Buckling Experiment on Anisotropic Long and Short Cylinders

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Abstract

A buckling experiment was performed on anisotropic, long and short cylinders with various radius-to-thickness ratios. The 13 cylinders had symmetric and anti-symmetric layups, were between 2 and 6 in terms of the length-to-radius ratio, between 154 and 647 in radius-to-thickness ratio, and made of two kinds of carbon fiber reinforced plastic (CFRP) prepreg with high or low fiber modulus. The theoretical buckling loads for the cylinders were calculated from the previously published solution by using linear bifurcation theory considering layup anisotropy and transverse shear deformation and by using deep shell theory to account for the effect of length and compared with the test results. The theoretical buckling loads for the cylinders were calculated from the previously published solution by using linear bifurcation theory considering layup anisotropy and transverse shear deformation and by using deep shell theory to account for the effect of length. The knockdown factor, defined as the ratio of the experimental value to the theoretical value, was found to be between 0.451 and 0.877. The test results indicated that a large length-to-radius ratio reduces the knockdown factor, but the radius-to-thickness ratio and other factors do not affect it.

Keywords: buckling, cylinders, anisotropy

1. Introduction

Many buckling tests have been performed on orthotropic and anisotropic cylinders, which are often made from CFRP. As summarized by the author [1] and as shown in Fig. 1, the values of the knockdown factor have been calculated from these tests are scattered between 50% and 100%.

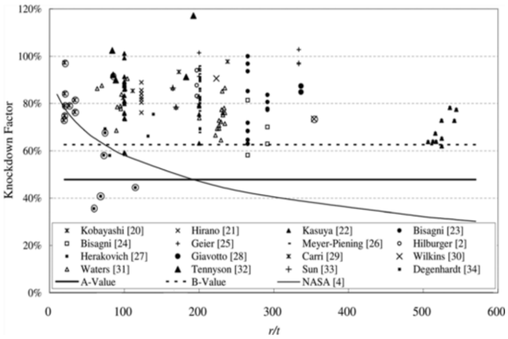

Fig. 1 Knockdown factor and *r*/*t* [1]

Note that the theoretical buckling loads were calculated by using the solution with the least amount of simplification in the linear bifurcation theory from among the previously published solutions [2]. The previous experiments and evaluations, however, mainly concentrated on the effect of the radius to thickness ratio (*r*/*t*). Recently, long CFRP cylinders have started to be used in large satellites [3], but no information is yet available on the effect of length on the knockdown factor. Thus, buckling tests were performed on long and short CFRP cylinders, and the results were used to calculate the knockdown factors.

2. Method

2.1. Making Specimens

The CFRP prepregs used to make the cylinders were TR350J075S, E_L = 114.7GPa (hereafter called "TR") and HSX350C075S, E_L = 260.3GPa (hereafter called "HSX"); both were made by Mitsubishi Rayon Co., Ltd. Here, E_L is the longitudinal Young's modulus measured in a tensile test, and the transverse Young's modulus E_T and shear modulus G_{LT} were assumed to be 6 GPa and 4GPa, respectively.

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The test specimens (CFRP cylinders) were made in-house by hand-layup. CFRP prepregs were layered manually on an aluminium mandrel (150 mm in diameter), and heat shrinkable tape was wound around them. The layup sequence is shown in Table 1. The CFRP prepregs on the mandrel were thermally cured in an oven kept at 130°C for 2 hours. The cured cylinders were cut by grinders, and both ends were bonded to steel rings by epoxy adhesive. To prevent thermal residual stress on the cylinders, the curing of the epoxy adhesive was conducted at room temperature.

Twelve sheets of three-axis strain gages were bonded on the top and bottom (5 mm from the steel end rings) and middle (the center of the length) of the cylinders in the circumferential direction, each separated by 90°.

2.2. Test Method

A typical compression test configuration is shown in Fig. 2. Section paper was laid under the specimen to align the centers of the cylinder and the universal testing instrument (Shimadzu AG-I 100kN). To make the load uniform, a rubber sheet and a silicone rubber sheet were laid on the top end of the cylinder, a 20 mm thick stainless plate was put over the sheets, and a rubber sheet was laid on the bottom end of the cylinder. To minimize the offset of the load, a small compression load was applied, and the strain outputs in the middle were checked. When a significant difference between the strains was observed, the location of the cylinder on the universal testing instrument was adjusted. When the difference between the strains no longer changed or a large offset was observed between the centers of the cylinder and the universal testing instrument, however, the difference between the strains was ignored and the test proceeded to the next step.

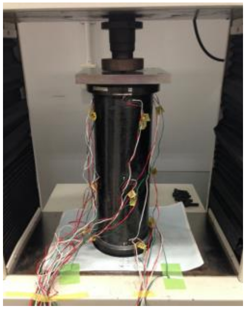

Fig. 2 Photograph of buckling test

The half level compression test (applying half the expected buckling load, including 0.5 of the knockdown factor) was performed to check for anomalies in the data. After that, the full level compression test was performed to buckle the cylinder. Load was applied until the cross-head displacement reached 1.5 of the buckling displacement.

3. Results and Discussion

Typical load and displacement results are shown in Fig. 3 and 4.

