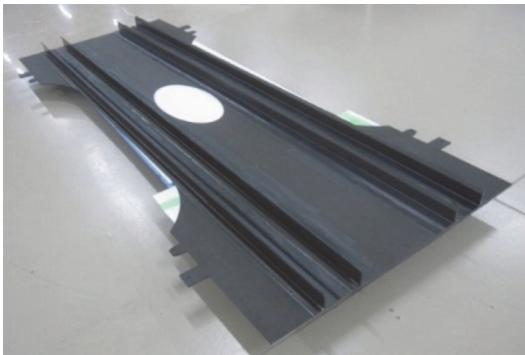


Demonstration of Weight Reduction by Tensile and Compression Test Using Large Composite Panel Designed with New Optimization Method

- 20% Weight Reduction of Reinforcement Material for Opening Area -

KOSUKE OKA^{*1}NAOTO AZUSAWA^{*2}AKIO FUKUDA^{*3}MASAHIRO KASHIWAGI^{*4}KIYOKA TAKAGI^{*5}TOSHIO ABE^{*6}

Composite materials with high specific strength are greatly advantageous to use in terms of structural weight reduction and have been widely applied to aerospace products. However, there is still much room for further leveraging of the weight reduction potential of composite materials by improving the design method for part details. This time, Mitsubishi Heavy Industries, Ltd.(MHI) focused on the structure around the opening area, which can be expected to be lighter and executed trial production and strength testing of a open-holed skin stringer panel using our newly devised optimization method, which provided good results. Comparing the around-hole reinforcement weight with the conventional design method, it was found that a weight reduction effect of about 20% could be obtained.

1. Introduction

Aerospace products are constantly required to be lighter in weight for safe and economical payload transport. For this reason, composite materials with high specific strength have been attracting attention for many years as excellent candidates for materials to be applied to aircraft. Composite materials have been highly applied to aircraft due to various improvements in the materials themselves, structural design and manufacturing methods and their presence has been increasing in recent years. The large-scale composite products that we developed in the past, such as the main wings of the F-2 support fighter and the Boeing 787, incorporate the results of continuous research and development on composite structures since the 1970s. In this report, we focus on the structure around the opening area, which can be expected to be even lighter compared with the conventional composite structure and try to devise and introduce an optimization method for the design of hole shapes and plate thickness transition zones. Chapter 2 outlines this method and chapter 3 reports the results of trial production and strength testing of a open-holed skin stringer panel using a part of this optimization method.

2. Development of design optimization method

Aircraft structures need to be provided with openings such as windows, doors and inspection holes. Therefore, due to the discontinuity of the structure, areas where strain and stress are concentrated locally occur near the openings when a load is applied and it is necessary to reinforce these areas. This problem arises with both metals and composite materials, but since the local stress

*1 Fixed Wing Aircraft Engineering Department, Integrated Defense & Space Systems, Mitsubishi Heavy Industries, Ltd.

*2 Strength Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

*3 Manager, Fixed Wing Aircraft Engineering Department, Integrated Defense & Space Systems, Mitsubishi Heavy Industries, Ltd.

*4 Chief Staff Researcher, Strength Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

*5 Deputy Director, Fixed Wing Aircraft Engineering Department, Integrated Defense & Space Systems, Mitsubishi Heavy Industries, Ltd.

*6 Engineering Research Department, Aerospace Division, Churyo Engineering Co. Ltd.

generated in metal can be accompanied by plastic deformation, it is sufficient to carry out design work in consideration of load redistribution. However, carbon fiber reinforced composite materials, which are brittle materials that do not undergo plastic deformation, are required to be designed so that locally generated strains and stresses are dealt with. One of the approaches to achieve weight reduction near the opening is the establishment of a design method that does not make strain concentrated. The two methods devised this time to reduce the strain concentration near the opening are described below. Hereinafter an inspection hole on the wing underside panel, which is a typical example of an opening, is assumed as the target opening.

