This article was downloaded by: [Siauliu University Library]
On: 17 February 2013, At: 07:01
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK


Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

# Low cost fabrication of HOPE-X all-composite prototype structure

Kiyoshi Uzawa , Kozo Nishiwaki , Mayuki Niitsu , Toru Kamita & Gaku Kimura

Version of record first published: 02 Apr 2012.

To cite this article: Kiyoshi Uzawa , Kozo Nishiwaki , Mayuki Niitsu , Toru Kamita & Gaku Kimura (2005): Low cost fabrication of HOPE-X all-composite prototype structure, Advanced Composite Materials, 14:3, 289-304

To link to this article: http://dx.doi.org/10.1163/1568551054922593

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

*Adv. Composite Mater.*, Vol. 14, No. 3, pp. 289–304 (2005)
© VSP 2005.
Also available online - www.vsppub.com

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

# Low cost fabrication of HOPE-X all-composite prototype structure

KIYOSHI UZAWA [1,*], KOZO NISHIWAKI [2], MAYUKI NIITSU [2], TORU KAMITA [3] and GAKU KIMURA [4]

[1] *The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[2] *Mitsubishi Heavy Industries Ltd., 10, Oye-cho, Minato-ku, Nagoya 455-8515, Japan*
[3] *Japan Aerospace Exploration Agency, 7-44-1, Jindaiji Higashi-machi, Chofu-shi, Tokyo 182-8522, Japan*
[4] *GH Craft Ltd., 11-6 Itazuma, Gotenba, Shizuoka 412-0048, Japan*

Received 20 June 2002; accepted 3 February 2005

**Abstract**—Two strict requirements were to be adhered to in the development of HOPE-X: to shorten the manufacturing lead-time and to reduce the fabrication cost for the lightweight prototype structure of HOPE-X. To meet these requirements, the design team adopted an all-composite monocoque structure instead of a conventional aluminum skin, stringer-frame structure. The all-composite structure was made of several large parts in order to reduce the total number of parts. These large parts were made by using the non-autoclave curing technique and assembled by bonding into a monocoque structure. The high-accuracy large lay-up tool and the custom-made oven played important roles particularly during these manufacturing processes, leading to reduction in both lead-time and cost. The structural design and the manufacturing strategy for the prototype structure are described in this paper. The development of the lay-up tool and the oven, which helped to realize low fabrication cost, is described here.

*Keywords*: Re-entry vehicle; all-composite structure; low cost; large parts; bonded joint; non-autoclave curing.

## 1. INTRODUCTION

HOPE-X (H-II Orbiting Plane-Experimental) is a Japanese experimental re-entry vehicle, and its prototype structure was developed by the National Space Development Agency of Japan (NASDA) and the National Aerospace Laboratory (NAL) from 1998 to 2002 to demonstrate its structural design and manufacturing processes. Mitsubishi Heavy Industry, Ltd. and GH Craft, Ltd. were assigned the responsibil-

*To whom correspondence should be addressed. E-mail: uzawa@giso.t.u-tokyo.ac.jp

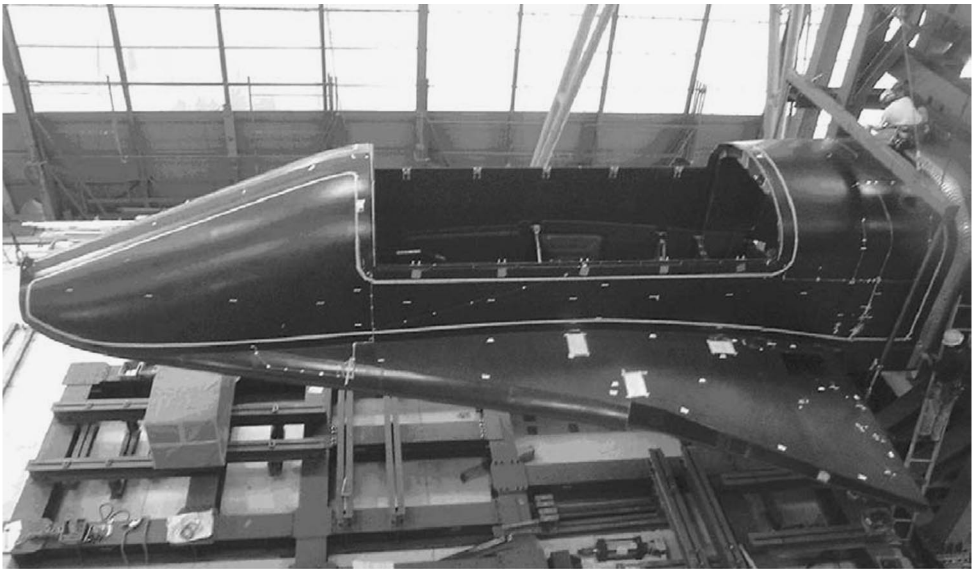

**Figure 1.** Overview of HOPE-X all-composite prototype structure.

ity of improving the structural design and building the prototype structure in this development.

The initial concept of HOPE-X was a conventional aluminum semi-monocoque structure with a length of about 13 m and a width of about 10 m. However, this concept was ineffective considering reduction in the weight, the cost, and the manufacturing lead-time. After careful study, the structural design was totally revised and changed to an all-composite monocoque structure with the following design concepts:

(1) Assembly of large monocoque parts, such as the upper fuselage and the lower wing-body to minimize the number of parts.
(2) Joining of parts not by mechanical fasteners, but by adhesion to reduce the weight and the cost.

Figure 1 shows the external view of the HOPE-X prototype structure.

