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Evaluation of Hoop Strength of Filament-Wound Cylinders By Newly-Proposed ISAS Ring Test and Burst Test

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Summary: The ISAS ring test, come of INSTITUTE OF SPACE AND AERONAUTICAL SCIENCE, is newly proposed to have a quick evaluation of hoop strength of filament-wound cylinders with arbitrary winding pattern, and the width variation effects are investigated. The obtained ISAS ring test values are roughly coincident with the usual hydraulic burst hoop strength, in general. The present evaluation of filament-wound cylinders through the ISAS ring test shows: 1) 50 to even 70 Kg/mm² hoop stress, 2) the winding pattern has a close relation with the strength, 3) the 2-to-1 orthogonal winding pattern gives the higher hoop strength than those obtained for the optimum 54.75° by about 22%, and 4) the strength is quite sensitive to the surface treatment of glass-filament.

1. INTRODUCTION

The ISAS ring test is newly proposed to evaluate the hydraulic burst hoop strength, which is important for the analysis of cylinder subjected to internal pressure, easily and quickly [*1*, *2* and *3*], and the characteristics of filament-wound cylinder with arbitrary winding pattern are investigated to be applied to the actual evaluation of several specimens. The well-known NOL ring test confines its evaluation only for the hoop winding pattern, however, the present ISAS ring test features the hoop strength evaluation for *arbitrary* winding pattern of filament-wound cylinders.

As a result of present survey, the close relation between the winding pattern, the surface treatment and the hoop strength is disclosed, and the possibility to produce the high strength filament-wound cylinder equivalent to even 200 Kg/mm² ultra-high strength steel is verified.

2. ISAS RING TEST

The NOL ring test is performed by using two pieces of split-ring and this aims the hoop strength evaluation only [*4*]. Here we are to propose a *new* method, ISAS ring test, in order to measure the circumferential strength of arbitrary winding pattern cylinder by using two split-cylinders.

The hoop stress is expressed as

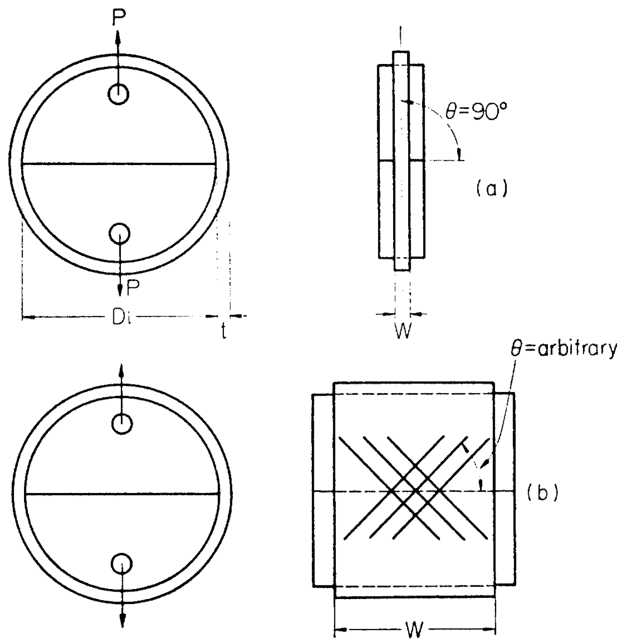

FIG. 1. NOL and ISAS Ring Tests

TABLE 1. Comparison Between NOL and ISAS Ring

	ISAS	NOL		
Winding Angle	0°∼90°	90°		
Specimen Dimensions	t and D_i are arbitrary W is variable	D_i	W	t
		$5\frac{3}{4}''$	$\frac{1}{4}''$	$\frac{1}{8}''$
		9″	$\frac{1}{2}''$	$\frac{1}{8}''\sim\frac{3}{8}''$
		6″	1″	Variable

$$\sigma=\frac{P}{2Wt} \tag{1}$$

The comparison between the NOL ring test and the ISAS ring test is shown in Table 1. In the ISAS ring test, it might be predicted that there are something like the ineffective widths for the end portion, since the very test is applied to the filament-wound cylinder with arbitrary winding pattern. This ineffective width concept is described in what follows.