2.1 Optimization of hole shape against strain concentration

As a method to reduce the strain concentration around a hole, we devised a method utilizing metaheuristics⁽¹⁾ with Hokkaido University. The purpose of the optimization is to optimize the hole shape so that the strain concentration around the hole when a unidirectional tensile load is applied in the long axis direction of the ellipse is minimized. In this method, the hole shape is represented by a spline curve composed of both end points and one control point in the range shown in **Figure 1** due to the symmetry. By adopting the x-coordinate value on the long axis side and the (x, y) coordinate values of the control point as explanatory variables in optimization, expressing a hole shape close to an elliptical shape is made possible. The objective function was the maximum principal strain acting on the hole edge obtained by FEM analysis. The optimization method used a genetic algorithm. **Figure 2** shows a hole shape to which this method is applied and the measurement result of the strain distribution around the hole acquired by DIC (digital image correlation method) in the strength test. It can be seen that the optimized hole has a blunt shape compared with the initial elliptical shape. In addition, when the new design method was applied, the maximum principal strain value acting on the hole edge was reduced by 15% compared with the conventional method, confirming the usefulness of this method.

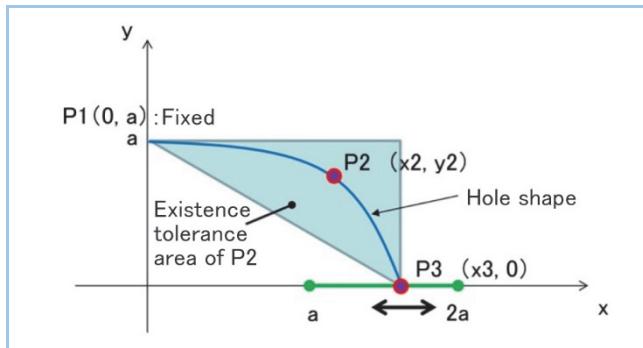


Figure 1 Schematic diagram of optimization method

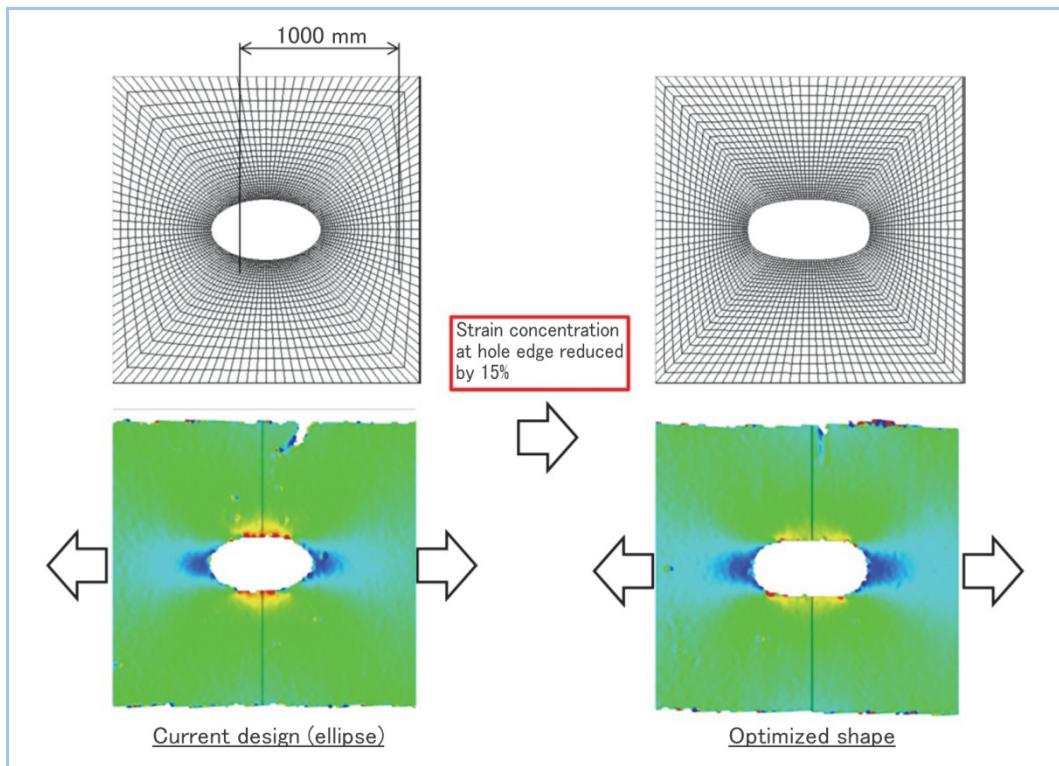


Figure 2 Optimized hole shape and strain distribution

2.2 Optimal design of plate thickness transition zone