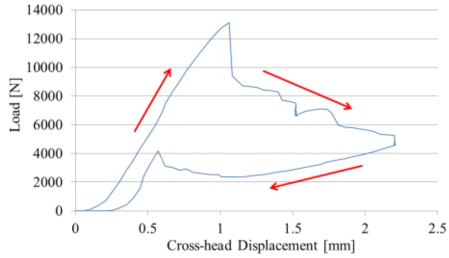

Fig. 3 TR 6 ply, *L*/*D*=1, gap allowed.

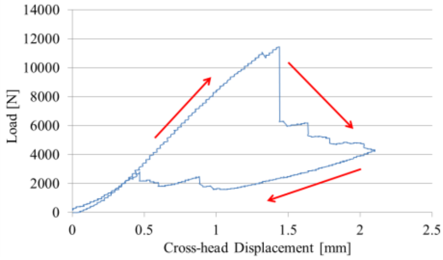

Fig. 4 TR 6 ply, *L*/*D*=3, gap allowed.

Table 1 summarizes the test results. Note that an extremely low knockdown factor 0.397 was caused by 8mm of offset load, and the modified knockdown factor considering the offset is 0.481. Accordingly, the knockdown factors are scattered between 0.451 and 0.877.

The knockdown factors of the longer cylinders are lower than those of the shorter cylinders, while other factors (symmetric or anti-symmetric, ply gap, fiber modulus and *L*/*r*) seem to have no effect on the trend. Thus, a regression analysis with categorical variables was conducted to check the effects. The results are shown in Table 2. A regression analysis can be used instead of an analysis of variance (ANOVA) when the sample size is unbalanced like in this case. Here, *r*/*t* (thickness) and the symmetric or anti-symmetric factor are multicollinear; thus, the symmetric or anti-symmetric factor should be excluded from the regression analysis.

Table 1 Summary of the test results

Specimen name	Layip sequence	Thick-ness t [mm]	Length L [mm]	Buckling load		Knock-down factor	Ply gap or overlap
				Theory P_a [N]	Test P_a [N]		
TR 6 ply L/r=2	(-70/70/0/0/70/-70)	0.488	136	21983	13197	0.600	Gap
TR 6 ply L/r=4	(-70/70/0/0/70/-70)	0.488	287	21986	11870	0.540	Gap
TR 6 ply L/r=6	(-70/70/0/0/70/-70)	0.488	436	21987	11537	0.525	Gap
HSX 6 ply L/r=2	(-70/70/0/0/70/-70)	0.349	136	21123	12997	0.615	Gap
HSX 6 ply L/r=6	(-70/70/0/0/70/-70)	0.349	443	21873	12647	0.578	Gap
HSX 3 ply L/r=2	(-70/0/70)	0.175	148	2060	1806	0.877	Overlap
HSX 3 ply L/r=6	(-70/0/70)	0.175	443	2061	1437	0.697	Overlap
TR 6 ply L/r=2	(-70/70/0/0/70/-70)	0.488	136	21983	12665	0.576	Overlap
TR 6 ply L/r=6	(-70/70/0/0/70/-70)	0.488	436	21987	8738	0.397 *	Overlap
HSX 6 ply L/r=2	(-70/70/0/0/70/-70)	0.349	136	21123	10366	0.491	Overlap
HSX 6 ply L/r=6	(-70/70/0/0/70/-70)	0.349	436	21873	9875	0.451	Overlap
HSX 2 ply L/r=2	(-50/50)	0.116	136	964	583	0.605	Overlap
HSX 2 ply L/r=6	(-50/50)	0.116	436	944	464	0.492	Overlap

*Note: 8mm of load offset was observed and modified knockdown factor considering the offset load is 0.481.

Table 2 Regression Tables

	Coefficients	Std Error	t	P-value	Lower 95%	Upper 95%
Intersept	0.611	0.095	6.459	0.02%	0.393	0.829
gap/overlap	-0.052	0.080	-0.646	53.62%	-0.236	0.133
TR/HSX	0.047	0.087	0.542	60.28%	-0.154	0.249
L/r	-0.025	0.017	-1.424	19.23%	-0.065	0.015
r/t	0.000	0.000	0.782	45.70%	0.000	0.001

The mean of the knockdown factors is 0.611 with 0.02% of P-value, and it is smaller than 5% (standard statistical criteria); hence, the value is statistically significant. Other effects, however, are not significant because their P-values are higher than 5%. Only the P-value of L/r, which is 19.23%, is smaller than the others. The mean of the knockdown factors is 0.627 for L/r=2 and 0.537 for L/r=6. The smaller value is 14.4% smaller than the larger value. Thus, the length may affect the knockdown factor. To clarify its effect, more buckling tests are required.

4. Conclusions

Thirteen buckling tests were performed on symmetric and anti-symmetric, long and short cylinders to investigate effect of varying the length. The difference in the mean knockdown factor between lengths was found to be 14.4%. A regression analysis, however, indicated that the difference was not statistically significant. More buckling tests considering other factors should be conducted in order to find the cause of the scatter in the knockdown factor.

References

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[3] Y. Takano, T. Masai, H. Seko, A. Takano, and M. Miura, “Development of the lightweight large composite-honeycomb-sandwich central cylinder for next-generation satellites,” Aerospace Technology Japan, vol. 10, pp. 11-16, 2012.