SHELL STABILITY PROBLEMS IN THE DESIGN OF LARGE SPACE VEHICLE BOOSTERS

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SUMMARY

A discussion of the current methods used to design the Saturn type booster shell structures is presented covering bending and axial compression, with and without internal pressure. Problem areas encountered in the application of available shell stability data to these designs are delineated; as well as, suggested areas of future research for shell configurations anticipated in advanced designs.

INTRODUCTION

The pressurized and unpressurized cylindrical shell portions of the Saturn Boosters have changed considerably in configuration as payload requirements became more stringent. Various cylindrical cross-sections were investigated to optimize structural designs, with corrugated skins in the unpressurized areas and "tee" stiffened tank walls indicating minimum weight structures. Additional weight savings might be realized with the use of multicell tanks for large diameter Boosters.

SYMBOLS

C_f	frame stiffness coefficient
D	shell diameter
E	Young's modulus of elasticity
F_c	ultimate compressive stress
I	area moment of inertia
K	shell buckling constant

L	shell length (between transverse frames)
q	axial load per unit of circumference
R	shell radius
t	monocoque shell thickness
$\bar{t}$	equivalent weight monocoque shell thickness
t*	equivalent strength monocoque shell thickness

DEVELOPMENT OF SHELL CONFIGURATIONS FOR THE SATURN C-1 BOOSTERS

Pressurized Areas

Pressurized shell designs for the Saturn C-1 Boosters were based on water hydrostatic test pressure requirements. The particular aluminum selected, 5456-H343, is a work hardening alloy and develops excellent mechanical properties after pressure cycling. Weld areas in the tanks have final tensile yield strengths as high as 90% of the parent material. Since the payload requirements were not critical for these Boosters, the test pressures shown in table 1 were acceptable, especially considering the resulting high structural integrity. Buckling instability of the monocoque shells, under combined bending and axial compression, is not critical compared to the hoop tension stresses.

Unpressurized Areas

The unpressurized cylindrical portions of the Saturn C-1 Boosters were designed more efficiently than the tanks although subsequent load reductions have increased their safety margins. The forward and aft skirts of the 70 and 105 inch diameter tanks are semi-monocoque shells except for short intermediate modified monocoque sections (as defined in reference 1) attaching these skirts to the tank walls. The most critical areas of these skirts, in each case, are the modified monocoque portions. The classical buckling equation, $F_c = KEt/R$, with a K value = 0.30, has been used to establish these shell thicknesses and compares favorably with the structural test results. The R/t range of from 140 to 390 as shown in table 1, falls within the limits of the application of the 0.30 constant suggested in reference 2.

ADVANCED SATURN C-5 BOOSTER SHELLS

Pressurized Areas

Development of the pressurized portions of the advanced Saturn C-5 Booster followed a completely different design philosophy from the early Saturn vehicles. Stringent requirements for maximum payload capacity, for both lunar and earth orbital rendezvous, dictated a refined approach to shell design. Initially, preliminary design concepts depicted an integrally milled 45° waffle pattern for the skins with a full length cruciform anti-slosh baffle dividing the tanks into four quarters. Further shell optimization studies, coupled with the possibility of a redesign of the baffles to annular rings, indicated a substantial structural weight reduction by incorporating integrally milled longitudinal "tee" stringers in place of the 45° waffle. A comparison of these shell designs are shown in tables 2 and 3. The values presented are for the actual C-5 design pressures, bending moments and longitudinal forces, within the plate thickness limitations for the 2219-T87 aluminum sheet sizes required. Since the skin thickness for the "tee" stiffened design is significantly influenced by pressure stresses, additional shell weights were investigated for both waffle and "tee" stiffened segments considering pressure increases. The "tee" stiffened cross sections were sized, based on optimization of skin to stiffener area ratios, with the skin fully effective in compression (no local buckling). The waffle sections were developed through application of the work accomplished by Seide (ref. 4).