Low costs cannot be realized easily during short-term development merely by replacing the aluminum structure by a composite structure. Larger composite parts need large facilities, and a bonded structure requires complex coupling flanges. Moreover, larger composite parts and bonded structure cannot lead directly to lower manufacturing costs. To work out a solution to these demands of weight, cost, and manufacturing lead-time simultaneously, not only improved structural design but also overall economy of fabrication in conjunction with material selection, tooling and processing, were necessary.

In the fabrication of the prototype, the following methods were adopted:

(1) Use a low-temperature curing prepreg with non-autoclave curing technology.
(2) Bond joints with additional wet lay-up.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

(3) Post-cure of the entire freestanding body after all parts are assembled in the final state.

Furthermore, for development of this prototype model, an innovative framework was constructed by DBT working jointly with a small, specialized molding company (DBT: Design and Build Team of NAL/NASDA/MHI and GH Craft). The preliminary design started in April 2000, the fabrication started in September 2000, and the vehicle assembly rolled out in September 2001. This indicates an extremely short schedule for development of a vehicle of this size. The DBT framework played a major role in this achievement [1].

This paper presents the key features of low-cost fabrication, describes the low cost and high-accuracy large lay-up tool, the custom-made oven, economic structural design, and the role of the small, specialized molding company.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

## 2. AFFORDABLE STRUCTURAL DESIGN AND MANUFACTURING STRATEGY

Comprehensive optimization covering all development processes using a total design spiral was considered an important concept. The simultaneous pursuit of low-cost and short-term development was made by new structural design and innovative manufacturing strategy.

The primary structure of HOPE-X was made of honeycomb sandwich panels with aluminum core and graphite/epoxy composite, which were selected as non-autoclave and low-temperature type materials [2, 3]. To minimize the number of parts, the structure was divided into two large parts, the upper fuselage and the lower wing-body, and the number of reinforcements, such as ring frames and longerons, was minimized to reduce manufacturing costs. Figure 2 shows the structural concept.

Most of the parts were bonded with adhesive paste to reduce the number of fasteners and the assembly cost. As these parts were bonded to the inside of the monocoque part, which had a three-dimensional shape, the airframes required complex coupling flanges. Simplifying the flange shapes has a large influence on tool making; therefore, one-sided L-shaped flanges were used with wet lay-up on the other side for coupling flanges. Adding the wet lay-up led to significant improvement in the bonding strength between the frame and the outer body. The strength increased by 50% compared to the simple one-sided flange. The use of this simple flange cut down the cost to less than half that of the conventional T-joint with two-sided flange at the frame fabrication stage, although the frame fabrication cost included the tool assembly cost. The bonding strength was confirmed eventually with the element tests of each fuselage part while building the vehicle. Typical joint configuration and assembly concepts of HOPE-X are shown in Figs 3 and 4, respectively.

The manufacturing schedule was decided to consider the best processes to match the decided structural concept. Figure 5 shows the complete schedule of the

