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EXPERIMENTAL STRENGTH ANALYSIS OF VARIABLE STIFFNESS WAFFEL-GRID CYLINDRICAL COMPARTMENTS. PART 1. Experimental Procedure

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This paper proposes a method of the experimental study of the static stress-strain state (SSS) of the variable stiffness tail section of a launch vehicle (LV). The tail section consists of a body and a support ring. The body is a welded structure made up of two waffel-grid shells and two end frames. On the upper and lower end frames, there are bolt holes and guide pins for mating the frames to the fuel tank and support ring, respectively. The shells are made of AMg6NPP, and the frames, of AMg6M aluminum alloys, respectively. The tail section body is loaded through the four support brackets of the power ring, which is part of the test assembly. The article summarizes the results of the experimental analysis of the static SSS of an optimized tail section body under the conditions of loading close to realistic ones. As a result of the experimental research, we achieved the following goals: obtained data on the tail section body strength taking into account the design features, manufacturing technology, and mechanical characteristics of the material; tested theoretical methods for calculating structural strength; determined stresses in the places where they can most reliably be found only experimentally; identified structural sections that have enough strength to be subsequently decreased. Different-size static force factors were applied to the tail section. The static loading of the structure was performed in stages without dynamic components. When the tail section body was tested, measurements of the displacements and deformations were made. The deformations were measured for three different values of the shell longitudinal coordinate and at various points along the circumferential coordinate of the structure. At each point, two rosette strain gauges were glued. One strain gauge was glued in the longitudinal, and the other, in the circumferential direction. With the help of the proposed method, we investigated SSS of the tail section that was designed by the Yuzhnoye Design Bureau.

Keywords: *tail section, waffle-grid cylindrical shell, strain gauges, load.*

Introduction

The system design of optimal mass LV compartments includes both an experimental and theoretical analysis of their strength. Based on the computational analysis, which is not the subject of this article, the strength of LV waffle-grid cylindrical compartments was investigated, and the optimal parameters of the reinforced structures with plating were selected. The waffle-grid compartment is a cylindrical shell, which consists of two shells. They are reinforced from inside by stringers and frames, evenly spaced along the circumferential and longitudinal coordinates, forming the so-called primary structure. The main feature of the waffle-grid compartment is that the case, stringers and frames have variable thicknesses, and the compartment has a variable stiffness. Based on these computational studies, an optimal cylindrical LV compartment was designed and manufactured. The variability in thickness allows us to strengthen the structure in the more loaded areas of the tail section. This article presents the results of the experimental analysis of the stress-strain state (SSS) of the LV variable stiffness compartment.

Waffle-grid shells are the carrier elements of LVs [1]. They are used for manufacturing various LV elements: fairings, tanks, tail sections. These cylindrical shells are the main structural elements for LV hulls. Therefore, a lot of effort has been made to study their dynamics and strength. A detailed review of the literature on these issues is presented in monograph [2]. In [3], the static stability of shell structures is investigated. In [4], SSS of shells are investigated by applying asymptotic procedures. In monograph [5], in order to calculate the strength of waffle-grid shells, simple, empirical relationships are presented. In [6, 7], the theoretical foundations of the finite element calculations of the shells are described. In article [8], a method and a program for designing a LV waffle-grid tank are proposed, with the shell losing stability under plastic deformations. In [9], the design of LV head fairings is considered. In [10], plastic deformations are taken into account in simulating the strength of LV compartments.

This article proposes a method of experimental study of the strength characteristics of the LV lightweight tail section. Based on this technique, the strength characteristics of the designed variable stiffness tail section are experimentally investigated.

Formulating the Problem and Methods of Experimental Research

The object of this research is the tail section body having a thin-walled waffle-grid structure, which is loaded by the weight of the fueled LV resting on the launch pad. Since LV is at rest on the launch pad, the article deals with the static SSS.

A sketch illustrating the experiment for analyzing the static strength of the tail section is shown in Fig.1. The tail compartment consists of a body (1) and a support ring (6). The body is a welded structure made up of two waffle-grid shells and two end frames 2 and 5. The upper and lower end frames have holes for bolts and guide pins for mating to the fuel tank and the supporting ring, respectively. The shells are made of AMg6NPP, and the frames, of AMg6M aluminum alloys, respectively.

On the tail section body, there are openings for locating filling pipelines, pipelines for supplying thermostatic air and compressed gases, as well as hatches for access to engines and filling lines, and a hatch for thermostatic air venting. The tail section body is loaded through the four support brackets of the power ring that is part of the test assembly (Fig. 1).

