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Preliminary Experimental Study on Low Cycle Fatigue of Filament-Wound Composites

By

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Summary: The low cycle fatigue of filament-wound composites is investigated, and the experimental verifications with the ISAS ring test are obtained for a 90% preloading case. Further discussions concerning the low cycle fatigue phenomenon due to the internal pressure in the rocket motor chamber combustion are made.

1. INTRODUCTION

The filament-wound composites are of high specific strength among the fiber reinforced plastics, and even well comparable with the maraging steel which has the highest one among the metal, as shown in Table 1, and therefore, the very filament-wound composites come to be widely adopted as the aerospace materials giving rise to the weight saving leading to the increase of vehicle performance.

One of their application is the filament-wound rocket motor case subjected to the internal burning pressure, and moreover, the merit of adopting the filament-wound composites can be thoroughly realized in such rocket motor case application. That is, the simultaneous fracture due to the internal pressure in both longitudinal and circumferential directions can be produced by taking the proper winding pattern,

TABLE 1. Comparison of specific strength

Material	Strength σ_b(kg/mm^2)	Density ρ(g/cm^3)	Specific Strength σ_b/ρ(10^6cm)
F.R.P. (Epoxy+Glass Cloth)	38—41	1.80	2.1—2.3
F.R.P. (Polyester+Glass Cloth)	25	1.60	1.55
F.R.P. (F.W.)	46—58	2.00	2.3—2.9
Maraging Steel	200	7.85	2.56
Carbon Steel	60—100	7.85	0.77—1.28
Stainless Steel	150	7.90	1.90
7075—T6 Al Alloy	64	2.80	2.28
2024—T4 Al Alloy	45	2.80	1.61
7%Mn—Ti Alloy	101	4.50	2.24

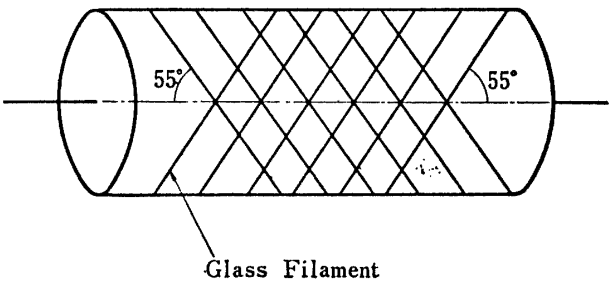

FIG. 1. 55 degree winding pattern sketch

say, with reinforcement twice the circumferential direction winding or with 55 degree inclination with respect to the longitudinal axis, as shown in Fig. 1. This results in the weight saving, which is quite favorable in view-point of increasing vehicle performance. After completion those filament-wound pressure vessels have to be subjected to the proof testing to guarantee the design pressure load in advance of actual mission. Usually rather high internal pressure close to the design pressure, say, the burst pressure, is applied to the vessels, so that the virgin state strength may be well supposed to be reduced due to the repeating cyclic pressure loading causing the low cycle fatigue effects, namely, the fatigue phenomenon due to low cycles with high acting stress.

The low cycle fatigue is a phenomenon in which the virgin state strength is gradually injured by repeating the high stress loading for several cycles as shown in Fig. 2. In Fig. 2, σ_{b1} which is lower than σ_{b0}, is to be obtained at the fracture test after one cycle ($N=1$) of 90% preloading compared with the virgin state strength σ_{b0}. If N, the number of preloading cycles, is increased, the ultimate breaking strength σ_{bi}, of course, will be lowered, and it can be well expected that σ_{bi} maintains the higher value in the 80% preloading case than in the 90% preloading one. Much works have been done concerning the low cycle fatigue of metallic materials heretofore. However, as to the orthotropic materials such as the filament-wound composites quoted here the low cycle fatigue survey is quite unexplored, therefore, the preliminary experimental study on low cycle fatigue of filament-wound composites is presented, as described in what follows.