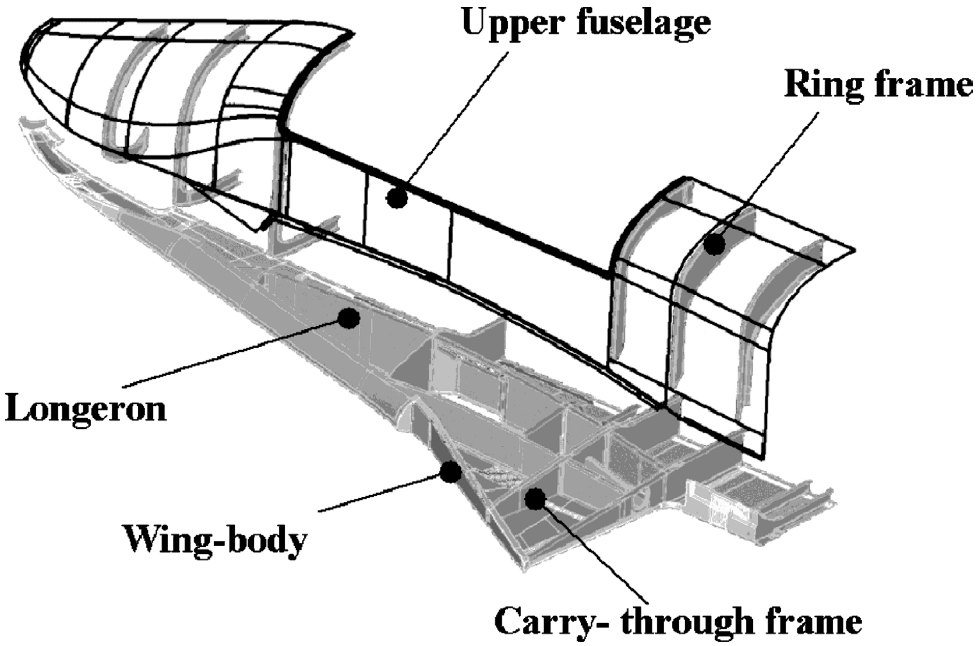


**Figure 2.** Structural concept.

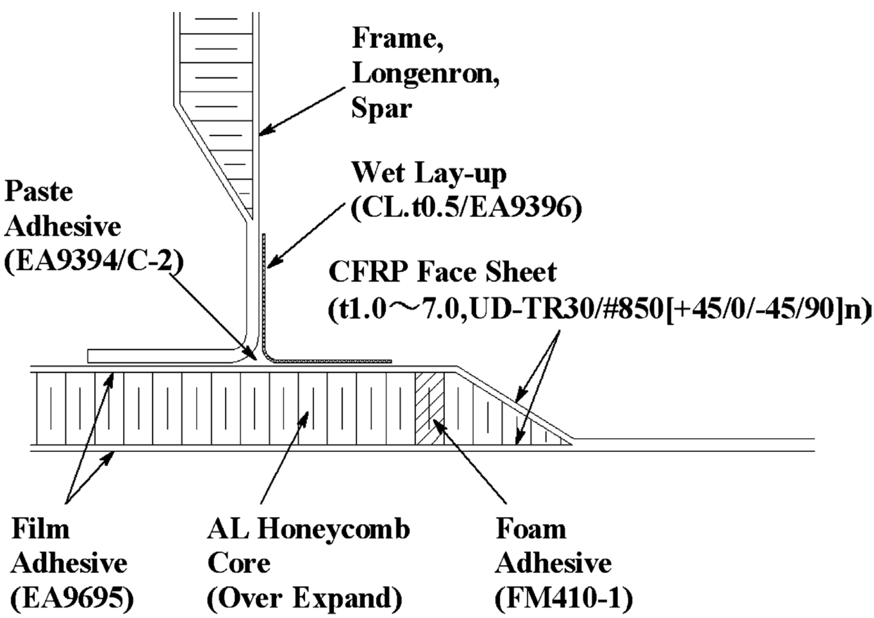


**Figure 3.** Joint configuration with wet-lay-up.

HOPE-X development. Over the five-month design-to-build timeline, the design team strived to decide the parts configuration. But the schedule did not allow

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

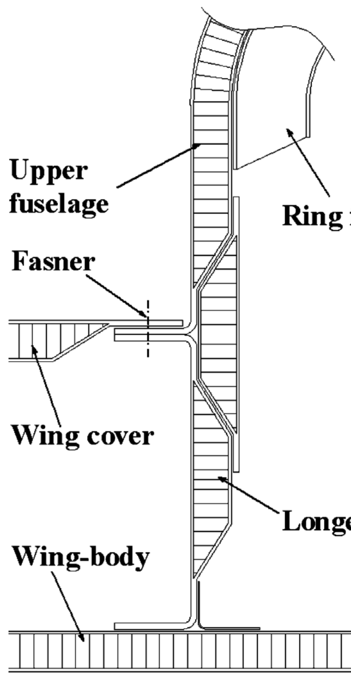


**Figure 4.** Typical assembly concept at mid-section.

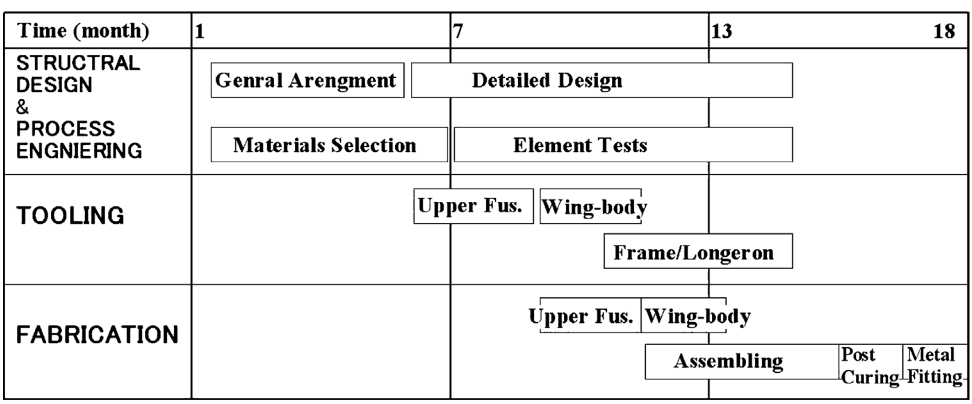


**Figure 5.** The outline of development schedule.

for adequate time to design all reinforcements. Work on the upper and lower lay-up tooling, which were molded in the outer mould line (OML), started first because considerable time was required to construct these two tools. The OML tool enabled parallel processing to be performed irrespective of the design of the internal structure. Until the completion of tooling, exact laminate design was decided by the design-team.

Fabrication technique is very important in the initial stage, but the technique at the mass production stage is an entirely different technique compared to that during

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

quality control. Detailed operating instructions and quality controls system were required to be as stringent as during the mass product stage. This necessitated considerable manpower. On the other hand, unexpected problems could occur during fabrication. An immediate response by regular troubleshooting, modifications, design changes, and so on, are necessary for short-term, low-cost development. To quickly and accurately resolve these problems, we needed to keep our organization as compact as possible with each team member having comprehensive ability. Therefore, an innovative development framework was constructed for this project, and a Design Building Team (DBT) consisting of selected engineers from each organization and company was established. A small, specialized molding company with good engineering skills and considerable experience in prototype development, working jointly with the DBT, was involved in the fabrication of the prototype, and was the key to the success of the project.

## 3. TOOLING

Generally in one-off manufacturing, the tooling cost accounts for a large portion of total fabrication cost. On the other hand, a molding tool must be accurate even if it is to be used for a one-off product. The important factors to be considered are how to realize low cost and how to attain high accuracy. Table 1 shows materials and processes using lay-up tools.

### *3.1. Upper fuselage and wing-body*

The number of parts was minimized to reduce the construction cost. Small parts were unified into large-sized parts, and consequently the tools became large. The share of the material cost in the total tool cost increased in direct proportion to the mold size. Low-temperature curing (100°C) was adopted in this development to reduce the material cost of tools. This enabled the plywood egg-crate structure and strip-planking panel to be combined, using FRP face-sheet as the hybrid material.

