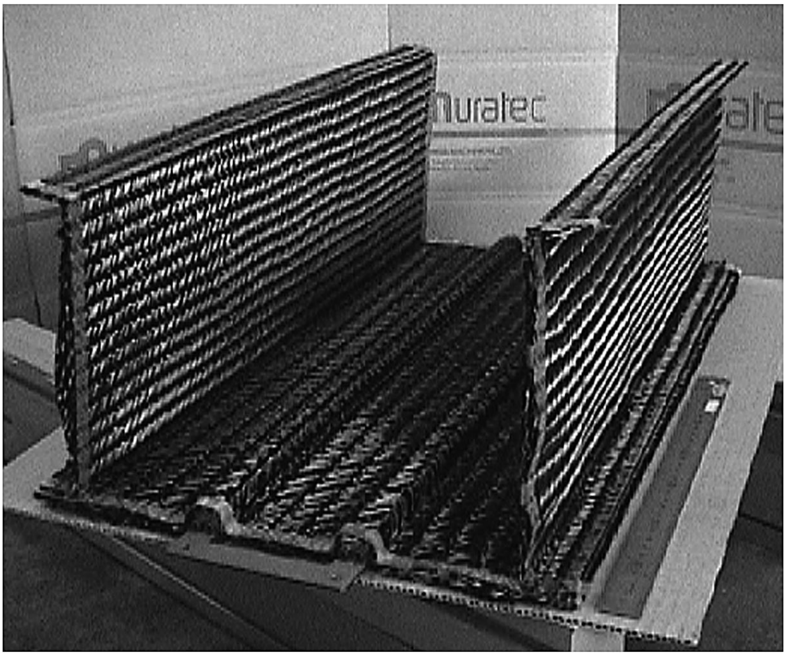


Figure 14. Box beam preform.

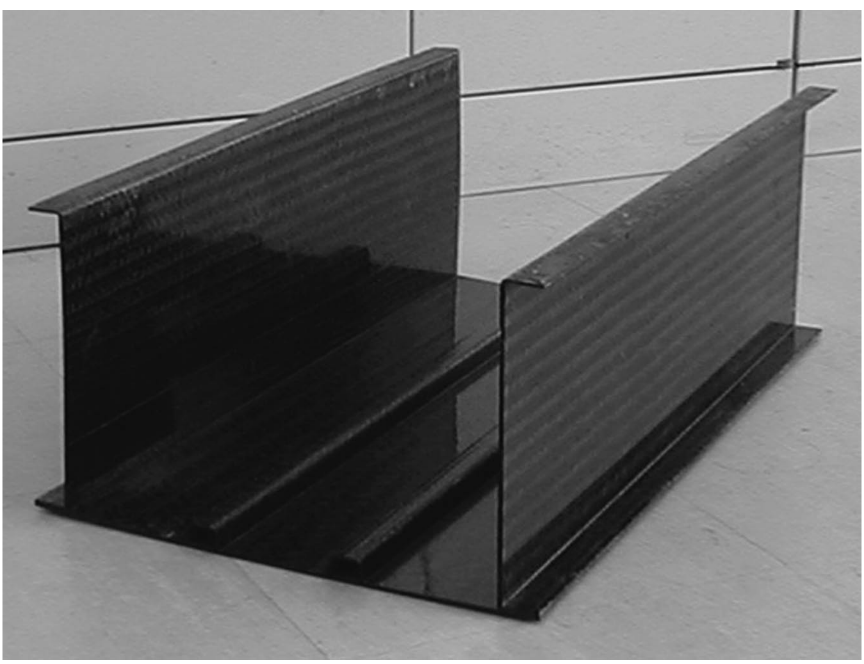


Figure 15. CFRP box beam.