3. EXISTENCE OF INEFFECTIVE WIDTH AND THEORETICAL ANALYSIS FOR WIDTH VARIATION EFFECTS [1]

Generally the cylindrical specimen used for measurement of mechanical properties is cut away from the original filament-wound cylinder with arbitrary winding pattern, and so the end portions are subjected to the strength-weakening effects due to the cutting-away of filament wound. The very effects have not been considered heretofore.

Now we are going to investigate the very effects, namely the width variation effects on the apparent strength for the ISAS ring test specimen with the assumption of ineffective width at the end portions of a specimen.

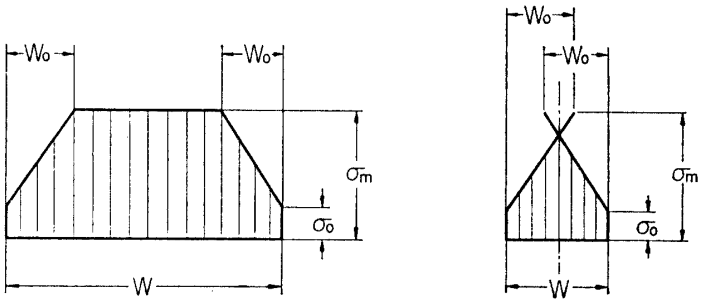

FIG. 2. Ineffective Width Concept at Ends

Assume the strength-width relation shown in Fig. 2: σ_m is for the middle portion intact of filament-cutting effects at ends, σ_0 for both ends, and the strength varies from σ_m to σ_0 for the width W_0. Then we have the followings for the apparent strength σ obtained by Eq. (1).

(1) For $W \geqq 2W_0$

$$\sigma = \frac{1}{W}\left\{W_0 \frac{(\sigma_m + \sigma_0)}{2} \times 2 + \sigma_m (W - 2W_0)\right\}$$

$$= \sigma_m \left\{\left(1 - \frac{W_0}{W}\right) + \frac{\sigma_0}{\sigma_m} \frac{W_0}{W}\right\} \tag{2}$$

Setting the ineffective width as W_i,

$$\sigma \times W = \sigma_m (W - 2W_i)$$

$$W_i = \frac{1}{2} W_0 \left(1 - \frac{\sigma_0}{\sigma_m}\right) \tag{3}$$

(2) For $W \leqq 2W_0$

$$\sigma = \sigma_m \left\{\frac{W}{4W_0} + \left(1 - \frac{W}{4W_0}\right)\frac{\sigma_0}{\sigma_m}\right\} \tag{4}$$

In view of Eqs. (2) and (4), the $\sigma \sim W$ relationship can be obtained provided three constants σ_m, σ_0 and W_0 are given. The results thus obtained and the experimental data are shown in Fig. 3. The theoretical curves fairly agree with the experimental results and the above-mentioned ineffective width concept might be deemed to be supported to meet the experimental verification.