To obtain accuracy in the shape, the tools were divided into 15 or 16 pieces, with modules of size 2–3 m approximately, and processed with the CNC machine at

**Table 1.**
Tooling table of HOPE-X

| | Upper fuselage/Lower wing-body | Wing cover/Cargo door | Frame/Longeron/Spar |
|---|---|---|---|
| | Large parts | Middle parts | Small parts |
| | Complex shape | Simple shape | Complex shape |
| Material | Plywood and FRP | Steel Plate and anglepipe | Solid plaster block |
| Process | CNC machining in each module | Hand finishing | CNC machining |
| Remark | Assembled by mult module | Affordable tolerance | Accurate shape |
| | Same heat expantion with CFRP | Cost-effective | Rapid toolng |

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

the mold face to a thickness of a few millimeters. Figure 6 shows the details of a module. Steel angle pipes were used to fix the modules on the base directly and level with the ground. This method is popular in boat building where one-off models are used, and can offer adequate overall accuracy at low tooling cost. The overall view of the wing-body tool after set-up is shown in Fig. 7.

At this stage, the coefficient of thermal expansion of the ground and the steel frame base, and that of plywood and the FRP tool were not same. The thermal expansion of the plywood was small, and could be ignored, but when maintained below 100°C, the plywood contracted because of the dryness. On the other hand, the thermal expansion of the FRP layer on the surface of the tool was greater than that of the CFRP of the fuselage. To attain a good balance between the coefficient of thermal expansion of tool surface and that of the CFRP of fuselage, the value $6.0 \times 10^{-6}\,°C^{-1}$ was taken, using a hybrid layer of glass fiber and carbon fiber for the tool. Since the thermal expansion of tool and fuselage was the same, they did not become displaced relative to each other irrespective of the number of repetitive cures. Furthermore, after curing of the parts, these tools could be taken to an assembly rig and the parts could be easily set because the cured panels remained in position while the tools were being leveled.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

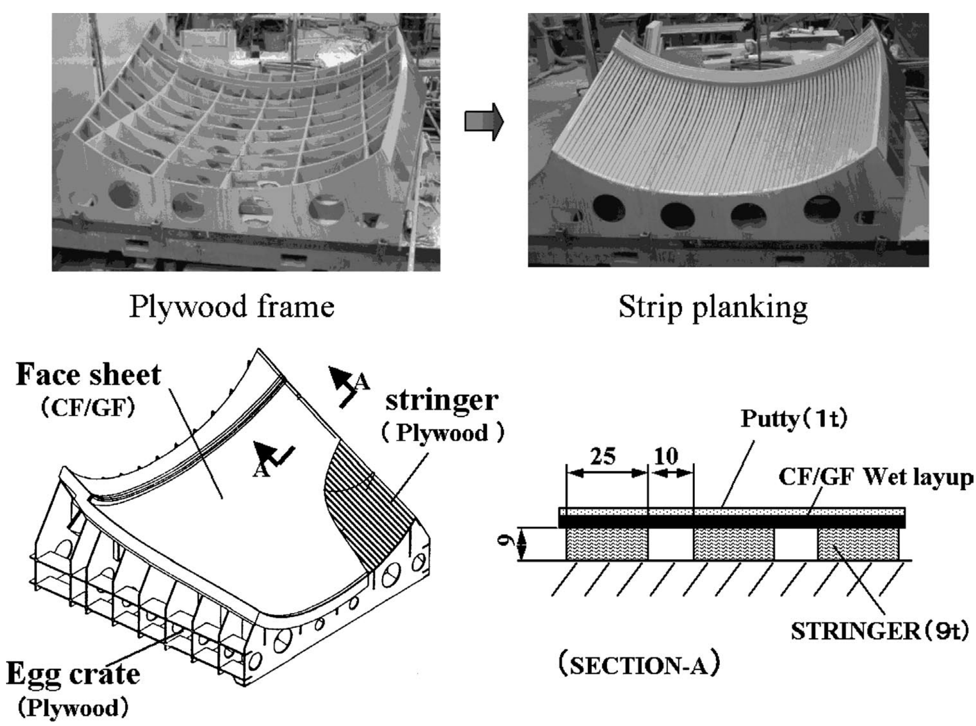


**Figure 6.** Module of upper fuselage tool.

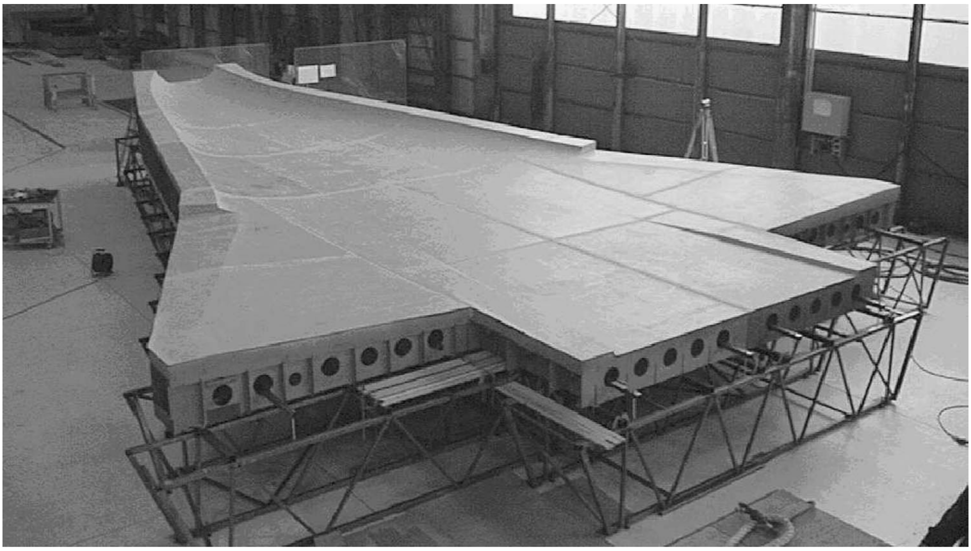

**Figure 7.** Lay-up tool of wing-body.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

### *3.2. Wing cover and cargo door*

The wing cover and cargo door were small and had simple shapes. Their lay-up tools were made using steel plates and angle pipes to achieve cost lower than that of the plywood /FRP hybrid tool. The facing sheets of these tools were made by connecting several thin steel plates and hand-finishing them without resorting to CNC machining. The tolerance of the mold line was within the accuracy limits even after hand finishing. A photograph of these tools is shown in Fig. 8.

