STUDY ON REPAIR OF CFRP LAMINATES FOR AIRCRAFT STRUCTURES

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Abstract

In this research, CFRP scarf joint were tested to evaluate the basic mechanical properties and impact characteristics when the scarf angles were changed. Tension and compression strengths of scarf joint were decreased when the scarf angle increased in static tests. As the impact test result, damage of scarf joint was increased when the scarf angle increased. Residual strength of scarf joint were decreased when scarf angle and impact energy increased. As the results of this study, it was found that the scarf joint strength and impact characteristics were influenced strongly by the changing of scarf angle.

1 Introduction

The proportion of the composite material in the weight of the airframe keeps increasing, and the weight rate of about 50% is scheduled on Boeing 787 . Such a situation has an important influence on not only the aircraft design but also the aircraft maintenance. Generally, the maintenance of the composite structures is more complex than the case of conservative metallic structures, and the advanced techniques are demanded for finding damages and the repair of structures.

Repair of composite structures [1][2][3] will increase as the usage rate of the composite material increases in near future. Therefore, it is thought that repaired composite structures are distributed on the aircraft. When such a situation will appear in the near future, there is a possibility that serious damage occurs on the repair regions. But, Japanese research works of the repair of CFRP laminates for aircraft structures are few.

Scarf repair is common method of bonded repair for aircraft composite structures. This research was aimed to understanding of the tension and the compression mechanical properties for the bonded scarf repair. In this research, the first stage was conducted to understanding of the basic characteristics of the scarf joint. The second stage was conducted to understanding of the impact characteristics of the scarf joint.

2 Specimens

The direct evaluation of the composite repair part is difficult, because shape of composite repair is very complex. Therefore, the repair part was simulated the scarf joint in this research as shown in Fig.1. The tensile and compressive test specimen of first and second stage is shown in Fig.2 and 3. Three scarf joints and parent specimens were prepared to examine the influence on strength characteristics when different angles of scarf. Three scarf angles were selected that angle is 3, 4.5, 6degrees. The angle of 3° is close to the actual composite repair method, and larger angle of 4.5 and 6 degrees were prepared to comparison between different angles. The material was used twill prepreg of intermediate strength and intermediate modulus carbon fiber, and film adhesive was used FM300M.

Scarf joint fabrication process is divided into the following some steps as shown in Fig.2. The first step is fabrication of parent material that cured by auto-crave at 180℃. The stacking sequence is total 12 plies of $[(\pm45)/(0,90)]_{3s}$. A parent CFRP laminate is machined obliquely to the desired scarf angles. A film adhesive is layed on the machined surface of the parent material. Twelve repair prepregs with the

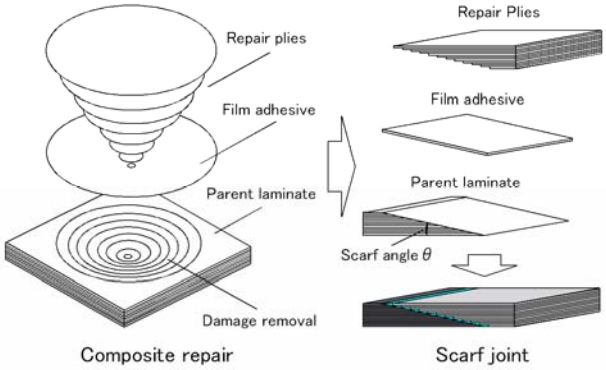

Fig.1 Simplification of composite repair part.

same stacking sequence of the parent part are layed onto the film adhesive. After laying, the specimens are cured by the auto-clave at cure temperature of 180 ℃. Finally, the Cured scarf joint panel is cut by diamond wheel cutter into the required specimen sizes.

The tensile and compressive test specimen is shown in Fig.3 and 4. Two tensile test specimen and one compressive test specimen were prepared at each scarf angle. The size of the specimens was decided by thinking about the impact test procedure to use the same specimen.

