STUDY OF DIRECT OUT-OF-PLANE TENSILE TEST METHOD FOR CFRP LAMINATES

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Abstract

Although several out-of-plane test methods are proposed in other research papers, their reliability remains to be established. The present study focuses on the flatwise tension test. Finite element analyses and experiments were carried out in order to investigate the suitable specimen configuration for evaluation of the out-of-plane strength.

Several variations of specimen configuration (cylindrical column and spool column) were examined. The "stress ratio" is defined as the representative value in which the nominal stress is divided by the maximum stress in order to discuss the apparent strength. In the case of spool specimens, the stress concentration near the minimum diameter at center of a specimen was predicted.

Several experimental tests for cylindrical and spool specimen were also carried out. Failure including delamination in adhesive layer was observed for cylindrical specimens, whereas failure at the center of the specimen was observed for spool specimens

1 Introduction

CFRPs are attractive structural materials in various applications because of their high performance characteristics. In the latest model aircraft, composites are used in major structural parts such as the center wing box, the wing, and the fuselage. With respect to the application of composites to aerospace structures, the interlaminar tensile property and interlaminar fracture toughness are the major concerns for improvement in weakness of composite structures. Recently, CFRPs in which high toughened resin has been inserted into the interlaminar, or in which tackyfire has been used in the interlaminar, have been created and made practicable. However, because of difficulties in measurement, out-of-plane interlaminar tensile tests have not been undertaken in general. Thus, when analyzing or designing the composite structures, many engineers may substitute the out-of-plane tensile property with 90 degree direction tensile property. Because the difference between an out-of-plane tensile property and a 90 degree in-plane tensile property is made clear through the use of tackyfire and through-the-thickness reinforcements, measurement of the out-of-plane properties are important Two basic approaches are described in MIL-HDBK-17[1]: direct out-of-plane loading of a laminate specimen bonded between two fixture blocks (flatwise tension test), and indirect out-of-plane loading using a curved beam (Figure 1).Several studies about indirect out-of-plane loading using many different kinds of curved beams are reported.[2] This testing technique takes advantage of the out-f-plane tensile loading induced in the elbow of a curved laminate beam subjected to an opening moment. The main differences between direct and indirect loading test methods are the method of loading, the figure of specimens, and the state of stress concentrated generation. The potential problems with the indirect loading test method are the dependence on strength at a narrow maximum stress area, difficulty with making a specimen, and a presence of a residual stress caused by the stacking sequence and the figure of the specimen. Although the direct loading method has problems concerned with the bonding between the specimen and loading metal tabs, it is at least expected that the maximum stress area under a direct loading method is wider than that of an indirect loading method specimen.

This study focuses on the flatwise tension test, and on unidirectional composites because of their most basic stacking sequence. The results are expected to be used in designing and analyzing other composites as well. The state of stress in the specimen was estimated with a linear finite element method. The geometry of the test specimen was suggested and investigated. The figures suggested were a square pillar, a cylindrical column (similar to those used for the flatwise test of sandwich constructions), a dog-born [3], and a spool, etc. This study focuses on the cylindrical column and the spool. The final purpose of this study is to propose an out-of-plane tensile test method which is simpler to carry out and more appreciable.

2 Analysis

2.1 Analysis models, Model geometry

The stress state generated in a specimen was estimated using a finite element method. The finite element commercial code ABAQUS 6.5 was used. The finite element models consisted of composite part and adhesive part. A number of different specimen geometries were modeled. A nominal stress was calculated from the result of the analysis by dividing the total value of the reaction force of the nodes on the bonding side by the section area of the model. The maximum stress in the out-of-plane direction was calculated from the result of the analysis as well.

Model geometry-Cylindrical column (Fig.1)

The thickness of models was varied between 2 mm and 100mm. The diameter of the specimen and adhesive of all models is a common 25 mm.

Model geometry -Spool column (Fig.2)

The thickness of all spool models was a common 8mm. The diameter of all adhesive models is D25 mm. And four types of the minimum diameter of models were considered: from d3.125 mm to d18.75 mm.

The thickness of adhesive lamina was a common 0.1mm.

2.2 Model material

The CFRP specimen models were modeled using orthotropic elastic finite elements with the mechanical properties of Toho Tenax CFRP IM600/#133. (Table1) The properties used for analysis, which were quoted from the Advanced Composites Database System: JAXA ACDB: Ver.05-1 (http://www.jaxa-acdb.com)

The adhesive layer models were modeled using deformation theory Ramberg-Osgood plasticity finite elements with the mechanical properties of AF163. AF163 is Structural Adhesive Film, produced of 3M Scoth-Weld^{TM}. Since the mechanical property for analysis was not found on catalogue of adhesive film, the tensile test for neat resin was carried out. The mechanical properties of Young's modulus 2.75 GPa and Poisson's ratio 0.33.