### *3.3. Frames and longerons*

Detailed frame design was carried out in parallel with the fabrication of outer structure in order to shorten the overall manufacturing lead-time. Since the OML tool was used for the upper fuselage and wing body, tooling could be started without fixing the design of parts details. On the other hand, tools for substructures could not start before design completely, and the shape of frame needed high precision because the bonding strength required the maximum thickness of the adhesive layer to be less than 1 millimeter. The Frame/Longeron lay-up tool shown in Fig. 9 was manufactured by processing the ceramics board directly by NC machining. The material used was plasterboard made of inorganic xonolite and glass fiber/resin, developed for use as insulation panels in the general construction field. It is inexpensive but easy to machine. It also gives good accuracy and has coefficient of thermal expansion of about $6.0 \times 10^{-6}\,^{\circ}\mathrm{C}^{-1}$.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

**Figure 8.** Lay-up tool of wing cover.

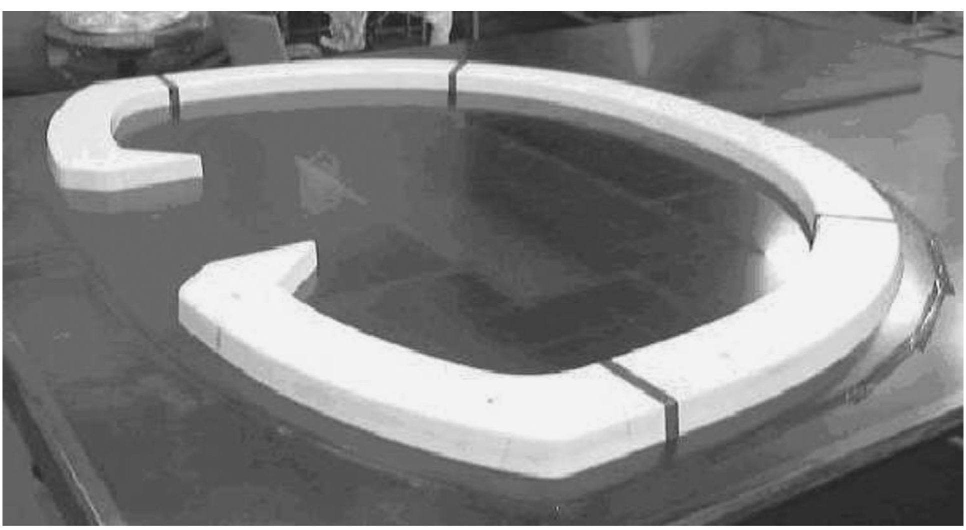

**Figure 9.** Tool of the ring frame part.

## 4. OVEN

As the lay-up tool was fixed on the ground, a temporary oven was built for curing. This oven was built with heat-resisting foam panels on the truss frame made of steel angle pipes. The foam panel was made of phenolic resin, which has a heat resistance

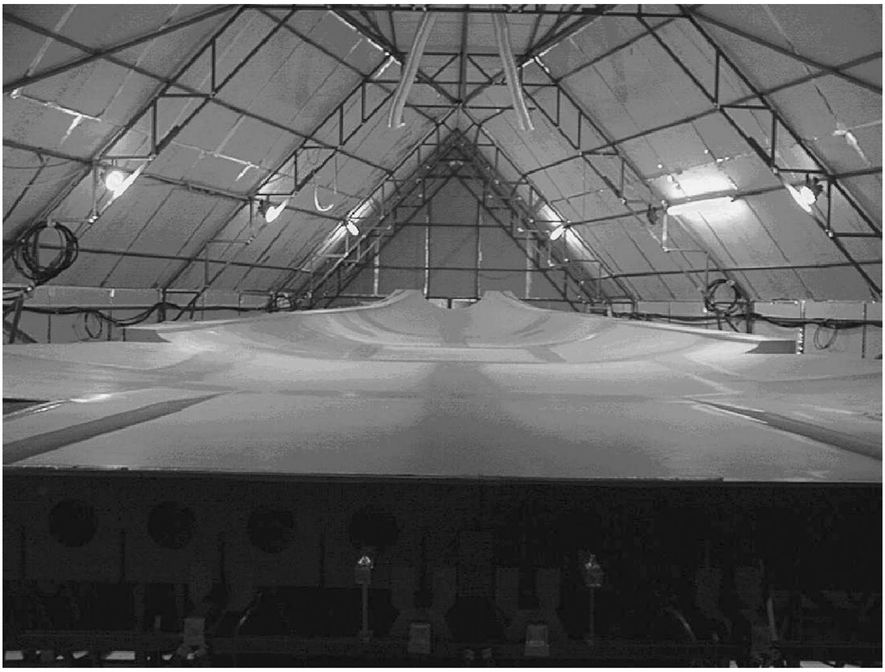

**Figure 10.** Framework of oven for wing-body part.

greater than 200°C. These heat-resistant foam panels are used as general building materials and are moderately priced; therefore, the construction cost can be kept low. Two ovens were fixed, one for the upper fuselage and the other for the wing-body. This facility was also used in a clean room for lay-up, and the wing-body oven was used twice, once for prepreg curing and once for post curing. Figure 10 shows the framework of oven for the wing-body part.