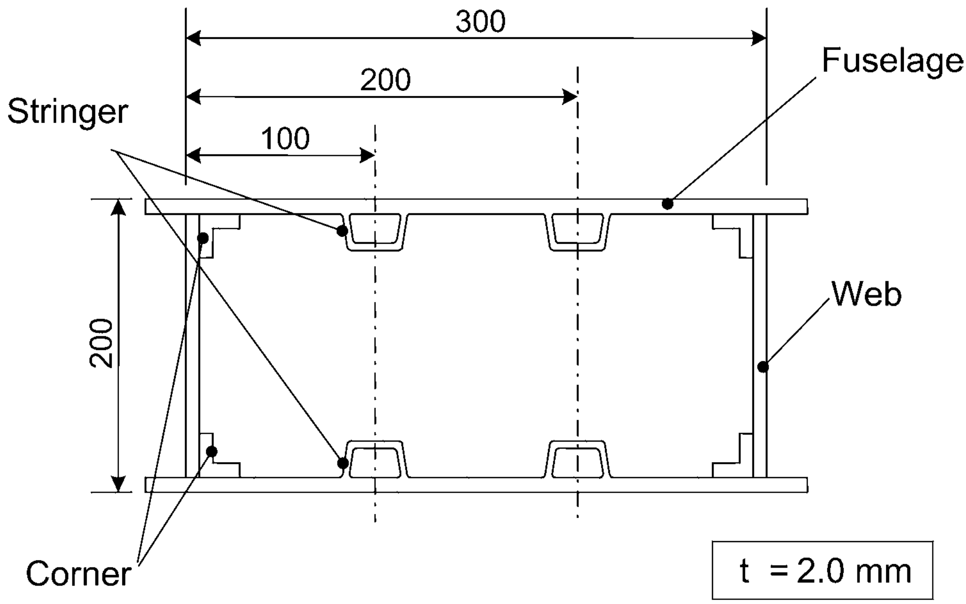


Figure 16. Configuration of the CFRP box beam for analysis model.

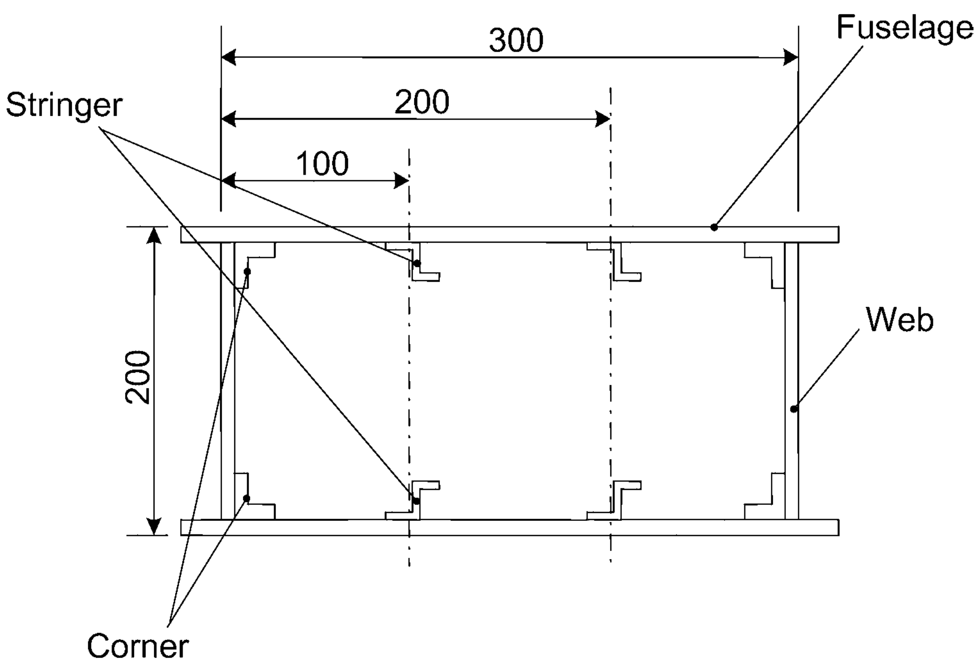


Figure 17. Configuration of the aluminum box beam for analysis model.

fuselage part, web parts, stringer parts and corner parts were the same, 2 mm. For aluminum box beam, the thickness of the fuselage part, the web parts, the stringer parts and the corner parts were 1.02 mm, 1.27 mm, 2 mm and 3 mm, respectively.

The dimensions of those box beams are approximately 200 mm height, 350 mm width and 600 mm length. The weight of the aluminum box beam is equal to that of the CFRP box beam.

In the analysis model, the box beams were expressed by using shell element for fuselage part and web parts, and by using beam element for stringer parts and corner parts. The displacements of the nodes on the four sides of a square with four vertexes A, B, C and D on the end of box beam were fixed in the X, Y and Z directions. Two types of loading conditions were considered. One of the loading conditions is 'cantilever type', where 490 N loads are applied in the $+Z$ direction at the connecting points of fuselage part and web parts on the ends of the box beam, as shown in Fig. 18. The other condition is 'torsion type', where 326.5 N loads are applied in the $+Z$ and $-Z$ directions at the connecting points of fuselage part and web parts on the ends as shown in Fig. 19. A rib structure was adopted at the