We devised a method for maximizing the strength of the plate thickness transition zone with Hokkaido University in the same manner as section 2.1. Since the plate thickness around a hole is designed to be thicker for reinforcement, a plate thickness transition is required for reducing the thickness toward the general plate thickness. When changing the thickness of a composite laminated board, usually the thickness is gradually reduced by cutting and thinning out the ply between the cover ply and the base ply as shown in [Figure 3](#). At this time, by using the laminating pattern of the lamination materials and the order of thinning out the plies as explanatory variables and the strength of the plate thickness transition zone as the objective function, optimization to maximize the strength of the plate thickness transition zone is possible. The outline of this method is described below. (Refer to Reference 2 for details.) The black shaded areas in Figure 3 are resin rich areas that do not contain fibers and generally fractures of the plate thickness transition zone start there. Therefore, in order to increase the fracture strength of the plate thickness transition zone, it is necessary to optimize the laminating pattern and the thinning order so as to suppress the fracture of the resin rich areas. The fracture strength of a resin rich area is represented by the fracture index calculated by individually determining the stresses at the three vertices of the triangular resin rich area using FEM analysis. In this method, the sum of the fracture indices of all the resin rich areas in the plate thickness transition zone is used as the objective function and the laminating pattern and thinning order are optimized so that they become minimized. As an example of analysis using this method, [Figure 4](#) gives the result of optimizing a 16 ply ([0₄/±45₄/90₄])-to-8 ply ([0₂/±45₂/90₂]) plate thickness reducing zone so as to maximize its strength. We executed a strength test using a test piece to which this method was applied and confirmed the effect of suppressing the occurrence of fracture from the resin rich areas, which demonstrates the effectiveness of this method.