The most important factor to be considered when designing the oven is the airflow around tools. The wind velocity must be maintained at 1m/s at least across the surface of the tools to ensure adequate heat transfer from the air to the tools. The temporary oven could be formed freely so that it enabled airflow around the shape for the upper fuselage and for the lower wing-body to be optimized rather easily. The hot-air heater with the kerosene burner was used as the heat source, and additional blowers were fitted to improve heat transmission to the tools and the environment inside the oven. During the curing operation, temperature was monitored at about 50 check-points on the tools. If conditions demanded, the operator went inside to adjust the blower nozzles or check the bag films. During the post-curing at 180°C, the environment was too hot for a person to enter, and electric heaters were fixed at several points for control before the curing operation to unify the overall oven temperature. Figure 11 shows the oven for post-cure.

The oven was a temporary facility but optimized to suit the shapes of the parts to be cured. Its quality was excellent and there was no variation in temperature.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

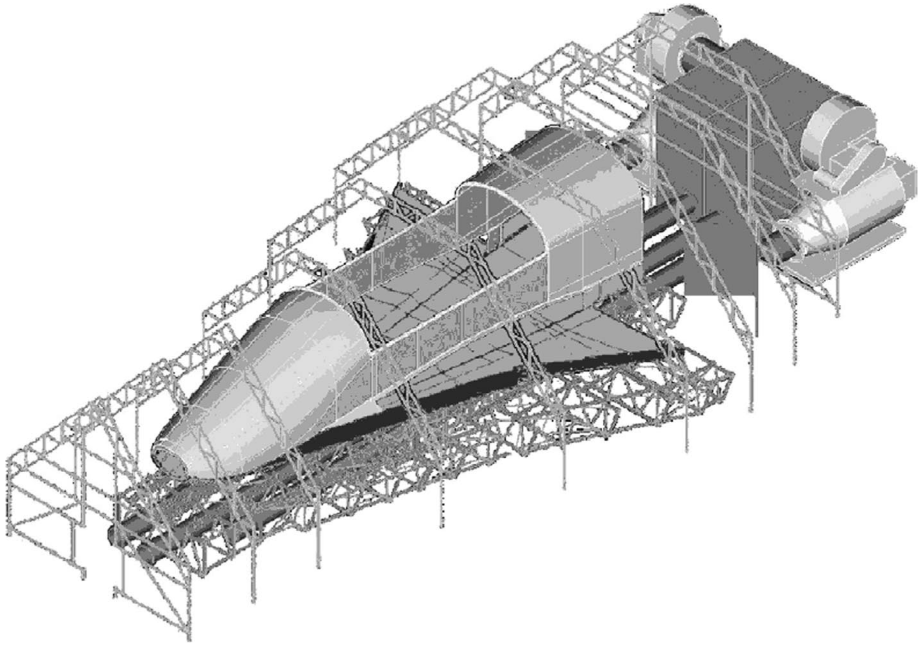

**Figure 11.** Post-cure with assembled body.

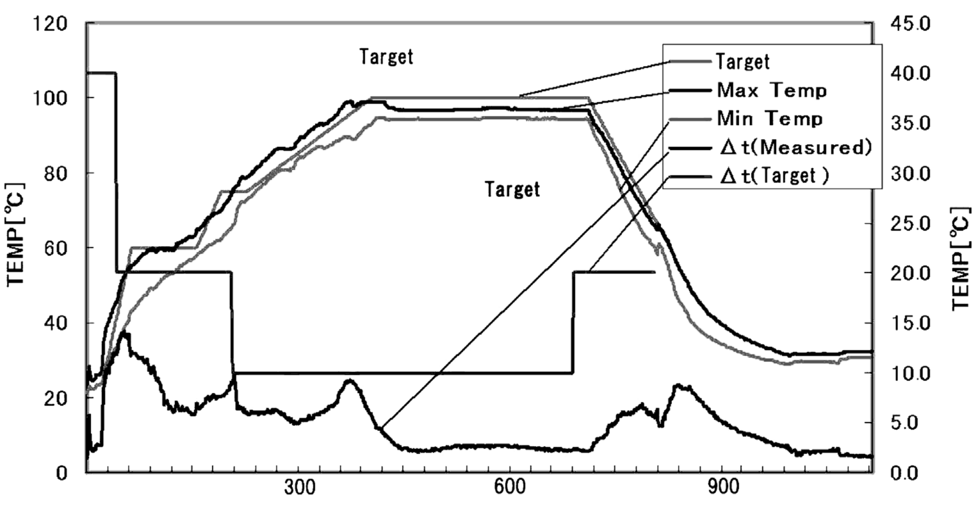


**Figure 12.** Data sample of measured temperature.

As a result, the variation of the material temperature during cure was maintained within ±3°C, and during post-cure, it was maintained within ±2°C. Figure 12 shows sample data.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

## 5. MANUFACTURE

All airframes were required to be of high quality with low void laminates at the same level as that of autoclave processing. Therefore, the honeycomb structure was cured in three steps — by outer skin, bonding core, and inner skin, and debulking process was conducted at every laminate procedure prior to the next ply. The debulking process needs enormous man-hours for the bagging operation of the whole mold, which amounted to half the hours required for the laminating operation. Production control was the key to finishing all laminating operations within 30 days of the prepreg service life because the laminating operations ranged from application of 4 plies in the cargo door to over 40 plies in the wing body. Figures 13 and 14 show the scene during lay-up and debulking, respectively.