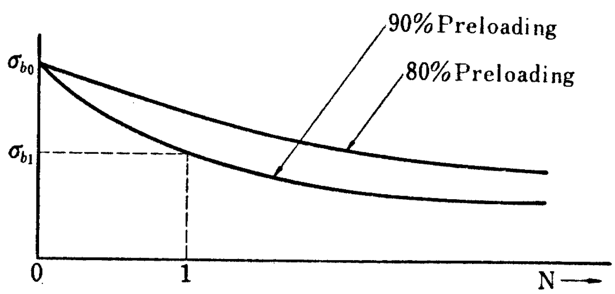

FIG. 2. Typical low cycle fatigue effects illustrated

2. Experimental Procedures

The test specimens are of cylindrical shape, manufactured in the present authors' laboratory by using a McClean-Anderson W-1 filament winding machine with a combination of epoxy resin and E-glass filament. Of course, it is desirable to adopt the internal pressure loading technique, so-called burst test, in order to evaluate the strength degradation due to the low cycle fatigue, however, the ISAS ring test, come of the Institute of Space and Aeronautical Science, University of Tokyo, proposed by the present authors [1] is used instead, because the internal burst pressure test requires (1) lots of specimen stuff quantity, (2) lots of time and labor, and (3) troublesome reinforcement on both ends of specimen cylinder subjected to internal pressure.

FIG. 3. Filament winding machine

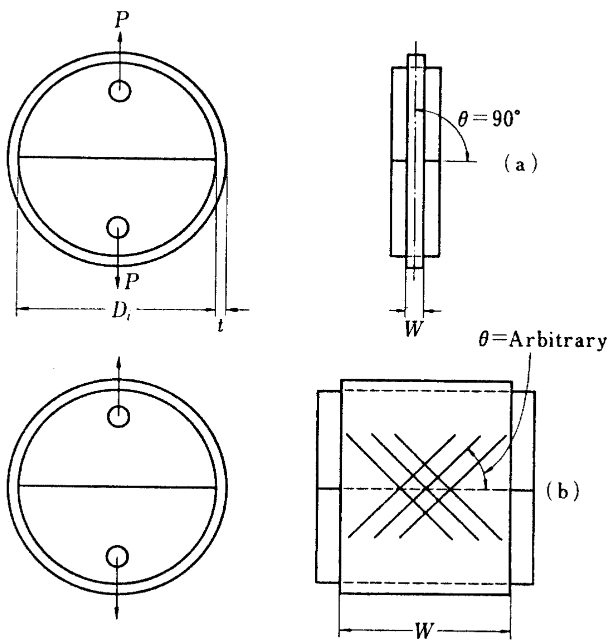

FIG. 4. (a) NOL ring test and (b) ISAS ring test

In the ISAS ring test, as shown in Fig. 4, a ring specimen is subjected to tension via two split-cylinder zigs placed inside to evaluate the circumferential strength. The main differences between the ISAS ring test and the NOL ring test [2], proposed by the U.S. Naval Crdnance Laboratory research staff, are that (1) the ISAS test can be applied to the arbitrary winding angle, while the NOL test can be only applied to the circumferential winding pattern, and (2) the ISAS test has no restriction as to the ring specimen length, its diameter and its thickness. Actually most of the filament-wound composites used nowadays are of arbitrary winding angles, say, 55 degrees, other than the circumferential 90 degrees, say, NOL rings. Therefore the very ISAS ring test might be quite a practical tool to evaluate the actual filament-wound composite strength.

The dimension, the manufacturing condition and the composition of filament-wound specimens used in the present test are shown in Table 2. The winding angle of E-glass filament is 55 degrees with respect to the axial direction. One lot of filament-wound cylinder manufactured by the filament winding machine is about 800 mm in length, and is cut into a number of ring specimens, whose dimensions are as shown in Table 2, by use of a lathe. The measurement of specimen dimensions is done by the vernier calipers for width and by the screw micrometer for thickness. The width is prepared in good accuracy through the mechanical cutting by use of a lathe, while the thickness has some surface waviness since it is only prescribed with the number of winding plies. The mandrel rotation in the curing oven is performed to alleviate this surface waviness.

As already mentioned, the ISAS ring test is taken in stead of the burst pressure test, therefore, the burst pressure is replaced by the circumferential breaking strength of a ring specimen and so the preloading ratio is defined with respect to the circumferential breaking strength. Now, the preloading ratio for the actual rocket motor chamber combustion will be investigated in the following.