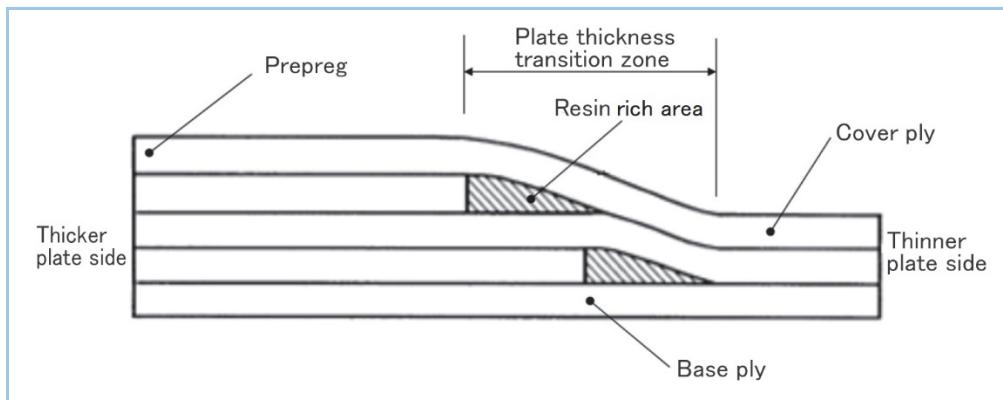


Figure 3 Ply dropping off section

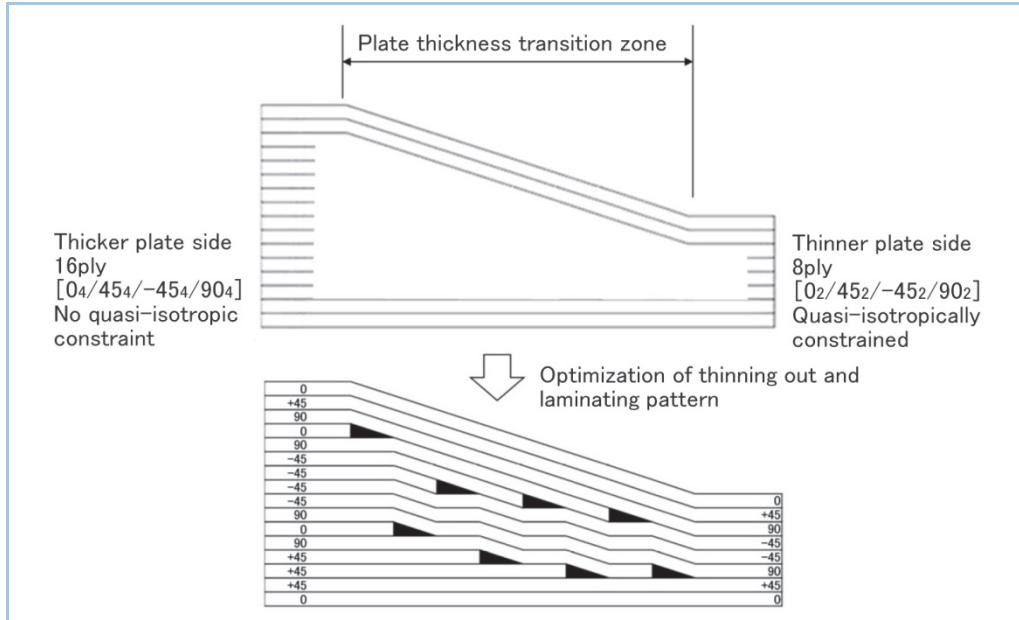


Figure 4 Optimized plate thickness transition zone

3. Demonstration test using skin stringer panel

A large, open-holed skin stringer panel (hereinafter referred to as the test piece) was designed and manufactured by utilizing the design method described in chapter 2 and the effectiveness of the design method was evaluated through a strength test. The design, manufacturing, testing and weight reduction effects of this test piece are described below. The test piece used a high-ductile composite material developed in SIP (Cross-ministerial Strategic Innovation Promotion Program)⁽³⁾. The characteristic data of this material were acquired through elemental tests conducted in advance and used in the design of this test piece.

3.1 Design of test piece

The test piece was designed assuming an area around a hole on a wing underside panel, which typically has many inspection holes and weight reduction can be expected. As the design loads, unidirectional tensile and compressive loads in the span direction were set assuming the intermediate underside panel of a small civil aircraft main wing. **Figure 5** shows the outer shape of the designed test piece. The size of this test piece was set to 3.1 m in length and 1.1 m in width in consideration of the capacity of the test equipment. This test piece consisted of a skin and four stringers and the stringers were installed to the cured skin by co-bonding. The test piece had an inspection hole in the center and a reinforcing thick plate zone (hereafter the pad-up zone) was provided around the hole. The hole shape was optimized using the method described in chapter 2 and the hole size was 540 mm in major axis and 300 mm in minor axis. Since the fracture strength of the plate thickness transition zone from the pad-up area to the general plate thickness area could be increased by using the method described in chapter 2, this test piece could be designed with a steep plate thickness transition of 1:30 in contrast to the normal ramp ratio of conventional plate

thickness transition zones of 1:50 to 1:100. This reduction in the ramp ratio reduced the excess thickness of the plate thickness transition zone, leading to weight reduction (**Figure 6**). Next, the characteristics of stringers are described. A stringer has a cross-sectional shape that the plate thickness on the free flange side is thicker to increase the bending rigidity and the crippling strength and on the other hand, the thickness of the base flange on the skin side is reduced compared with one of the free flange to increase the adhesive strength between the skin and the stringer. In addition, the shape of the end of the base flange is tapered to reduce the rigidity smoothly so that the adhesive does not peel off between the skin and the stringer.