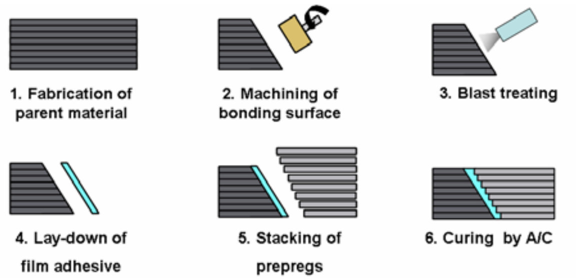

Fig.2 Fabrication process of scarf joint

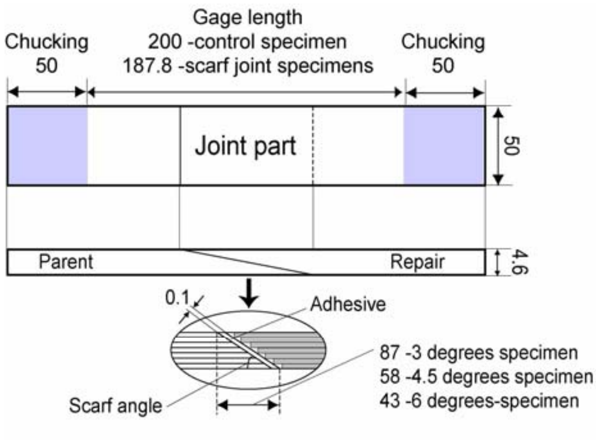

Fig.3 Schematic of scarf joint specimen for tensile test.

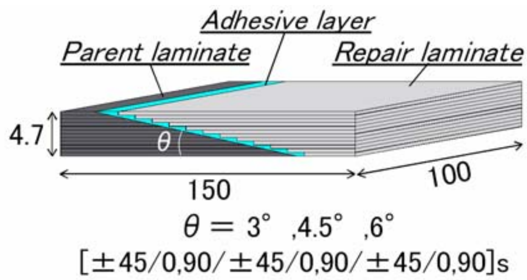

Fig.4 Schematic of scarf joint specimen for compressive test.

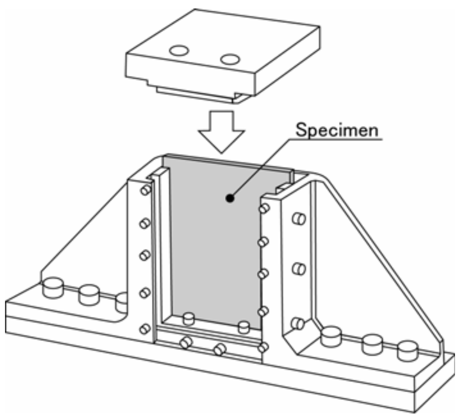

Fig.5 Compression test fixture

3 Test Methods

3.1 Tensile Test Method

The tensile test and residual tensile test were selected the original method that used small width specimen to increase the test parameter when the small quantity of specimen. The tensile tests were conducted by the electric hydraulic testing system of the Instron 8502. The test speed rate was set at 0.5 mm/min. The specimens were clamped at the region of 50 mm from the specimen edges by a pair of hydraulic grips. Strain gages were bonded to the specimen to evaluate the distribution of deformation along the load direction.

3.2 Compressive Test Method

The compressive test and residual compressive strength test methods were referenced by the some CAI (Compression After Impact) test methods [4]. The specimen were installed the test fixture as shown in Fig.5. In this case, side edges of specimen were clamped as simply supported, loading edges of specimen were clamped as fixed. The compressive test was conducted by the electric mechanical testing system of the Instron 1128. The test speed rate was set at 1.0 mm/min. Strain gages were bonded to the specimen to evaluate the distribution of deformation along the load direction.

3.2 Impact Test Method

The objective of the impact test is to investigate the damage characteristics of the scarf joint under the low velocity impact loading. The impact load was applied by a drop-weight impact tester of the Instron Dynatup 9250HV to the center of the scarf joint as shown in Fig.6. The striker weight including an load-cell and an adjustable mass system is approximately 5.8 kg. The specimen support base was used as a picture frame type with a circular cut-out of 35 mm in diameter for the tensile specimen, as shown in Fig.7. In this condition, it is thought that boundary condition of specimen was simply supported along the circular cut-out edge. The tensile specimens were given impact energies (normalized by specimen's thickness) that changed from 1.67 to 3.34J/mm. In compressive test, the specimen support base was used as a picture frame type with a rectangular cut-out and toggle clamp system, as shown in Fig.8. In this condition, it is thought that the boundary condition was a condition between fixed support and simple support along the cut-out edge. The compressive specimens were given impact energies that changed from 1.67 to 6.67J/mm. After impact test, these specimens were inspected by the nondestructive test method of ultrasonic testing to evaluate the damage. Also, the destructive test of cross-sectional observation was conducted to investigate the detail of internal damage along the load direction.