An interesting phenomena, concerning the annular rings, developed in the optimization studies. To suppress sloshing within acceptable limits, the ring baffles required a depth of approximately 30 inches, several times that necessary to provide column stability for the stiffened shell. In addition, longitudinal structural ties between rings on the inner flanges were required to support the normal forces on the ring webs due to sloshing pressures. This configuration of deep rings, with the inner flanges supported against lateral instability, permitted reduction of the $\bar{t}$ contribution by the rings. A standard ring section, required to stabilize the shell, was generated using the following equation from reference 3:

$$EI = \frac{C_f q \pi D^4}{4L} .$$

This ring would add .078 inches to the skin-stringer $\bar{t}$, compared to .048 inches for the deep anti-slosh rings. Sketches of the typical C-5 tank structures are shown in figures 1 and 2.

Unpressurized Areas

Cylindrical skirt areas of the Advanced Saturn without internal pressure have been designed based on minimum weight criteria from reference 3 and are of fabricated (riveted) 7075-T6 aluminum sheet and stringer combinations, with the exception of the inter-tank shell. This section attaches the fuel tank to the oxidizer tank and is composed of 7075-T6 corrugated sheet with transverse stabilizing ring frames. In contrast with the C-1 Boosters, the monocoque skirt areas are restricted to negligibly short segments which exist only at bulkhead to shell junctures. Weights of the skirts are as follows:

SEGMENT	WEIGHT PER INCH
Forward Skirt	40
Intertank Skirt	35
Aft Skirt	48

Manufacturing and access requirements preclude the use of corrugated skins for all of the skirts, although this cross section is structurally the more efficient.

FUTURE RESEARCH

Monocoque Buckling Allowables

Tables 2 and 3 present weights for waffle pattern designs based on three sources for buckling allowables (references 5 and 6). The basic waffle dimensions are established from reference 4, but when the t^* value is selected from each buckling reference, different shell weights are developed. For Boosters in the size range of the Advanced Saturn and Nova, these differences amount to thousands of pounds of structural weight. Extensive research should be conducted to establish uniform, generally accepted cylinder buckling curves.

Multicell Designs

An area which shows extreme promise in future space vehicle designs is the multicell configuration. Extensive studies accomplished at Marshall Space Flight Center on cylindrical versus multicell tanks and total Booster structures indicate weight savings for the multicell, which increase in percentage with larger vehicles. Figure 3 presents the results of these studies ranging from a 360 inch diameter Booster to 600 inches. The typical cross section, shown in figure 4, does not present unusual structural problems except in the transition areas between the shell walls and bulkheads. These areas are geometrically difficult to define and defy presently available methods of analysis for local shell stability.

CONCLUDING REMARKS

Minimum weight designs for large space vehicle Booster cylindrical shells require comprehensive studies to establish each individual configuration. Shell skins with integral milled stiffeners appear especially attractive for propellant tanks. The selection of mill patterns such as 45° waffle or longitudinal "tees" depends on loads and other design criteria peculiar to that tank. Uniformly accepted and proven cylinder buckling curves would permit further refinement of shell designs. For future Boosters, research is needed on multicell designs and their stability problems.

REFERENCES

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4. Seide, P.: The Effectiveness of Integral Waffle-Like Stiffening for Long, Thin, Circular Cylinders Under Axial Compression, Part II, Mechanically Milled Sheet. Ramo-Wooldridge Corp. Report AM-6-10, STL Report GM-TR-38, June 15, 1956.