The manufacture of the two large composite parts, upper fuselage, and wing body started first. Ring frames and longerons were bonded by adhesive paste. Figures 15 and 16 show the upper fuselage and lower wing-body assembly. Each of these was assembled just after the curing of the inner skin, which retained hold on the tool. Finally, the upper fuselage assembly was removed from the tool and coupled to the lower wing-body assembly using adhesive paste. Figure 17 shows the coupling of the fuselage and the wing body. Subsequently, the complete vehicle was post-cured at 180°C for 4 h. Figures 18 and 19 show the final assemblies.

Table 2 shows the cost breakdown over the entire development stage. The tooling cost was less than 20% of the total cost and the material ratio of tooling was only 5%.

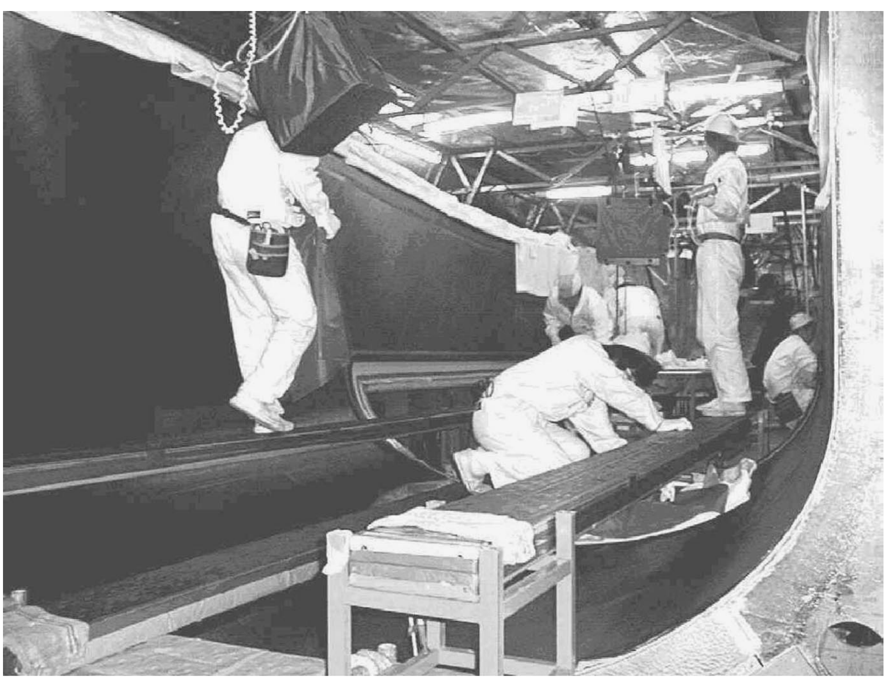

**Figure 13.** Lay-up of upper fuselage part.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

**Figure 14.** Debulking of upper fuselage part.

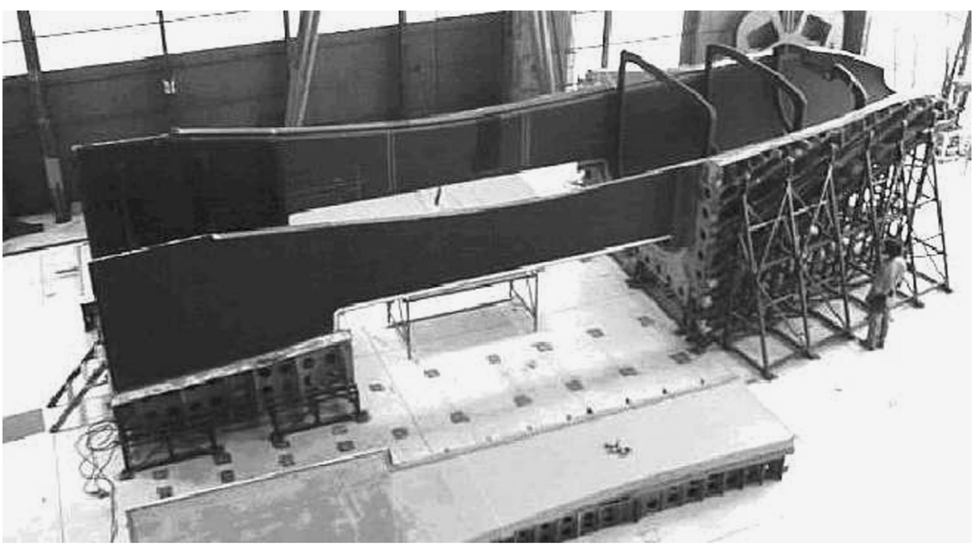

**Figure 15.** Removing tool after ring frame assembly.

Even though the cost of tooling and utilities could be minimized, manpower could not be reduced. Thus, manpower cost accounted for 35% of the fabrication cost, but this percentage was small considering that the project was a prototype project. This