Fig.6 Photo of impact test machine

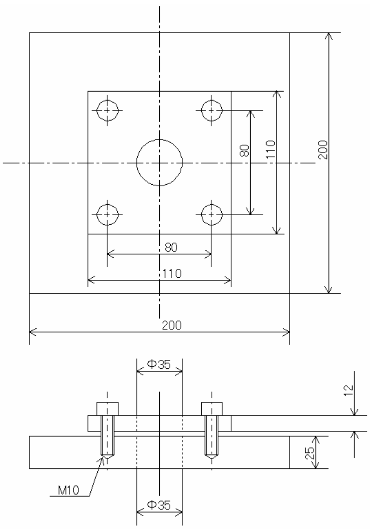

Fig.7 Impact support base for tensile specimen

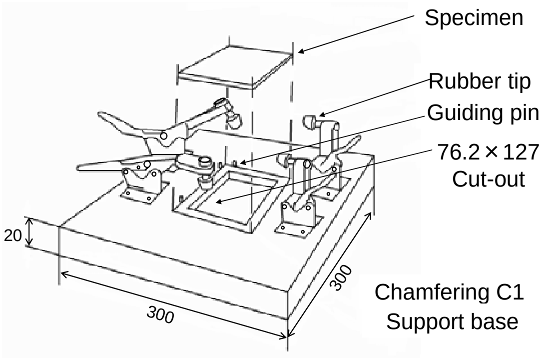

Fig.8 Impact support base for compressive specimen

3 Test results and Discussion

3.1 Tensile and compressive Test Results

Tensile and compressive test results were shown in Fig.9. As the result, tensile strength of scarf joints decreased significantly compared with parent material. This reason seem to be that carbon fiber was cut into the loading direction when the load path was only through the adhesive layer. In compression case, strength of scarf joints were not decreased significantly compared with parent material. This reason seem to be that the compressive strength of parent material was originally low. Strength of scarf joints were decreased with increase of scarf angle in case of tension and compression loading condition. This strength reduction seem to be attributed to the decrease of the adhesive area due to increase of scarf angle. Failure modes of scarf joint were cohesive failure in adhesive layer that excluded end brooming failured 3 degrees specimen in compressive loading condition. From the strain measurement result, It was found that initial failure occurred at the edge of the adhesive layer before the final failure occurs. The load was increased for a while after initial

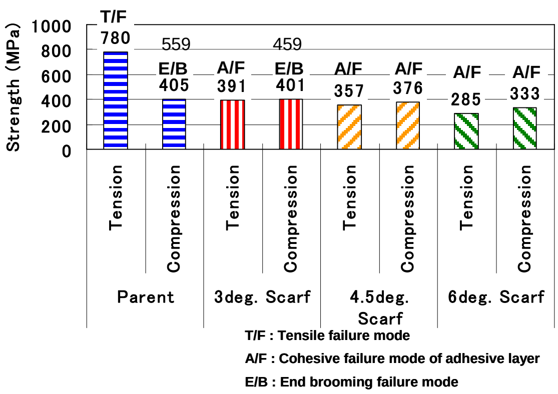

Fig.9 Results of tensile and compressive specimens

failure in case of tensile loading condition. But, specimen were failured quickly by buckling after just initial failure occurred in case of compressive loading condition.

3.2 Residual Strength Test Results

3.2.1 Results of Tensile Specimen

After impact, residual tensile strength tests were carried out with same method of tensile test. Results of residual tensile strength test are shown in Fig.10. Failure modes of the scarf joint were cohesive failure in adhesive layer. The delamination between adhesive and CFRP that thought to be generated by impact loading was observed on the fractured surface of adhesive layer as shown in Fig.11. The parent material and the 3 degrees specimens were not decreased with increase of impact energy. But, 4.5 and 6 degrees specimens were decreased with increase of impact energy. As the results of the Fig.10, it is found that the residual tensile strength of scarf joint was decreased by impact energy when scarf angle is larger than 3 degrees. Therefore, it is necessary to note that residual tensile strength of after impact when composite structure was repaired by large scarf angle.