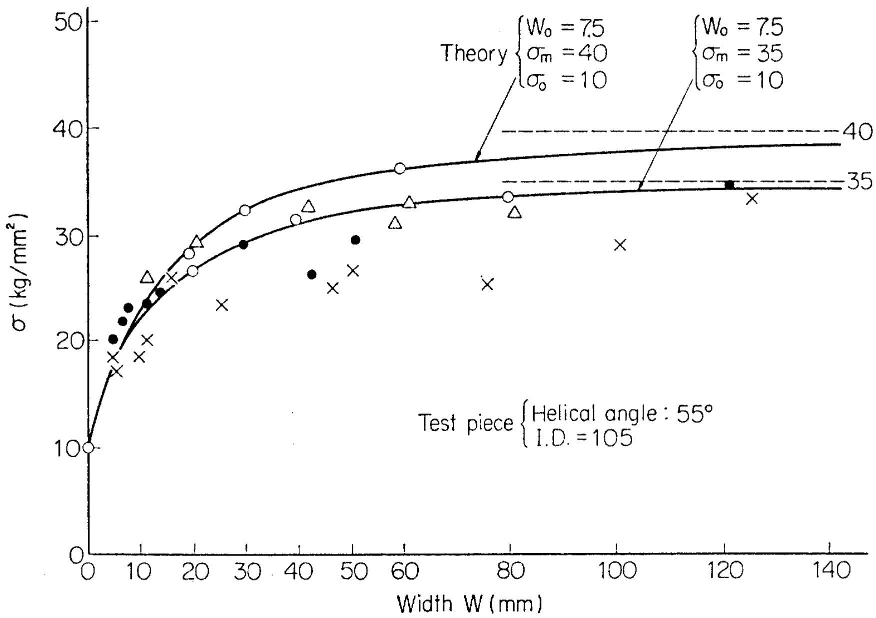

FIG. 3. Strength vs. Width Relations
(—○— Theoretical; ●, △, × Experimental)

4. EVALUATION OF FILAMENT-WOUND CYLINDERS BY ISAS RING TEST AND HYDRAULIC BURST TEST

Since the characteristics of ISAS ring test have now been clarified, as mentioned above, we are to perform the evaluation of filament-wound cylinders with arbitrary winding pattern by altering the material parameters systematically through the ISAS ring test, and to try to compare with those of hydraulic burst test. The test specimens used in the present work are shown in Table 2. These specimens are same in dimensions, but their constituents are different. In Table 2, R-123-888 means roving of 12 ends with silane finishes for polyester use of Asahi Fiber Glass make, while -801 is for epoxy use of Owens-Corning Fiberglass make. The resin used is of the same epoxy family and the curing conditions are same for all specimens. For the winding pattern, Nos. 1 and 2 specimens are of 55° and they have no axial roving ($\theta=0°$). That is, they are almost equivalent to the optimum specimens of 2-to-1 principal stress distribution resulting in $\theta=54.75°$ derived from the netting analysis. On the other hand, Nos. 3 to 5 specimens have such a combined pattern of 2 rovings for $\theta=86°$ and 1 roving for $\theta=0°$. The rovings for Nos. 1 to 3 are common, and the treatment for Nos. 4 and 5 is different.

The ISAS ring test is performed by using the above-mentioned cylindrical specimens, whose width ranges from 2 to 120 mm. The test specimens after the ISAS ring test are shown in Fig. 4. The obtained results are also shown in Fig. 5.

Fig. 5 shows a conspicuous dependence of $\sigma \sim W$ relation upon the winding pattern. In Nos. 1 and 2 specimens stress is very small for small width, (σ is minimum at $W=2$ mm.), and increases with the increase of width W. On the contrary the stress level is high even for the small width of 2 mm. in case of Nos. 3 to 5 specimens, and there exists the maximum for $W=10$ to 20 mm., say, $W=9.4$ mm. for

TABLE 2. Parameters and Strength of Filament-Wound Cylinders

Test Specimen No.*	1	2	3	4	5
Glass Tape	None	ATE-111002	Do.	Do.	Do.
Roving	R123-888	R123-888	R123-888	R153-801	R123-801
Winding Angle	55°	55°	86°	86°	86°
Glass Content (in weight) Axial Roving / Helical Roving	0/1	0/1	1/2	1/2	1/2
Mean (%)	74	74	74	74	74
Resin	Epon 828 Epon 815 AGE K61-B	Do.	Do.	Do.	Do.
ISAS Ring Test** Value (Kg/mm²)	16.1 ↓ 49.4	13.2 ↓ 52.0	41.9 ↓ 63.3	51.1 ↓ 64.0	61.9 ↓ 76.2
Burst Hoop Stress (Kg/mm²)	50				

* Inner diameter 105mm, thickness 2.5mm.
** ISAS ring test width 2–120mm.

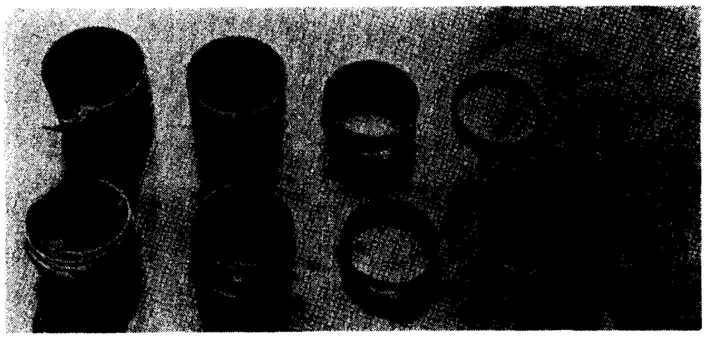

FIG. 4. ISAS Ring Test Specimens tested

No. 3, $W=19.8$ mm. for No. 4 and $W=19.9$ mm. for No. 5, and then the stress σ decreases slightly with the increase of width W.