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TABLE 1.- PRESSURE, SHELL THICKNESS, AND R/t VALUES FOR SATURN C-1 TANKS

BOOSTER	TANK	FLIGHT DESIGN PRESSURE	HYDROSTATIC TEST PRESSURE	PRESSURIZED SHELL THICKNESS	UNPRESSURIZED SHELLS			
					THICKNESS		R/t	
					FORWARD	AFT	FORWARD	AFT
		(psig)	(psig)	(inches)	(inches)	(inches)		
SATURN C-1, BLOCK I	70" FUEL	41	53	.090	.090	.100	389	350
	70" LOX	78	92	.119	.190	.190	184	184
	105" LOX	78	92	.250	.305	.375	172	140
SATURN C-1, BLOCK II	70" FUEL	40	51	.081	.090	.100	389	350
	70" LOX	79	109	.131	.249	.249	141	141
	105" LOX	79	109	.173	.305	.305	172	172

TABLE 2.- COMPARISON OF WAFFLE AND "TEE" STIFFENED DESIGNS FOR C-5 BOOSTER OXIDIZER TANKS

% DESIGN PRESSURE	NO. OF RING FRAMES	45° WAFFLE PATTERN									PRESENT C-5 "TEE" STIFFENED SHELL	
		BUCKLING ALLOWABLE PER REFERENCE 5			BUCKLING ALLOWABLE PER REFERENCE 6 (99% Probability)			BUCKLING ALLOWABLE PER REFERENCE 6 (90% Probability)				
		t*	$\bar{t}$	TOTAL SHELL WEIGHT (1)	t*	$\bar{t}$	TOTAL SHELL WEIGHT	t*	$\bar{t}$	TOTAL SHELL WEIGHT	$\bar{t}$	TOTAL SHELL WEIGHT
		inches	inches	lbs.	inches	inches	lbs.	inches	inches	lbs.	inches	lbs.
100	2	.750	.467	28,850	.862	.535	33,090	.728	.453	28,040		
	3	.740	.444	27,740	.793	.479	29,880	.692	.421	26,230		
	4	.740	.446	29,380	.774	.465	29,280	.674	.409	25,860		
	12	.690	.536	35,540	.656	.386	26,840	.584	.359	24,800	.383	26,740
150	2	.740	.623	38,400	.723	.608	37,530	.604	.536	33,120		
	3	.740	.591	36,860	.627	.514	32,050	.558	.501	31,260		
	4	.720	.600	37,470	.605	.504	31,630	.551	.491	30,870		
	12	.697	.539	35,740	.460	.421	28,540	.460	.414	28,140	.416	28,800

(1) Total Shell Weights Include Required Ring Frames.
$\bar{t}$ Values Do Not Include Frames.

TABLE 3.- COMPARISON OF WAFFLE AND "TEE" STIFFENED DESIGNS FOR C-5 BOOSTER FUEL TANKS

% DESIGN PRESSURE	NO. OF RING FRAMES	45% WAFFLE PATTERN									PRESENT C-5 "TEE" STIFFENED SHELL	
		BUCKLING ALLOWABLE PER REFERENCE 5		(1)	BUCKLING ALLOWABLE PER REFERENCE 6 (99% Probability)			BUCKLING ALLOWABLE PER REFERENCE 6 (90% Probability)				
		t^*	$\bar{t}$	TOTAL SHELL WEIGHT	t^*	$\bar{t}$	TOTAL SHELL WEIGHT	t^*	$\bar{t}$	TOTAL SHELL WEIGHT	$\bar{t}$	TOTAL SHELL WEIGHT
		inches	inches	lbs.	inches	inches	lbs.	inches	inches	lbs.	inches	lbs.
100	2	.920	.543	16,500	.901	.533	16,170	.787	.430	13,180		
	3	.860	.512	15,800	.828	.485	15,000	.742	.393	12,300		
	4	.820	.469	14,770	.795	.457	14,430	.706	.371	11,910		
	12	.750	.414	14,160	.717	.382	13,240	.648	.326	11,160	.274	9,500
150	2	.920	.543	16,490	.901	.532	16,160	.787	.475	14,530		
	3	.865	.501	15,530	.828	.480	14,890	.742	.436	13,590		
	4	.820	.476	15,060	.795	.461	14,580	.706	.412	13,130		
	12	.755	.441	14,960	.719	.448	15,160	.658	.363	12,620	.356	11,900

(1) Total Shell Weights Include Required Ring Frames.
$\bar{t}$ Values Do Not Include Frames.