2.3 Loading and Boundary conditions

The loading and boundary conditions consisted of tensile displacement applied in the z-direction (out-of-plane direction) to the top surface of the adhesive lamina, while the midplane of the specimen was constrained in the z-direction considering the symmetry of the model. The tensile displacements were 1% of the specimen thickness. (Fig.1) For example, in order to calculate the 6 mm thick specimen, 0.03 mm tensile displacement was applied to the 3 mm thickness model.

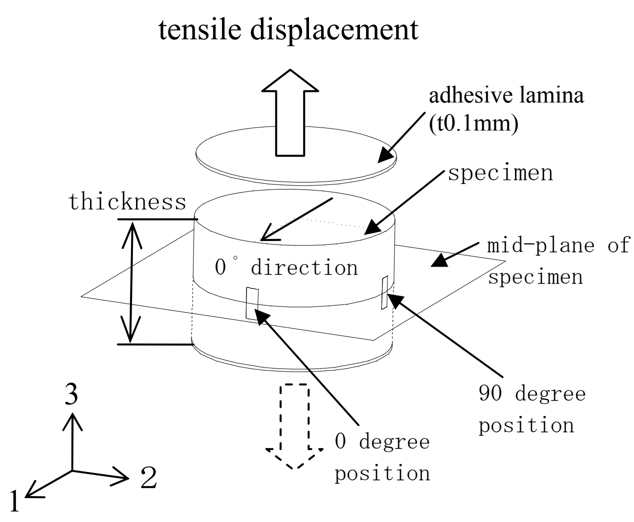

Fig.1 Analisys model of cylindrical column

Table 1 Properties of model

E1 G Pa	E2 G Pa	E3 G Pa	ν 12	ν 13	ν 23	G12 G Pa	G13 G Pa	G23 G Pa
153	8.20	8.20	0.335	0.335	0.5	4.36	4.36	3.07

(an assumption) $E_3=E_2$、$\nu_{13}=\nu_{12}$、$G_{13}=G_{12}$、$\nu_{23}=0.5$、$G_{23}=E_2/\{2(1+\nu_{23})\}$

E:extensional moduli of elasiticity、ν:poisson's ratio、G:shear moduli

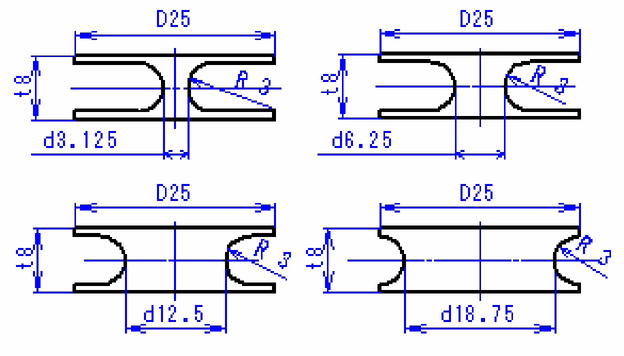

Fig.2 Analisys models of spool column

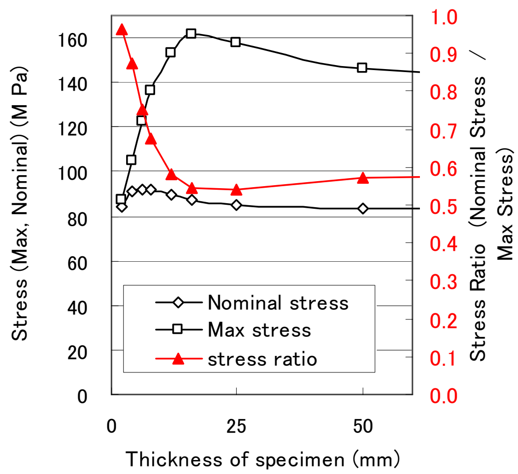

Fig.3 The Stress Ratio as a function of a thickness of cylindrical specimen

2.4 Analysis results

2.4.1 Cylindrical column

The position where the maximum out-of-plane stress appeared was near the adhesive lamina, in the 90 degree position. (Fig.1) The matters that turns out through analysis results were as follows.

1) stress distribution was not uniform
2) not only out-of-plane stress but also other plane stresses and shear stresses were generated.
3) several maximum stresses were generated near same positions.

When the specimen is made to be homogeneous, it is thought that the maximum stress reaches the strength and the entire specimen breaks. Then, the stress ratio is defined as the value in which the nominal stress is divided by the maximum stress. Fig. 3 shows the relationship between the stress ratio and specimen thickness.

2.4.2 Spool column

The position where the maximum stress appeared was located on the midplane. (Fig.1) Fig.4 shows the relationship between stress ratio and diameter of center.