That is to say, Nos. 3 to 5 specimens having $\theta=0°$ and $\theta=86°$ winding angles keep the fairly high stresses for low width W and also converge at higher stresses compared with Nos. 1 and 2 specimens, both with $\theta=55°$, even with the same glass content and the same resin used. For example, when we compare No. 3 specimen with No. 2 one, the former has approximately 22% higher strength. In comparison of Nos. 4 and 5, the specimen with 12 ends is stronger than that with 15 ends. Also No. 5 specimen with the glass fiber treated so as to fit the epoxy resin is superior to No. 3 specimen whose glass fiber is treated for polyester resin in the stress level.

On the other hand, the hydraulic burst test is performed in the usual way. The

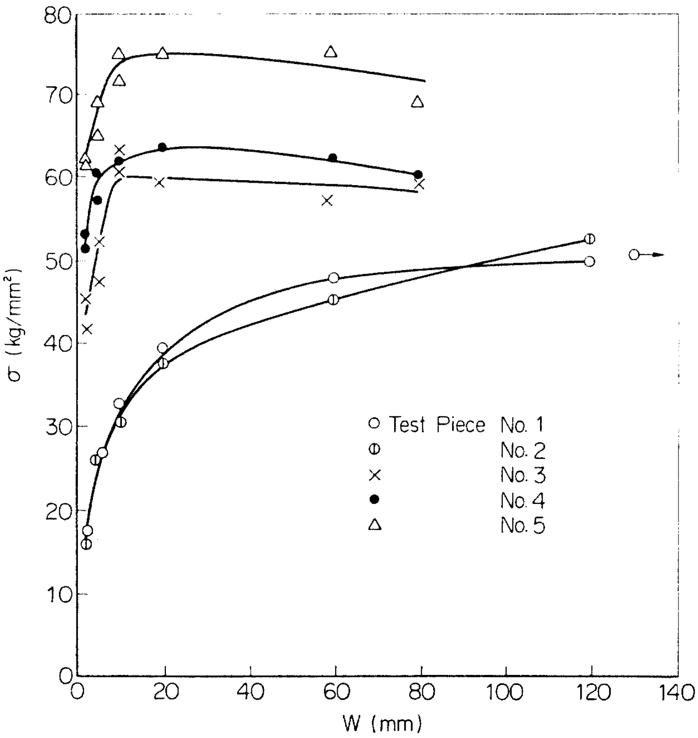

FIG. 5. Evaluation of Hoop Strength of Filament-Wound Cylinders through ISAS Ring Test and Burst Test

hydraulic pressure pump is a type of three-plunger pump with a capacity up to 1000 atmospheric pressure by use of 3 HP drive. The hydraulic oil used is of highly viscous one such as Idemitsu's Daphne Hydraulic Oil No. 65: e.g. 110.7 centistokes at room temperature. The whole set-up is shown in Fig. 6.

In Fig. 5 the stress value corresponding to infinite width in the ISAS ring test and the usual hydraulic burst test value in the circumferential direction almost coincide with each other for No. 1 specimen. However, in cases of axial fracture or existence of leakage of hydraulic oil, in the burst test, the ISAS ring test value and the usual hydraulic burst test value do not always agree with each other.

As a possibility to evaluate the filament-wound material as the rocket chamber component, here comes a comparison with 200 Kg/mm^2 ultra-high-strength steel in term of strength-weight ratio. Since the density of the present filament-wound cylinder is 1.9 to 2.0 g/cm^3 while that of steel is 7.8 g/cm^3, the favorite stress value for filament-wound cylinder is $\sigma=50$ Kg/mm^2 or more. In the above-mentioned ISAS ring test values, we might foresee this criterion.