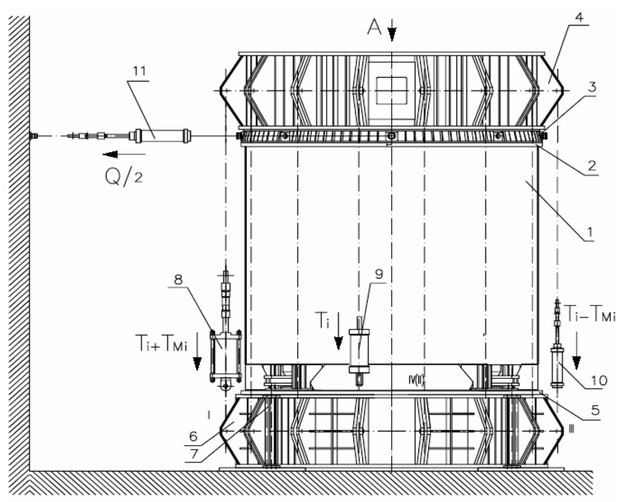

Fig.1. Tail section installation scheme for an experimental analysis

Fig. 2 presents the reinforcement scheme of the LV tail section. The solid horizontal and vertical lines show stringers and frames that form the reinforcement cells. Such cells have a constant size of 136×137 mm. Near the openings and hatches, there are reinforcement ribs for smoothing stress jumps. The ribs are marked by the sign (*X*). In order to ensure reinforcement, we increase the thickness of the skin up to 9.5 mm. In the upper shell of the tail section, the thickness of the reinforcement ribs is 6 mm, and in the lower side, 8.5 mm. The ribs of the upper and lower shells have different thicknesses. The thickness of the upper shell casing, marked by the sign (*Z*), is 4 mm, and in the unmarked cells the shell thickness is 2.7 mm. The thickness of the bottom shell in the area marked by the sign (*Y*) is 5 mm, and in the unmarked area, 2.7 mm. As follows from Fig. 2, such a reinforcement of the tail section is made near possible stress concentrators, with the reinforcement ribs smoothing out the SSS jumps along the tail section.

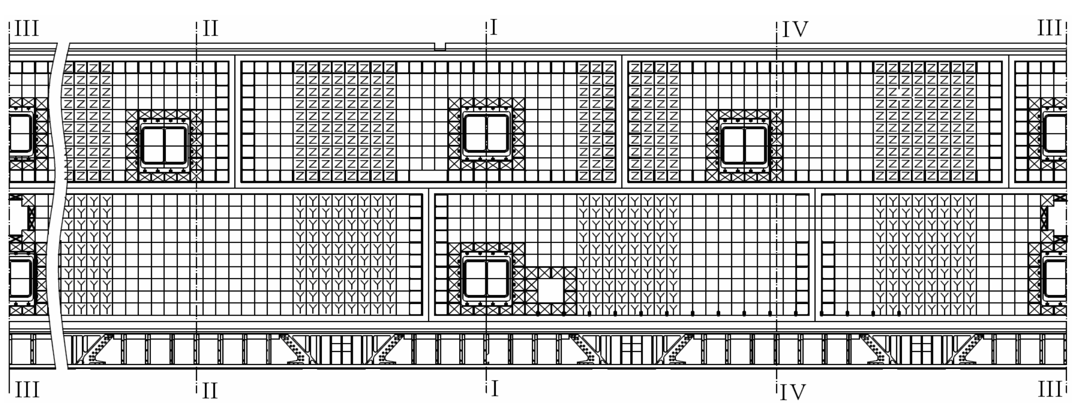

Fig.2. The inner side of the tail section waffle-grid cylindrical shell

The article summarizes the results of the experimental analysis of the static SSS of an optimized tail section body under the conditions of loading close to realistic ones. As a result of the experimental research, we achieved the following goals:

– obtained data on the tail section body strength, taking into account the design features, manufacturing; technology, and mechanical characteristics of the material;

– tested theoretical methods for calculating structural strength;

– determined stresses in the places where they can most reliably be found only experimentally;

– identified structural sections that have enough strength to be subsequently decreased.

The main task was to conduct the tests without destruction and the appearance of plastic deformations in the load-bearing elements of the body, to further use the tail section as the LV component.

The pattern of testing the tail section under the action of the loads that simulate static forces from a fully fueled RL on the launch pad is shown in Fig. 3. The tail section is subjected to different-size static force factors, whose values are given in Table. 1, 2. The static loading of the structure is performed in stages without dynamic components. Note that the force T, presented in Tables 1 and 2, includes the weight of the upper tooling. Stage 4, described in the Tables, corresponds to the operational loads acting on the tail section. Stage 5 and 6 correspond to the calculated values of the loads. The safety factor was taken as *f*=1.3 and *f*=1.5, respectively.

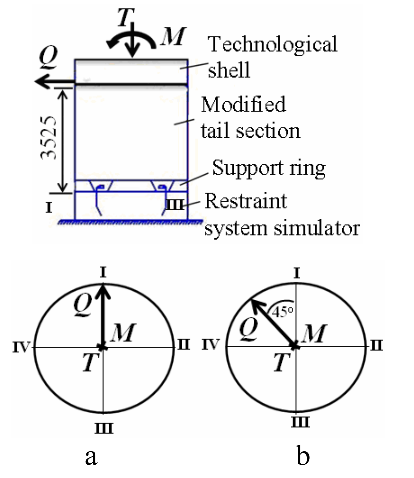

Fig. 3. Tail section loading scheme modeling a fueled LV on the launch pad:
a – first case of loading;
b – second case of loading

Table 1. Loads acting on the tail section of the fueled LV without transporter-erector support