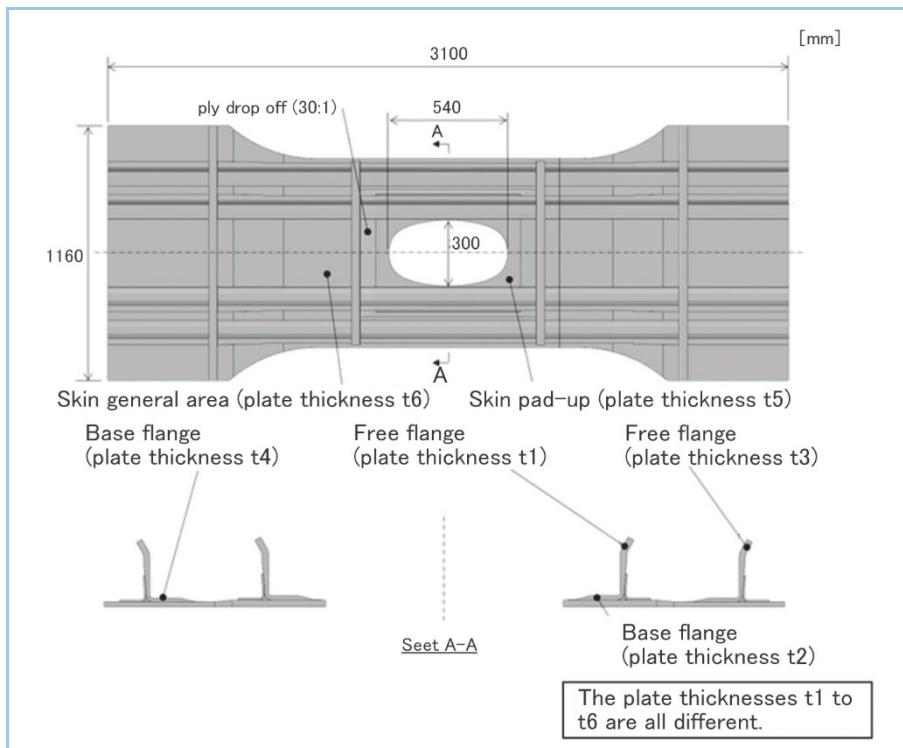


Figure 5 Overview of open-holed skin stringer panel test piece

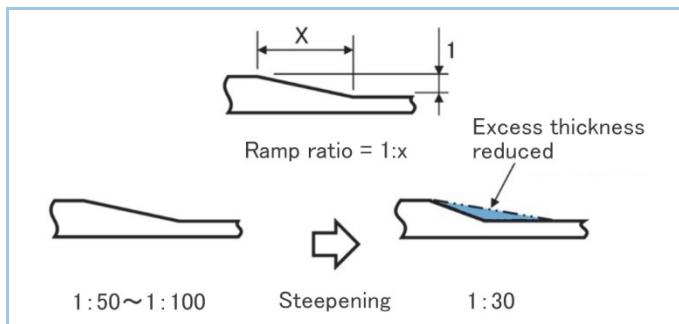


Figure 6 Ramp ratio and weight reduction due to steeper ramp

3.2 Test piece manufacturing method

We adopted a vacuum hot drape molding method that can form a cross-sectional shape at low cost for stringer molding. The vacuum hot drape molding method is, as shown in **Figure 7**, a method to form a desired cross-sectional shape by simply-laminating pre-creeps on a flat plate first, heating it to soften and pressing against the mold with vacuum pressure. In molding a difference in peripheral length due to the plate thickness that occurs at rounded areas, etc., it is necessary to ensure good sliding between pre-creeps at cross-sectional shape changes. If the proper slip between the pre-creeps is not obtained, fiber wrinkles (fiber waviness) occurs, leading to a decrease in strength. Therefore, we conducted a detailed study on the molding process including control of the temperature and evacuation. Even though molding the stringer in this test piece was difficult because there is a change in the plate thickness in the cross section and also ramps with a ramp ratio of 1:30 exist, we ultimately established a process that enables the molding in one shot. The

stringer in an uncured state was adhered to the pre-cured skin by co-bonding to manufacture the test piece.