3.2.2 Results of Compressive Specimen

After impact, residual compressive strength tests were carried out with same method of compressive test. Results of residual tensile strength test are shown in Fig.12. Failure modes of the impacted scarf joint were almost typical CAI failure on center of specimen as shown in Fig.13. Other failure modes showed that were end brooming failure and cohesive failure when only impact energy at 1.67Jmm. Each residual compression strength of specimens were decreased with increase of impact energy. The residual strength of parent material and 3 degrees specimen showed almost same tendency with increase of impact energy. But, residual compressive strength of 4.5 degrees specimen was not same tendency compared with parent material and 3degrees specimen that reduced slightly at 6.67J/mm. But, residual compressive strength of 4.5 degrees specimen was not same tendency compared with parent material and 3degrees specimen when impact energy is 6.67J/mm. In case of 6degree, the residual compressive strength was reduced significantly when impact energy is more than 3.34J/mm. Therefore, it is found that residual compressive strength of scarf joint was changed by relation between scarf angle and impact energy.

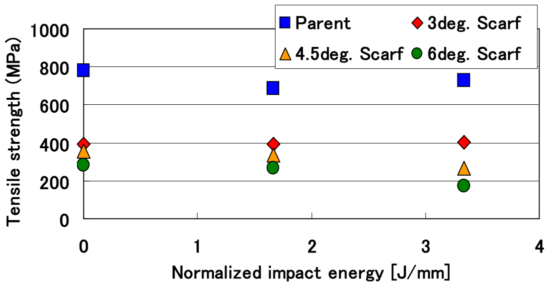

Fig.10 Residual tensile strength of scarf joints

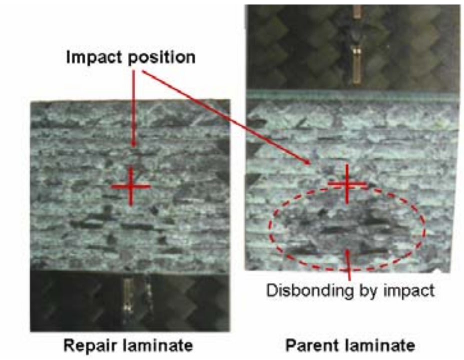

Fig.11 Failure mode of 6deg. scarf specimen after tension test
(applied impact energy of 3.34J/mm)

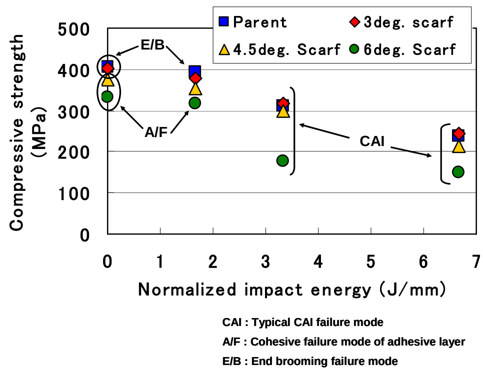

Fig.12 Residual compressive strength of scarf joints

Fig.13 Typical failure mode of compressive scarf joint specimen

3.3 Impact Test Results

3.3.1 Results of Tensile Specimen

The damaged area of the specimen after the impact was inspected by ultrasonic C-scanner system. The results of the ultrasonic inspection are shown in Fig.14 and Fig.15. B-scope images of this picture are magnified in the thickness direction in Fig.15. It was found that the delamination area of the scarf joint specimens was almost same comparison with each other. In this result, it is thought that residual strength is not relate to the amount of delamination. But, residual tensile strength of scarf joint was decrease when large impact energy and scarf angle. Therefore, We conducted cross-sectional observation to clarify the detail of damage distribution in scarf joint, and to understand the relation between damage and residual strength.

The damaged area in the specimen after the impact was observed by an optical microscope. The specimens were cut through the impact point along the length direction of the specimens. The photographs and illustrations of impact damaged specimen of 6-degrees is shown in Figs.16. The location of the impact is on the upper side in this figure. The fine lines of Fig.16 denote the delaminations and transverse cracks in the CFRP layers. The dotted lines of Fig.16 represent the adhesive layer and the bold line denotes the debonding in the adhesive layer. Regardless of the presence of the scarf joint, dalamination and transverse cracks in the CFRP layer were present in the shape of a trapezoid so that it might spread toward the lower surface from impact point. Moreover, for the 6-degrees specimen, a large debonding was present in the adhesive layer and it was spread toward the lower surface from the middle of the specimen, extending near the joint edge. A similar tendency was also observed on the other scarf joint specimens (3-degrees specimen and 4.5-degrees specimen). The relationship between the residual strength and the crack length is shown in Fig. 17. This results show that, when the scarf angle increased, the total delaminaton and transverse cracking decreased. However, the total debonding length of the adhesive layer increased with the increase in the scarf angle. Moreover, when the debonding length of the adhesive layer increased, the residual strength decreased. That is, the adhesive layer directly carries the applied load and it is natural to conclude that due to the damage of the adhesive layer, the residual strength decreased. Therefore, it is belived that debonding of the