5. CONCLUSIONS

(1) The ISAS ring test is *newly proposed* to evaluate quickly the hoop strength of filament-wound cylinder with arbitrary winding pattern and the associated characteristics are surveyed. The ISAS ring test value σ varies with the specimen width W and well agrees with the calculated value based on the ineffective width concept.

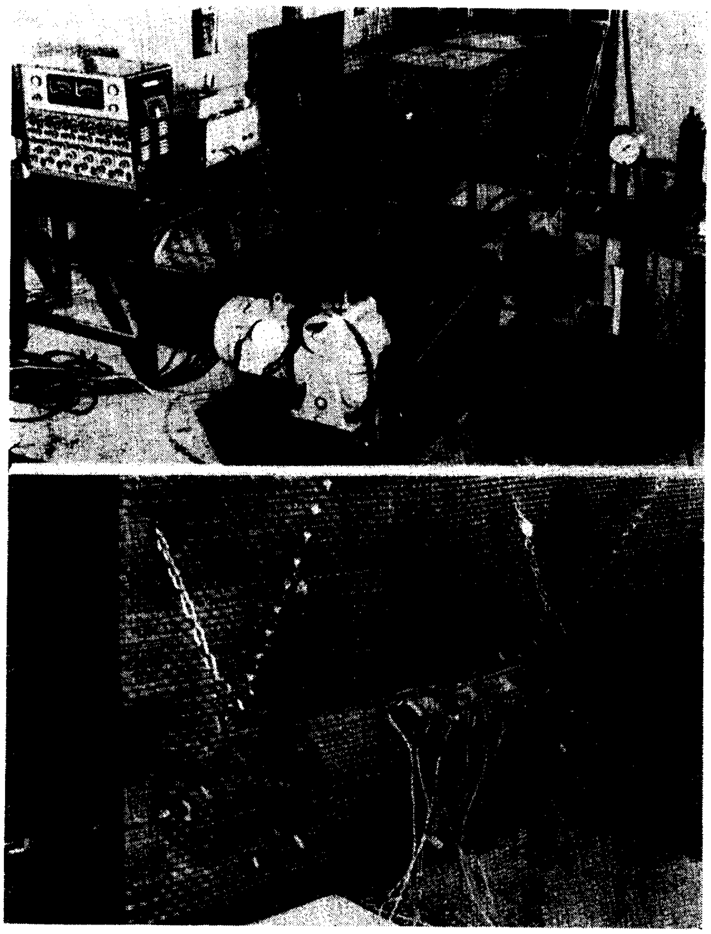

FIG. 6. A Whole Set-Up and Burst Test Installation

(2) $\sigma \sim W$ relation is conspicuously dependent on the winding angle θ of filament-wound cylinder. At $\theta=55°$ the stress σ remarkably decreases to approach the bonding strength for small width, but for $\theta=86°$ and $0°$ the width variation effects are small and the width showing the maximum is different respectively.

(3) The circumferential strength of filament-wound cylinder with different winding patterns and with different roving treatments is evaluated through the ISAS ring test. In case the test specimens are manufactured by altering the winding angles only, the present results show that 2-to-1 orthogonally filament-wound cylinder presents the higher strength compared with the $\theta=55°$ specimen by 22%. This may justify to judge the netting analysis as only a rough evaluation technique.

(4) The roving treatment effects on the strength are considerably high.

(5) The hydraulic burst test value might be roughly estimated from the ISAS ring test value. Exceptions are for the cases of axial fracture or leaking oil.

(6) The ISAS ring test might be adopted as a method to evaluate the circumferential burst strength of filament-wound cylinder quickly.

(7) As for the strength-weight ratio, it is found that the equivalent filament-wound cylinder stronger than 200 Kg/mm^2 ultra-high-strength steel can be obtained in the circumferential strength.

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[3] Kozo Kawata, Shinji Fukui, Akira Kobayashi and Shozo Hashimoto: Preprint, 9th Symposium on Space Technology, Japan Society for Aeronautical and Space Sciences, January (1966) p. 121–.
[4] cf. "Symposium on Standards for Filament-Wound Reinforced Plastics," ASTM Special Technical Publication No. 327 (1962) p. 13–.