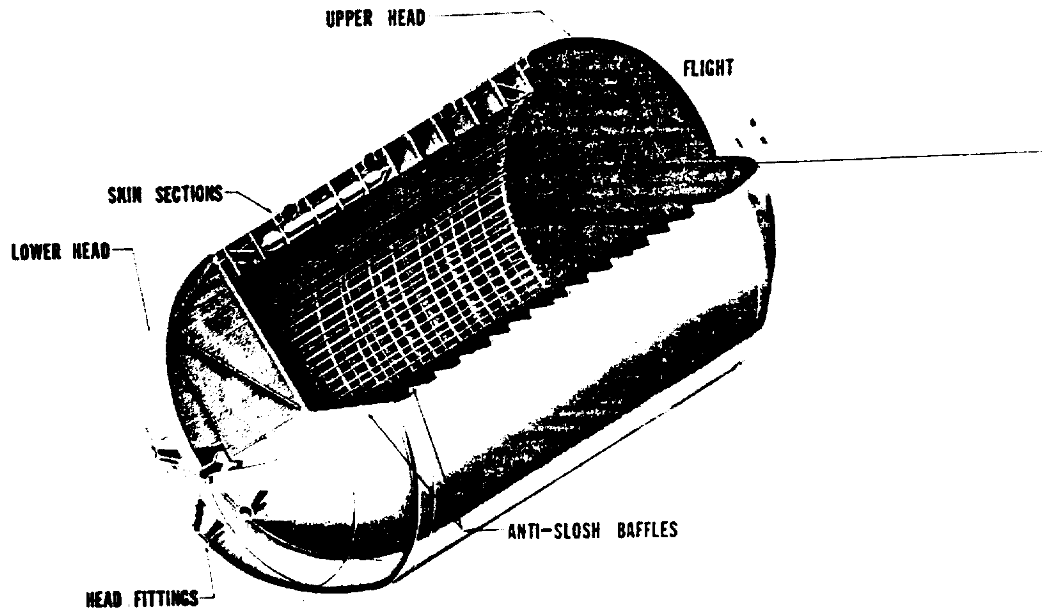

Figure 1.- Typical tank assembly for Advanced Saturn C-5 Booster.

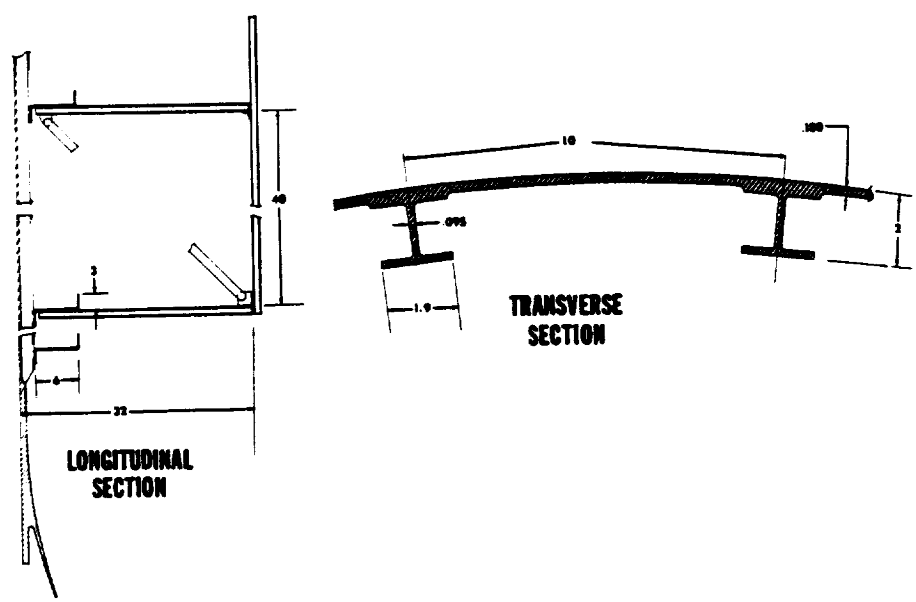

Figure 2.- Cross-sections of the C-5 Booster tank assembly.