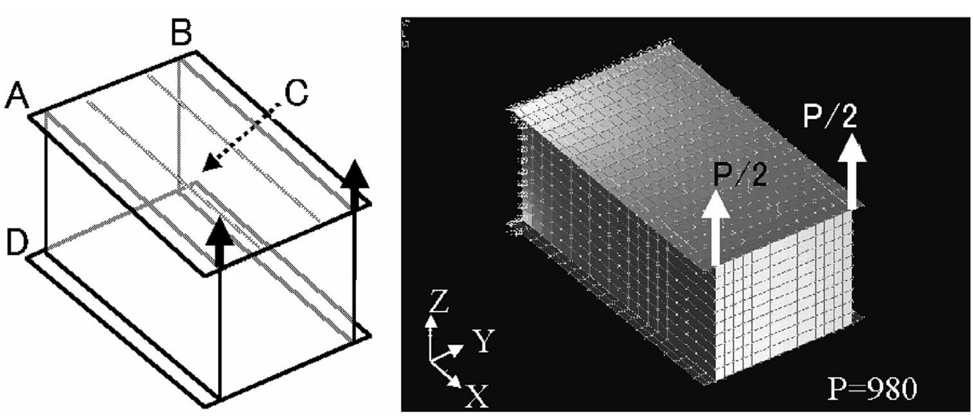


Figure 18. Loading condition in 'cantilever type'.

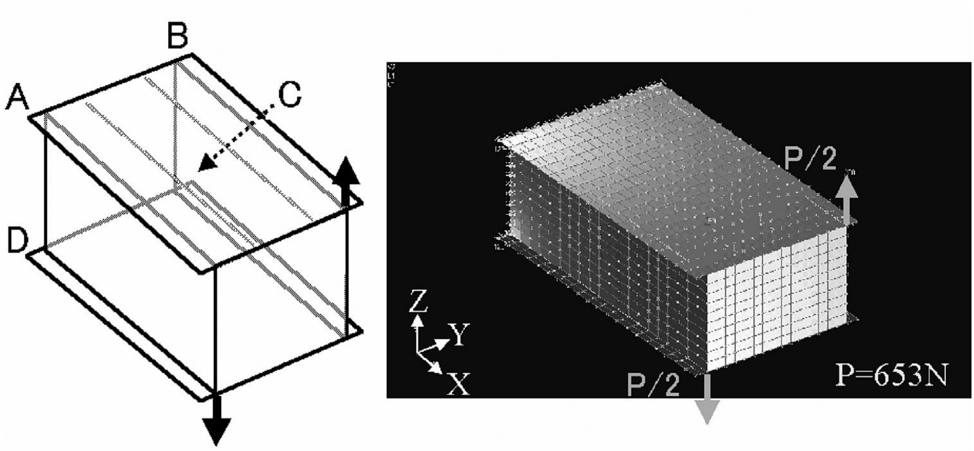


Figure 19. Loading condition in 'torsion type'.

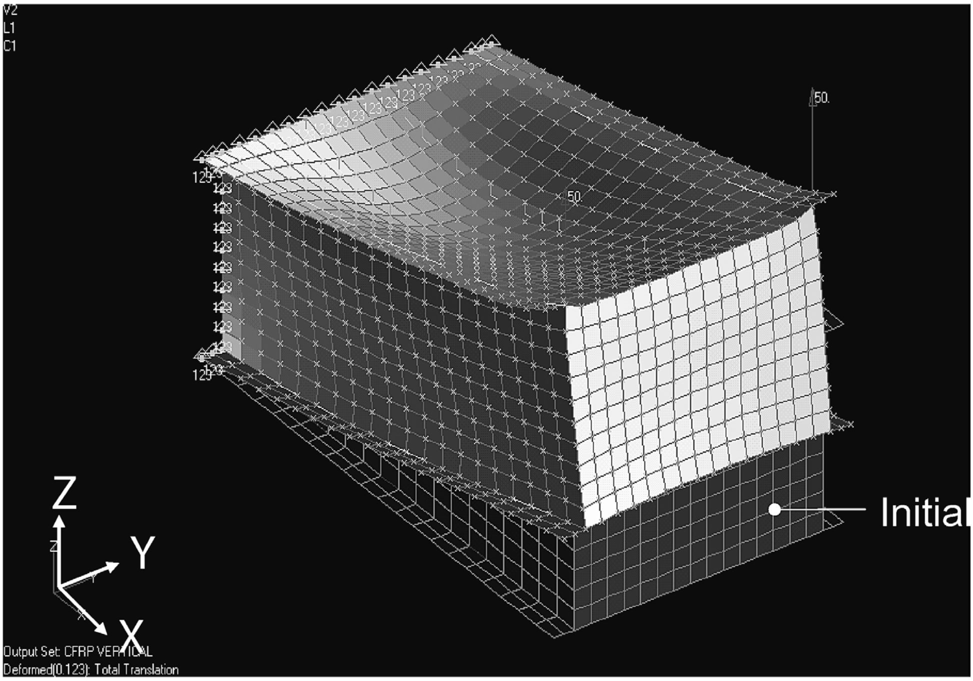


Figure 20. Deformation state of CFRP box beam for 'cantilever type'.

end on where loads are applied. The material constants of the fuselage part and the web parts were obtained from tensile test results of P-60 shown in Table 2, and the material constants of the stringer parts and the corner parts were obtained from tensile test results of P-45 shown in Table 2. Using the displacements under the same loading condition, the stiffness of CFRP box beam was compared with aluminum box beam.