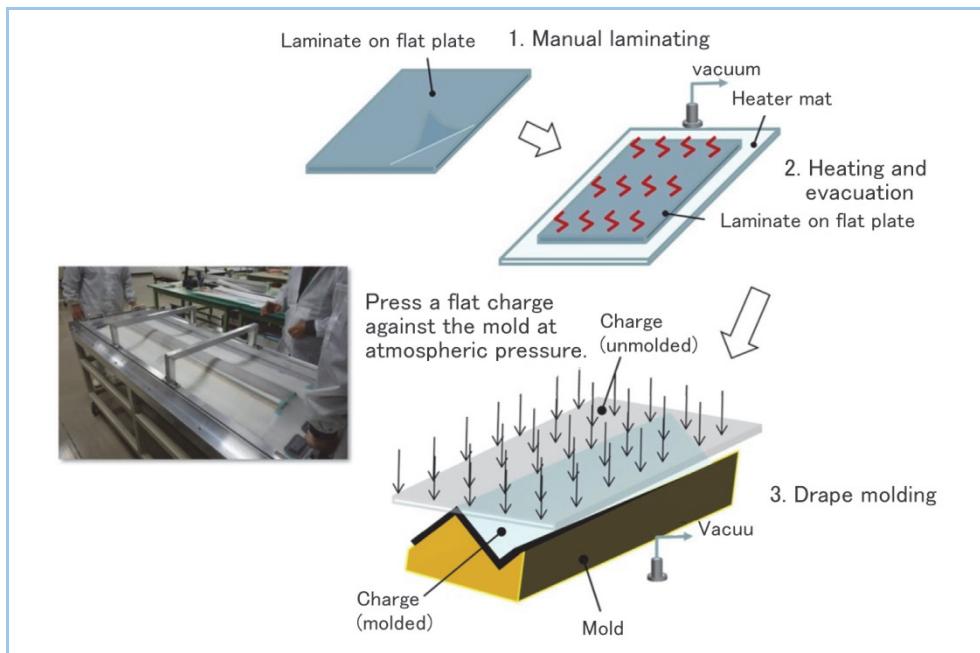


Figure 7 Schematic diagram of hot drape molding method

3.3 Applying impact damage

In order to confirm the strength robustness of the test piece, an impact was applied to two points on the test piece with a falling weight tester before the strength test was performed. The impact energy to be applied was determined by assuming a fall of a tool with a certain weight from a certain height. **Figure 8** is a schematic view of the falling weight test and the appearance of the test piece after the impact was applied. The points to which impact was applied were the skin near the hole and the free flange end of the stringer, which are considered to be critical in terms of strength. As a result of ultrasonic flaw detection inspection of the damage caused by the impact, peeling was seen at the free flange end of the stringer, but no damage was seen on the skin. The strength test described below was carried out using this test piece that had been impact tested.

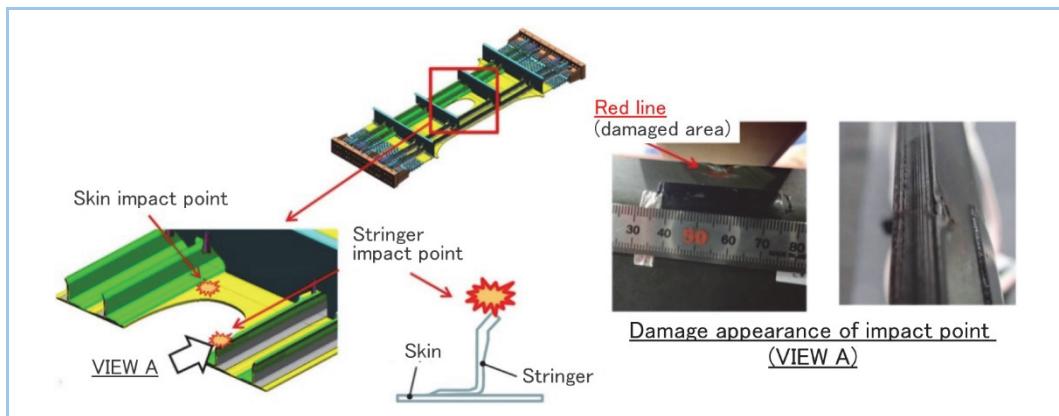


Figure 8 Schematic view of impact test and damage appearance

3.4 Strength test equipment configuration

For this test, a tensile and compression test was conducted using the 10 MN fatigue tester at the JAXA Chofu Aerospace Center Aerodrome Branch. **Figure 9** is a schematic view of the test equipment configuration. The jig connecting the test piece and the tester was fastened with multiple rows of bolts to the skin and stringer so that displacement was uniformly applied. In the compression test, as shown in **Figure 10**, a buckling suppression jig was attached to restrain the out-of-plane displacement of the rib position, assuming the wing box structure of the actual product.