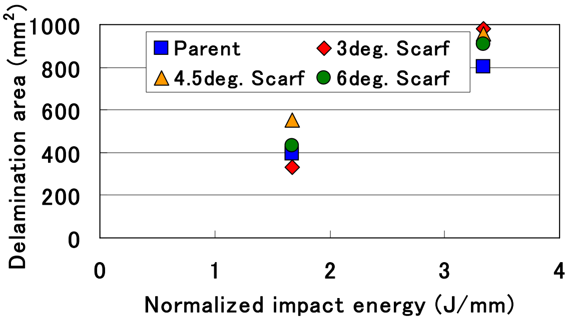

Fig.14 Relation between normalized impact energy and delamination area of tensile specimen

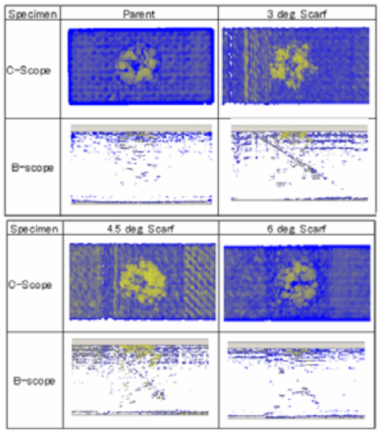

Fig.15 C and B scope images by ultrasonic testing of tensile specimen (applied impact energy of 3.34J/mm)

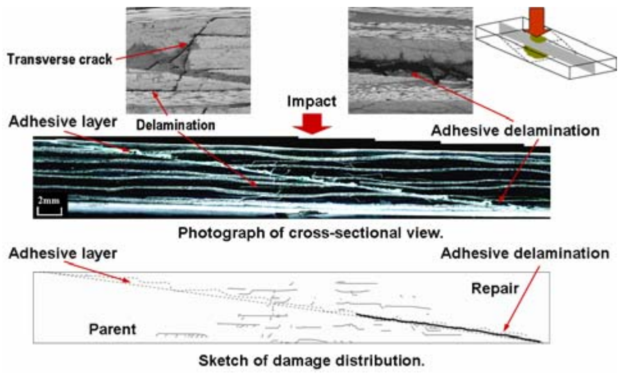

Fig. 16 Cross-sectional observation of 6-degrees specimen.

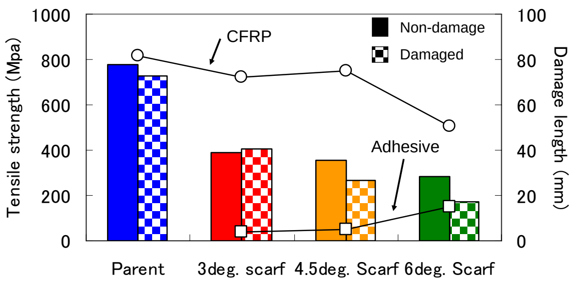

Fig. 17 Relationship between residual strength and crack length.

adhesive layer affects the deterioration of the scarf joint strength after impact.

3.3.2 Results of Compressive Specimen

The results of the ultrasonic inspection are shown in Fig.18 and Fig.19. B-scope images of this picture are magnified in the thickness direction in Fig.19. It was found that the delamination area of parent, 3 degrees, and 4.5 degrees specimens were almost same tendency. But, the large amount of delamination occurred in the specimen of 6 degrees. This damage was observed up to width of cut-out of impact support base at the edge of the adhesive layer. In this result, it is thought that the impact damage of the scarf joint is greatly different according to the scarf angle when boundary condition is near the simply supported condition. It is thought that the residual compressive strength was decreased by large amount of delamination in 6 degrees specimen, furthermore, the proportion of damage in the bonding area influenced the decrease of residual strength. The cross-sectional observation of compressive specimen is shown in Fig.16. It is found that the delamination of adhesive occurred in opposite side of impact position. Especially, The delamination of 6 degrees specimen extended from adhesive tip to neutral axis. It appears that the delamination of adhesive layer was generated by bending force due to impact loading. Because, the normal stress due to bending stress in adhesive layer was increased by increase of scarf angle. Moreover, the tensile strength of adhesive is greatly lower than the shear strength of adhesive [5]. It is necessary to note the damage due to the impact loading when the scarf angle is large.