TABLE 2. Filament-wound ring specimen used

Composition:				
E-Glass	O.C.F.	R-153-801	×2	30 Ends
Epoxy Resin	Araldite	LY 556	Weight Ratio:	100
Hardener		HT 907		85
Accelerator		DY 063		4
Weight Percentage:				
Glass: 67%		Resin: 33%		
Curing Conditions:				
Cure:	120°C×2 Hours (1 Revolution/second)			
Post Cure:	150°C×3.5 Hours			
Ring Specimen Dimensions:				
Width:	50±0.01 mm			
Inner Diameter:	100 mm			
Thickness:	2.8±0.1 mm			

FIG. 5. Filament-wound specimens: a lot specimen and a ring specimen

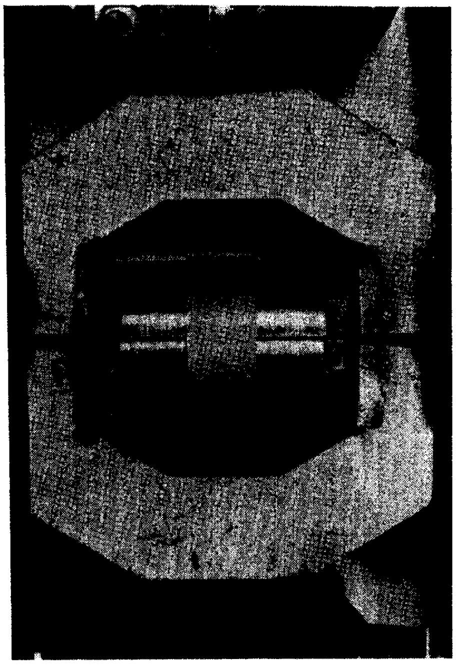

FIG. 6. A ring specimen under ISAS ring test in tension

1. Suppose the burst pressure is 70 Kg/cm^2, and the proof test pressure will be 55 Kg/cm^2, considering 10% fluctuation of internal combustion pressure of 50 kg/cm^2. Then the preloading ratio becomes $100\% \times (55/70) = 78.6\%$.
2. If the burst pressure is designed at 60 Kg/cm^2, while the proof test pressure is also 55 Kg/cm^2, then the preloading ratio will be raised to $100\% \times (55/60) = 91.6\%$.

In the present test, two preloading ratios, i.e., 80% and 90%, are taken. The ISAS ring test is performed by use of a usual tensile tester whose capacity is up to 35 tons. The tensile speed is 1 mm/minute throughout the whole tests.

3. Experimental Results and Discussions

Shown in Figs. 7 and 8 are the experimental results obtained, where σ_b=the ultimate strength in case of low cycle fatigue, and σ_{b0}=the ultimate strength without any load cycling, i.e., the virgin state strength, and N=the number of load cycling. In view of Fig. 7, which is a 80% preloading case, the σ_b/σ_{b0} ratios are about 0.9 or more for $N=1$ and $N=2$, irrespective of data scattering; and finally become 0.85 for $N=10$, showing almost steady tendency. On the contrary, in Fig. 8 for a 90% preloading case, the σ_b/σ_{b0} ratios decrease to 0.8 even for $N=1$; and not a few specimens show the fracture at $N=1$ or $N=2$, although the low cycle fatigue tests of the order of $N=5$ or $N=10$ are attempted.

As seen above, the low cycle fatigue effects might be perceived for a 90% preloading case so far as the present test results are concerned. The values of virgin state strength σ_{b0} keep almost steady for each lot specimen and range from