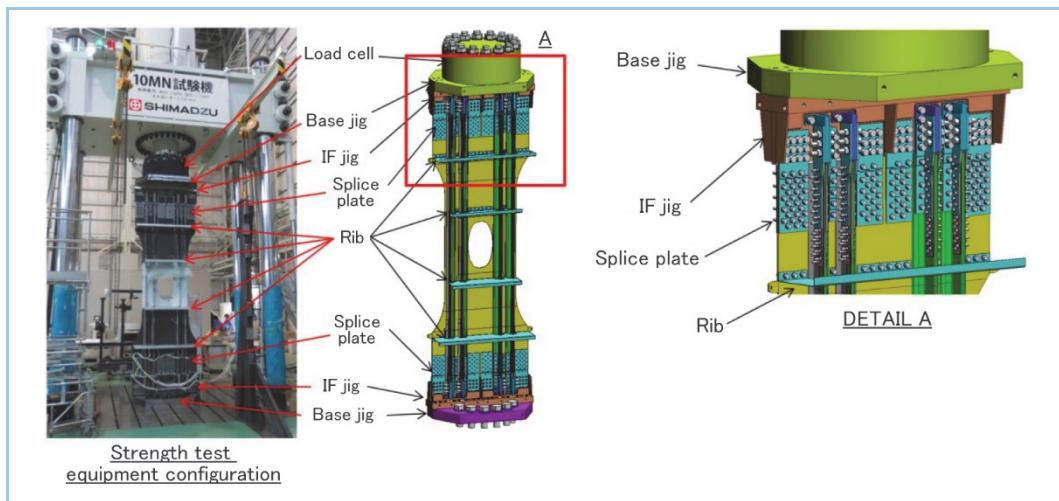


Figure 9 Fastening test piece to tester for strength test

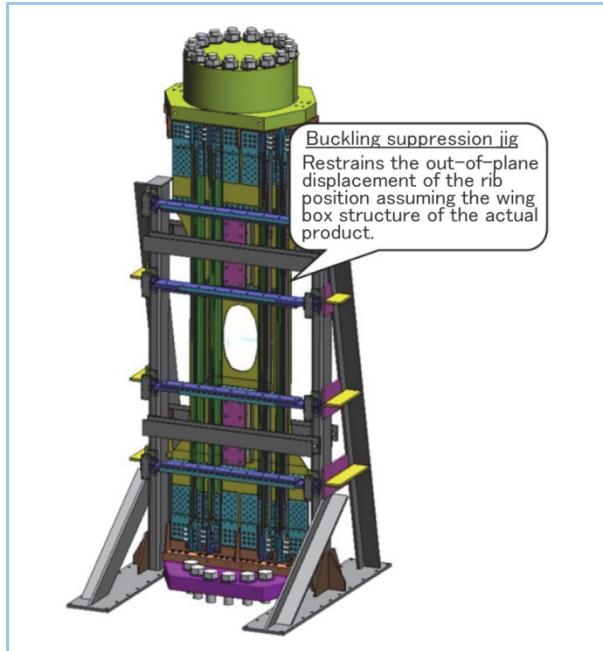


Figure 10 Schematic view of compression test jig and test equipment configuration

3.5 Strength test result

For the strength test conducted, loads up to 1.5 times the flight load were applied in the tensile test and up to 1.2 times, for convenience, were applied in the compression test and it was confirmed that the test piece could withstand the loads. **Figure 11** plots the strain data of each part of the test piece acquired in this strength test and the expected strain value obtained by the preliminary analysis using the FEM model in the vertical and horizontal axes, respectively. The strain data were obtained from strain gauges attached to areas to be monitored for evaluating the condition of the test piece, for example, around a hole edge, bonded zone, etc. From this figure, it can be seen that the test data and the analysis data are well matched within the range of $\pm 10\%$. In addition, the influence of the impact damage was not critical, so the robustness of the structure was confirmed. Finally, a notch was made at the edge of the hole on the test piece and a tensile fracture test was carried out. **Figure 12** presents the state of the test piece on which the notch was made and the test piece after tensile fracture. The data obtained in this fracture test were used for studying the fracture mechanism and improving analysis technology.