Figures 20 and 21 show, respectively, the deformation states of CFRP box beam in the case of the 'cantilever type' and 'torsion type'. Table 3 shows the maximum value of the displacements in the Z direction at the loading point for both the CFRP box beam and aluminum box beam with each type of loading condition. The maximum displacements of CFRP box beam were 0.104 mm in the case of the 'cantilever type' and 0.0292 mm in the case of the 'torsion type'. They are close to those of aluminum box beam. The numerical results indicate that the CFRP box beam has equivalent stiffness to the aluminum box beam. It is suggested that using superior carbon fiber, such as Torayca T800 and T700, can increase mechanical properties of CFRP box beam in order to be superior to aluminum box beam.

6. COST ANALYSES

Cost analyses of two production concepts for box beams were based on a production plan for 1840 mm long box beams. One concept is the use of the braiding/RTM

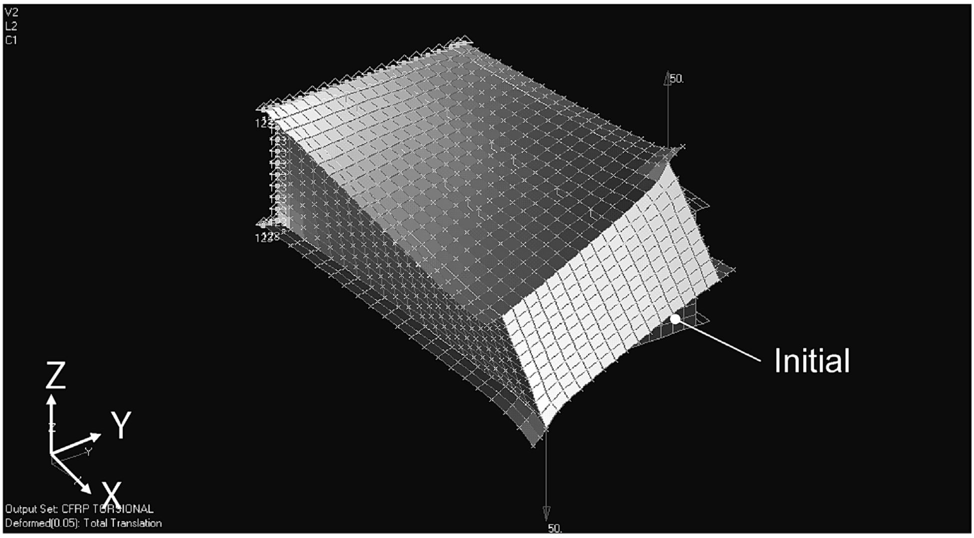


Figure 21. Deformation state of CFRP box beam for 'torsion type'.

Table 3.
Maximum displacements of CFRP box beam and aluminum box beam

Loading type	CFRP box beam	Aluminum box beam	Difference (Al/CFRP)
Cantilever type	0.104 mm	0.108 mm	1.04
Torsion type	0.0292 mm	0.0312 mm	1.07

process, the other concept is the use of the conventional method, prepreg hand-lay-up/autoclave process. In the prepreg hand-lay-up/autoclave process, prepreg sheets are laminated by hand and they are cured using an autoclave process. Cost predictions were also based on a box beam in the case of a total production run of 300 ship sets. Labor costs, material costs, tooling costs and supplies expenses were calculated. The results of the cost studies are shown in Fig. 22. These results indicate that the braiding/RTM process has approximately a 34% cost advantage over the prepreg hand-lay-up/autoclave process. The material costs and the labor costs are responsible for the differences in the total cost. Especially the braiding/RTM process has a cost advantage in terms of labor costs.

The details of the labor costs are shown in Fig. 23. In the preforming process the labor cost of the braiding/RTM process is much lower than that of prepreg hand-lay-up/autoclave process because of an automatic preforming system by using a braiding process. In the preparation for curing the prepreg hand-lay-up/autoclave process requires greater and more expensive set-up labor cost than the braiding/RTM process.