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

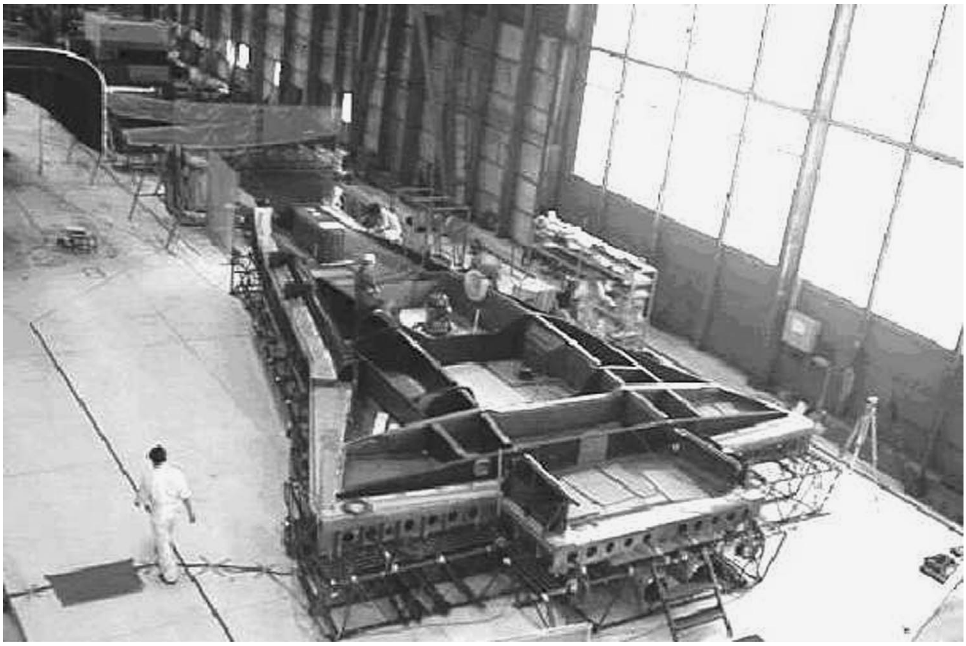

**Figure 16.** Frame/Longeron/Spar assembly.

**Figure 17.** Coupling upper fuselage onto wing-body.

is because the average man-hour cost of the small, specialized molding company was less than that of the aerospace industry.

Downloaded by [Siauliu University Library] at 07:01 17 February 2013

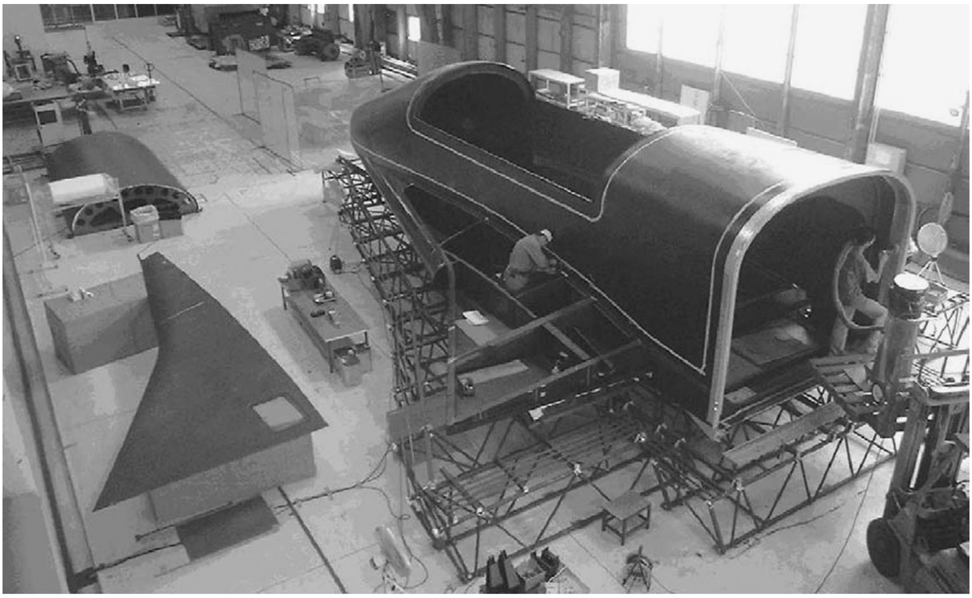

**Figure 18.** Frame/Longeron/Spar assembly.

**Figure 19.** All composite monocoque structure.

**Table 2.**
Fabrication cost breakdown

| | |
|---|---|
| Structural design and process engineering | 20% |
| Tooling (tools and oven) | 20% |
| Building | 15% |
| Materials | 5% |
| Fabrication | 60% |
| Building | 35% |
| Materials | 25% |

## 6. CONCLUSIONS

Low cost and easy fabrication without using huge facilities were realized during the HOPE-X prototype construction by using economic structural design and improved manufacturing techniques. The period from the structural design stage to the completion of the prototype was quite short at only 18 months. Furthermore, a 20% weight reduction was achieved.

The total manufacturing cost has been reduced to almost one-fifth that of the conventional vehicle with aluminum structure. It should be noted that the low fabrication cost was achieved by improving the existing non-high-tech appliances and by optimizing the entire process, and not by any large breakthroughs. At the same time, the total manpower remained constant in this prototype development. Good quality workmanship together with the low unit price offered by the joint-venture company played an important role in realizing low fabrication cost.

## REFERENCES

1. Y. Yamamoto, S. Asada, K. Nishiwaki, M. Niitsu, T. Kamita and G. Kimura, Development of HOPE-X All-composite Prototype Structure, *AIAA paper*, 2001–1780 (2001).
2. M. Niitsu, T. Kamita and K. Uzawa, Development of HOPE-X all-composite prototype structure, in: *Proc. 7th Japan Intern. SAMPE Symp.*, pp. 317–320 (2001).
3. T. Kamita, H. Igawa, K. Miho, T. Akimoto and J. Kochiyama, Development of low-cost composite prototype structure for HOPE-X, in: *Proc. 3rd European Conf. on Launcher Technology*, pp. 441–446 (2001).

Downloaded by [Siauliu University Library] at 07:01 17 February 2013