4 Conclusion

We conducted the some test of scarf joint to investigate the basic strength and impact characteristics when the scarf angle is change from 3 degrees to 6 degrees. The major results are described as follows.

1. The tensile strength of scarf joint was large compared with parent material, however, compressive strength of scarf joint was not decreased significantly compared with parent material.
2. The strength of scarf angle was decreased when the scarf angle increased.
3. The residual tensile strength was not decreased in parent material and 3 degrees specimen, but, 4.5 and 6 degrees specimen were decreased.

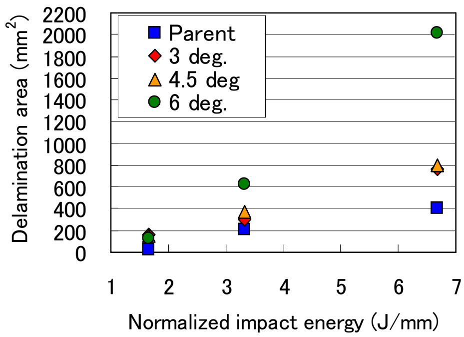

Fig.18 Relation between normalized impact energy and delamination area of compressive specimen

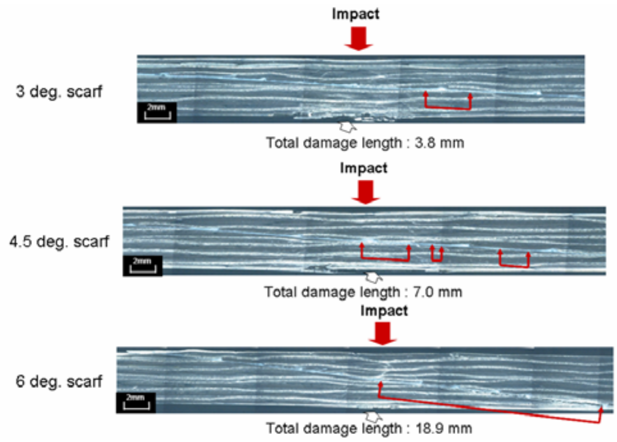

Fig. 16 Cross-sectional observation of scarf joint

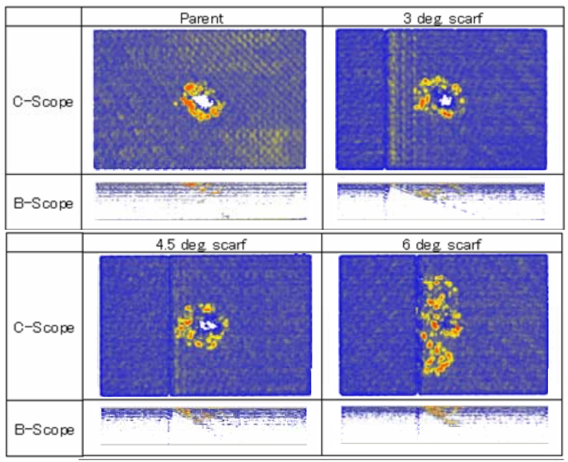

Fig.19 C and B scope images by ultrasonic testing of compressive specimen (applied impact energy of 6.67J/mm)

4. The residual compressive strength of the parent material 3 degrees, and 4.5 degrees specimen was same tendency, but, the 6degree specimen decreased when impact energy is large

5. The impact damage of scarf joint was increased with the increase of scarf angle.

As the results, the strength of repaired composite structures recovers when the scarf angle is reduced. But, the repair area and the repair cost are increased due to the increase of removed parent material when the small scarf angle. Therefore, it is seems to be that the optimum scarf angle for the composite repair can not be selected easily from only the viewpoint of the strength recovery. But, thinking about the residual strength, the optimal scarf angle can be selected from the deterioration of the joint strength. In this research, it is thought that the optimal scarf angle is more than 3 degrees. Because it is seems to be that the optimal scarf angle should be decided residual strength and required static strength of structures.

4 References

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