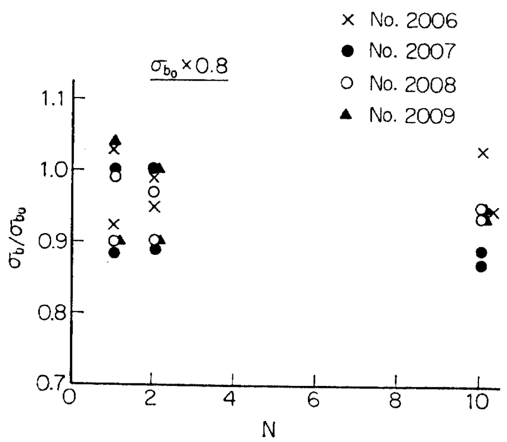

FIG. 7. 80% preloading case

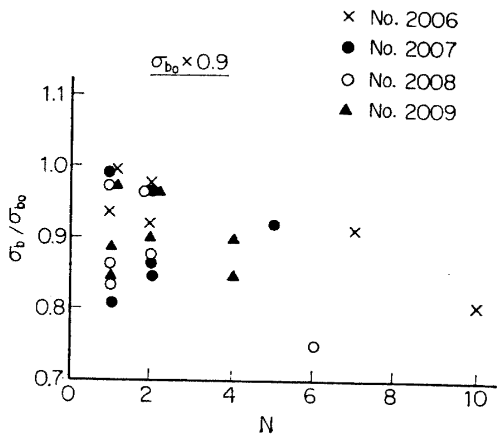

FIG. 8. 90% preloading case

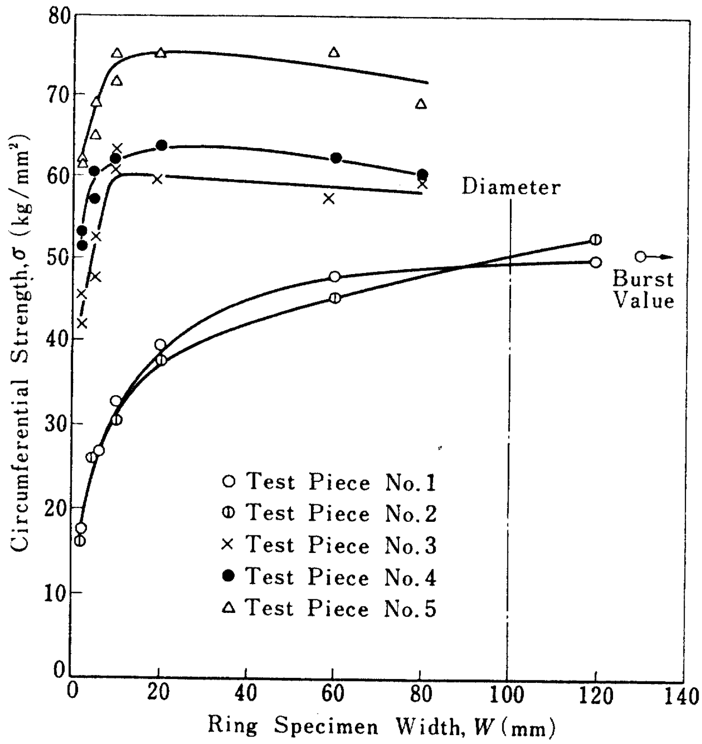

FIG. 9. Ring specimen width effects on circumferential strength: ISAS ring test and burst test

44 Kg/mm² to 47 Kg/mm² for the region where the present tests cover. However, in Figs. 7 and 8, the actual obtained data show rather large scatter for $N=1$. This may indicate that the structure-sensitive property, which is a nature of breaking strength, will tend to be enhanced by the low cycle fatigue phenomenon of repeated load cycling.

In the experimental results previously obtained by the present authors [*1*], as shown in Fig. 9, the hydrostatic burst pressure value could be estimated through the asymptotic tendency where the ring specimen width becomes of the order of diameter or more; although the bi-axial stress state is realized in the hydrostatic burst pressure test, while the uni-axial stress state is achieved in the ISAS ring test. If this relation may be kept valid even with the fatigue test, then the present ISAS ring test results of low cycle fatigue may be applied to evaluate the low cycle fatigue characteristics due to internal pressure; although the ring specimen width used in the present test is rather narrow, however, the evaluation of general tendency of low cycle fatigue may be justified. The reasons of manufacturing such narrow width specimens are due to (1) the necessity to prepare lots of specimens to have much data, and (2) the load limitation imposed upon the tensile tester used, whose capacity is up to 35 tons.

4. Conclusions

The low cycle fatigue phenomenon of filament-wound composites is experimentally verified, especially in case of 90% preloading case so far as the present test data are concerned. Further efforts will be continued.

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[2] N. Fried: "Survey of methods of test for parallel filament reinforced plastics," ASTM Special Technical Publication No. 327, pp. 13–39 (1962).