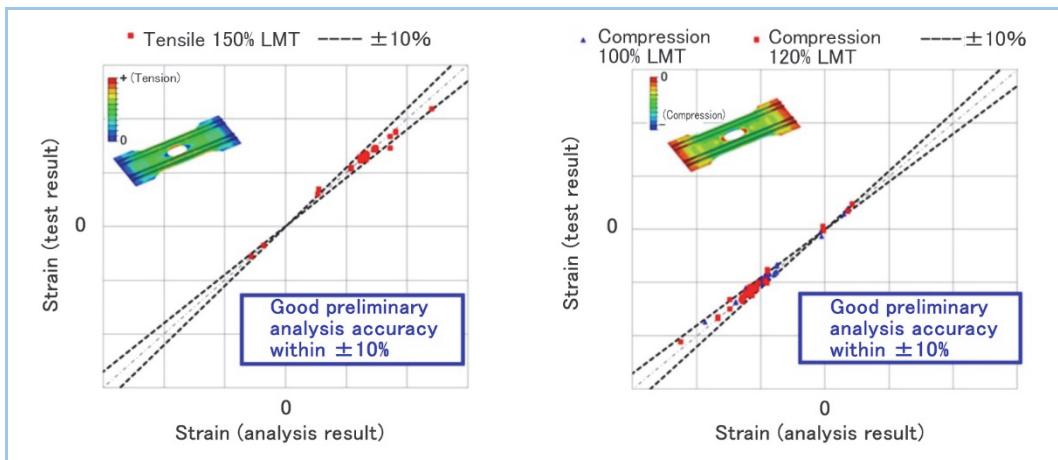


Figure 11 Comparison between test-obtained strain data and predicted strain data

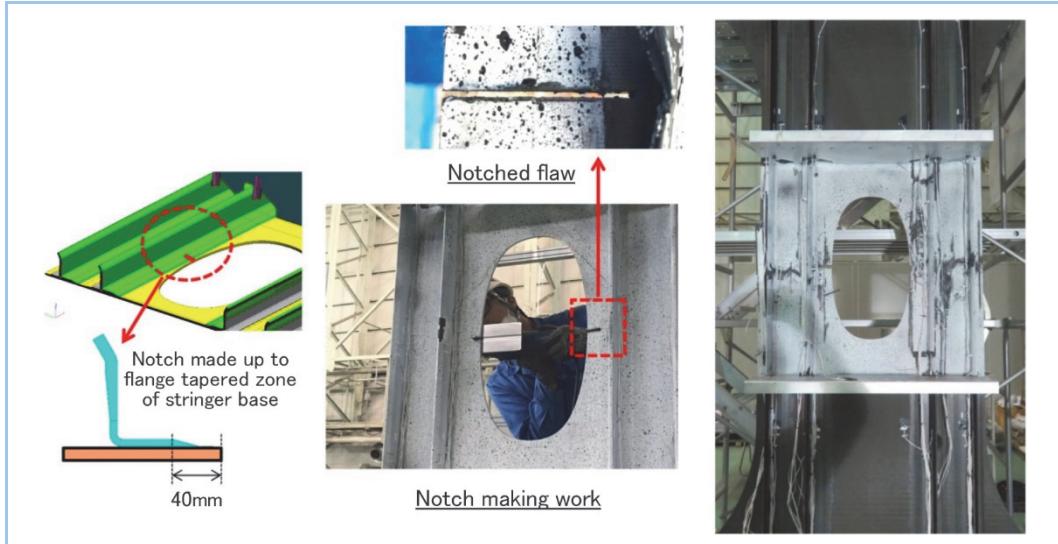


Figure 12 Test piece fracture test

3.6 Weight reduction effect

The weight reduction effect was calculated and quantified by comparing the reinforcement weight around the hole of the test piece designed using the new design method and that of one designed using the conventional design method. This was done because of its superior generality in comparison to assuming a certain aircraft scale and comparing the weight of its wings or the total weight of the aircraft. It was assumed that the conventional design method used a ramp ratio of 1:70. In addition, since the unidirectional axial load acts mainly in the longitudinal direction (wing span direction), it was assumed that the ramp ratio in the lateral direction had been set sufficiently small in the conventional design and only the ramp ratio in the longitudinal direction was improved. As a result of calculation based on the above assumptions, it was found that the weight of the reinforcement can be reduced by about 20% by using a new design method with the ramp ratio set to 1:30.

4. Conclusion

Aircraft structures have openings for a variety of purposes, such as windows, doors and inspection holes. This report explained our development of a new design method for weight reduction and its demonstration test focusing on the area around the inspection hole on the wing underside panel, which is one of the typical openings. The new design method introduced a metaheuristic method into the design of the hole shape and the ply drop-off section of plate thickness transition zone. We also established manufacturing processes for high-ductile composite materials developed in SIP—such as vacuum hot drape molding and co-bonding molding—and manufactured a large test piece. As a result of the strength test using this test piece, the test values and the prediction analysis values were in good agreement, so the validity of the design using the

new design method and the considered manufacturing process was confirmed. Finally, the weight reduction effect due to the use of the new design method was calculated and it was found that the new method could reduce the reinforcement weight of the area around the hole by about 20%. Future issues related to composite material design include the development of a new design method suitable for production using automatic laminating equipment, which has been introduced globally in recent years, in particular. Recent automatic laminating equipment enables accurate laminating of even complicated laminating patterns and multiple-curved surfaces in a short time. For this reason, it will be more important than ever to make products differentiated in the design phase. We are now in SIP (Cross-ministerial Strategic Innovation Promotion Program) Phase 2 (planned for 2018-2023), promoting the introduction of automatic laminating equipment in cooperation with JAXA, while working on the development of an optimized design method to maximize the advantages of the AFP (Automated Fiber Placement) manufacturing method.

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