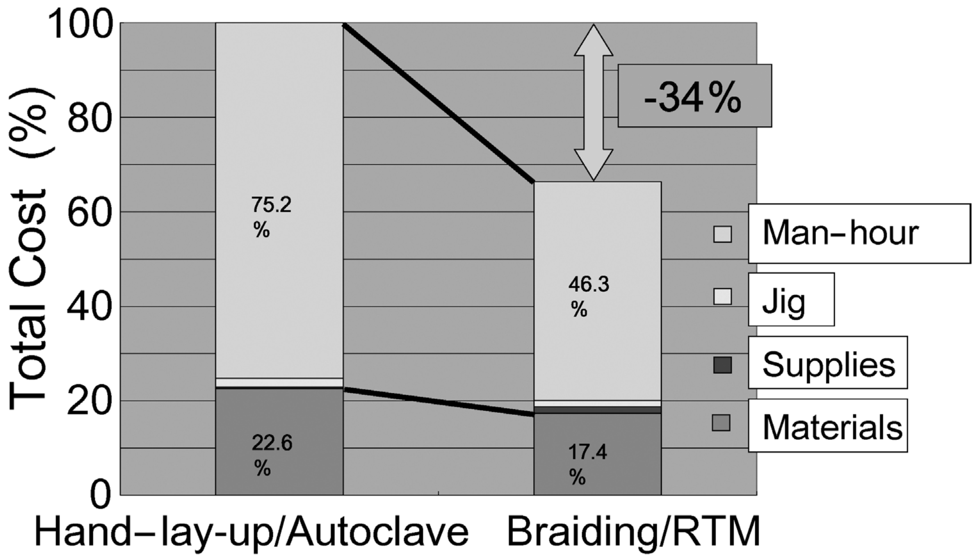


Figure 22. Cost study results.

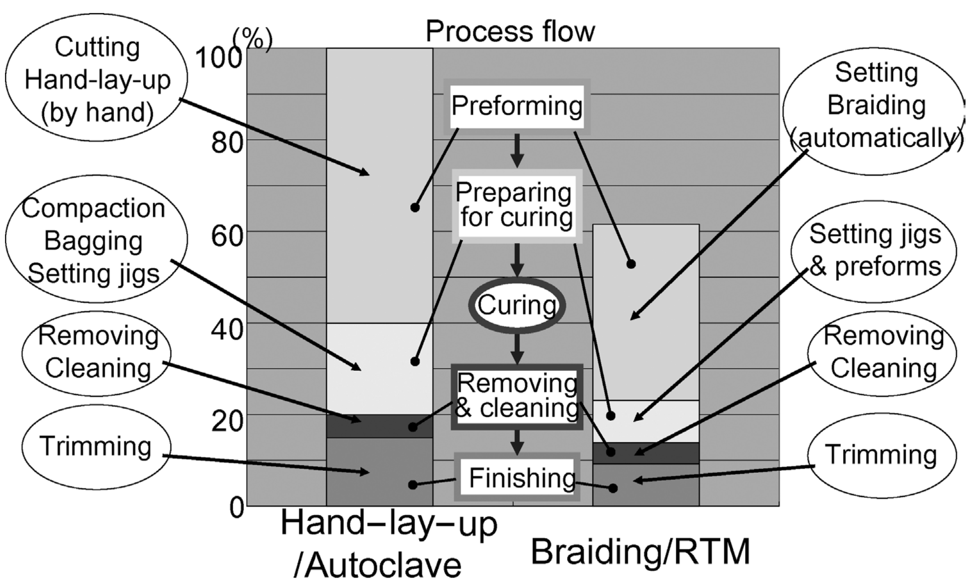


Figure 23. Details of labor costs.

7. CONCLUSIONS

Braided preforms were produced with carbon fiber for aircraft frames, by the use of a new preforming process that consisted of a conventional tubular braiding process and deforming process. The preforms were molded using resin transfer molding (RTM) process with epoxy resin into I-beam frames. Braided composite frames indicated superior tensile properties to aluminum materials. The test results make it clear that braided composite frames qualify for use in aircraft applications. The capability of applying a braiding/RTM process to aircraft element structures was affirmed by trial manufacture of CFRP stringer panel and CFRP box beam through this braiding/RTM process. The numerical results indicated that the CFRP box beam has equivalent mechanical properties to the aluminum box beam.

Furthermore, cost analyses were also investigated. The results of cost studies indicated that braiding/RTM process has approximately a 34% cost advantage over hand-lay-up followed by an autoclave process. The braiding/RTM process is applicable to various frame configurations, and the process is expected to extend the range of applications of composites for aircraft.

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