Table2 indicates each maximum stress and ratio that was calculated from

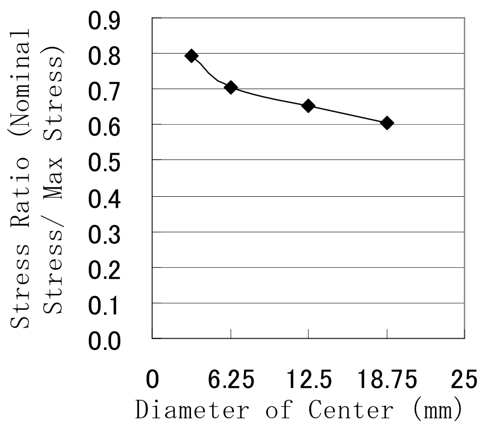

Fig.4 The Stress Ratio as a function of a Diameter of center

Table2 Maximum Stresses and Ratio of Maximum Stresses

Diameter of center	Maximum Stress						Ratio of Maximum Stresses (S_{XX}/S_{33})				
	S_{11}	S_{22}	S_{33}	S_{12}	S_{13}	S_{23}	S_{11}/S_{33}	S_{22}/S_{33}	S_{12}/S_{33}	S_{13}/S_{33}	S_{23}/S_{33}
mm	M Pa						%				
3.125	26.2	34.4	185.5	10.3	39.6	42.1	14	19	6	21	23
6.25	33.8	43.1	170.0	11.8	36.6	39.2	20	25	7	22	23
12.5	37.6	51.7	165.8	14.5	36.9	42.3	23	31	9	22	26
18.75	41.4	62.9	173.1	16.4	37.4	41.7	24	36	9	22	24

2.5 Discussion and conclusion

2.5.1 Cylindrical Column

There is a possibility that delamination propagates into the adhesive lamina beyond the delamination onset, because maximum stress position is located near the adhesive lamina. This stress distribution is essential problem of cylindrical specimen. However, stress ratio closed to 1 by decreasing the thickness of specimen.

2.5.2 Spool Column

Within the cases of the same thickness, when the minimum diameter decreased, the stress ratio approached 1. This change is thought to be caused by the following reasons; the change in the stress decreases (in midplane), the aspect ratio (diameter/thickness) of the specimen becomes small and the stress state approaches the same state as that of uniaxial stress. The “true” strength may be obtained using an appropriate spool specimen. It is thought that spool specimen possibly fractures near the midplane. (An adhesive lamina influence decreases.)

2.5.3 Comparison between cylindrical and spool specimen

The difference of stress distribution between cylindrical and spool specimens was confirmed. And test method with spool specimens was superior to method with cylindrical.

Although the same spool specimens, It has been understood that stress ratio becomes close to 1 by decreasing the diameter at center of the spool specimens. Further investigations on the connection between the “true” strength and the measured strength from the cylindriacl/spool specimens are necessary for the design of the standard out-of-plane tension test.

3. Experiments

3.1 specimen, test procedure

The material of test specimen was CFRP IM600/#133 (0.145 mm thick unidirectional Carbon / Epoxy prepreg) using the stacking sequence $[0]_n$. The three type Spool specimens and one type cylindrical specimen were prepared. The three type diameters at center part of Spool specimen were 6.25mm / 12.5mm / 18.75mm respectively. The diameter of cylindrical specimen was 25mm. The nominal thickness of specimens was 8mm. The diameter of bonding part of specimen was set to be 25mm.

All specimens were machined on the lathe with a whetstone. Adhesive film, AF163, was used for bonding between the specimen and fixture blocks. The bonding surfaces on specimen and fixtures were blasted with abrasive (white corundum / alumina) before bonding procedure.

3.2 Test results

The experiments of Spool and Cylindrical specimen were carried out. A part area of adhesive lamina of cylindrical specimen was included as fracture surface area where the specimen was broken. On the other hand, fracture surfaces of all spool specimens were observed at the center part of the specimen. The nominal strengths were calculated with breaking force divided by the area at center of specimen. Fig.5 shows the relationship between nominal strength of Spool specimens and cylindrical specimen and a center diameter. The nominal strength of Cylindrical specimen is shown in Fig.5 as diameter 25mm. Nominal strength has increased as the center diameter decreases.

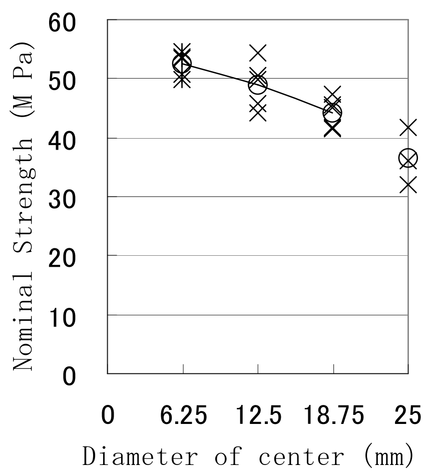

Fig.5 The Nominal Strength as a function of a Diameter of center

4. Conclusion

The fracture surface position of spool specimen in the experiences and the maximum out-of-plane stress position in analysis results were same region. Compared to the test methods with cylindrical specimen, stability of spool specimen was confirmed as test methods because it was predicted that stress distribution of spool specimen closed to uniaxial stress state. The test methods with spool specimen were more suitable than test mehod with cylindrical specimen because the above-mentioned point.

As decreasing diameter at center spool specimen, nominal strength increases. This tendency for nominal strength was consistent with analysis results. And it is expected that true out-of-plane strength is higher than the experimental results in this study.

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