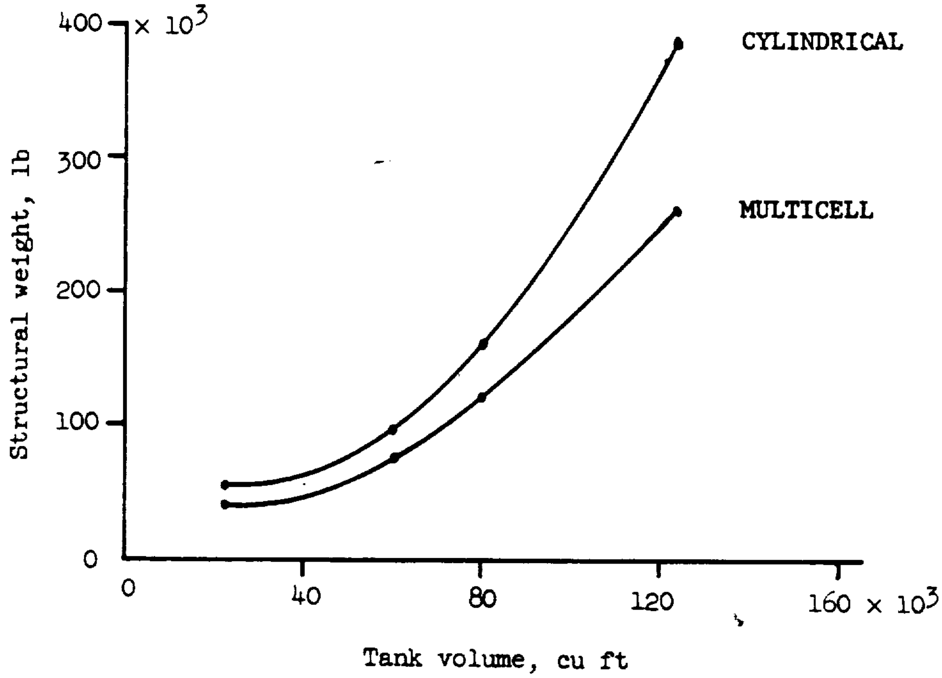

Figure 3.- Multicell versus cylindrical tank weights.

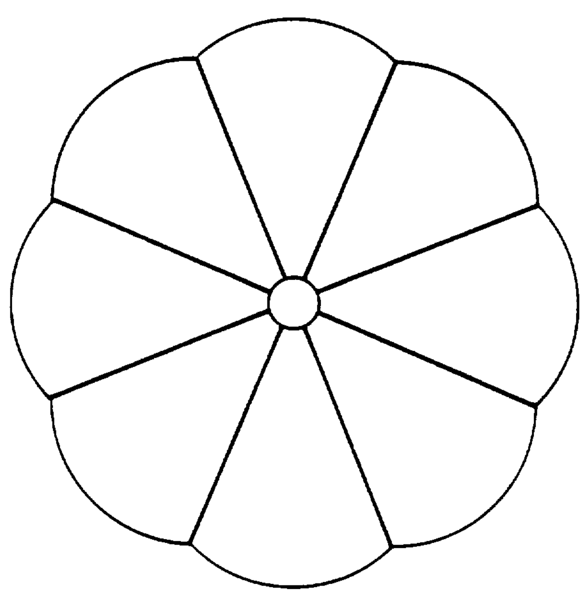

Figure 4.- Typical division of tank into cells.