Force factors	Loading stages				
	1	2	3	4	5
T (tf)	74.53	147,18	220.97	294.00	381.30
M (tf·m)	31.83	68,06	102.00	135.81	176.65
Q (tf)	1.80	3.60	5.40	7.20	9.40

Table 2. Loads acting on the tail section of the fueled LV with transporter-erector support

Force factors	Loading stages				
	1	2	3	4	5
T (tf)	87.39	175.58	262.38	350.11	454.29
M (tf·m)	27.13	55.02	82.01	109.09	141.55
Q (tf)	1.60	3.20	4.80	6.53	8.50

When the tail section body was tested, measurements of displacements and deformations were made. The layout of the gauges is shown in Fig. 4. The places where the deformations were measured are marked by an inverted "T". So, the deformations were measured for three different values of the longitudinal coordinate of the shell and at various points along the circumferential coordinate of the structure. At each point (Fig. 4), two rosette strain gauges were glued. One strain gauge was glued in the longitudinal, and the other, in the circumferential direction.

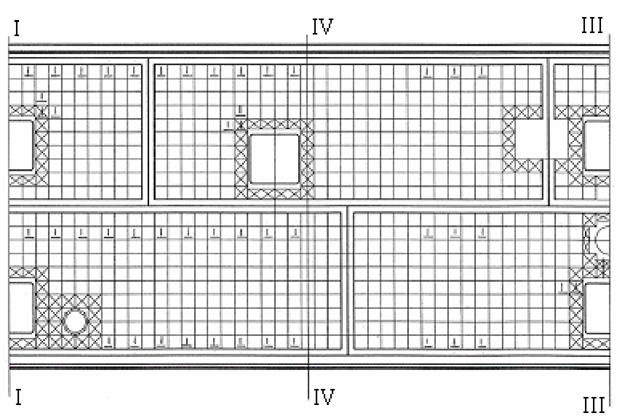

Fig. 4. Layout of strain gauges

Fig.1. shows a sketch of the tail section. The tail section and the support ring are installed and fixed by a restraint system on a technological ring. The tail section upper end had a technological ring, an adapter ring and a load-carrying shell attached.

Now we will consider how the power loading was implemented. The scheme of loading the power factors *T* and *Q* is shown in Fig. 1. The axial compressive load T was implemented in the form of 16 parallel T_i forces transmitted to the assembly through the upper and lower technological shells. When loading the structure, we took into account the force value *T* as including the weight *G*=19.11 tf of the technological tooling.

The bending moment was created by a pair of forces with a shoulder *L*=4.433 m applied to the tail section upper end. We describe the way to create this bending moment. Fig. 1 shows that the generated compressive forces on the opposite sides of the tail section are T_i+T_{Mi} and T_i-T_{Mi}. Due to such magnitudes of the loads applied, a bending moment will occur. The transverse force Q was applied to the adapter ring that is attached to the tail section upper end.

The loading of the tail section with *T, Q* forces was carried out in stages according to Tables 1 and 2. The stages presented in the tables correspond to the first case of loading (Fig. 3). For each case of loading, one test was carried. In this case, the concentrated forces lie in the plane I – III.

When the 4th stage of loading was reached, a retention interval of 10 minutes followed. When the values of static loads of the 5th stage (Tables 1 and 2) were reached, the loading was stopped and the loads were reset to zero. At all stages of loading, displacements and deformations were measured.

After the above described tests had been conducted, the second case of loading was performed. This case is also shown in Fig.3. In this case, all the force factors are applied at an angle of 45° to the plane I – III. The magnitudes of the loads applied are presented in Tables 3 and 4. The shell under study is rather expensive. Therefore, we conducted all the tests using the same sample. The fact is that, as the experiments show, the shell is in the region of elasticity, and irreversible plastic deformation does not occur.

In fact, the loads acting on the tail section of LV, when the latter is on the launch pad, are presented in the last columns of Tables 1–4.

Table 3. Loads acting on the tail section of the fueled LV without transporter-erector support

Force factors	Loading stages				
	1	2	3	4	5
T (tf)	74.72	109.83	221.09	294.04	382.36
M (tf·m)	31.95	68.70	102.46	136.48	177.80
Q (tf)	1.80	3.61	5.42	7.21	9.42

Table 4. Loads acting on the tail section of the fueled LV with transporter-erector support

Force factors	Loading stages				
	1	2	3	4	5
T (tf)	87.48	176.10	263.20	350.29	454.81
M (tf·m)	27.48	55.76	83.07	110.18	143.36
Q (tf)	1.60	3.20	4.80	6.50	8.50

Conclusions

In this part of the work, a design of the LV variable stiffness tail section is described and a methodology for conducting experimental studies is presented. Based on this methodology, experimental studies were conducted. The studies will be discussed in detail in the second part of the article.

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Експериментальний аналіз міцності вафельних циліндричних відсіків змінної жорсткості. Частина 1. Методика проведення експерименту

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Запропоновано метод експериментального дослідження статичного напружено-деформованого стану (НДС) хвостового відсіку ракети-носія змінної жорсткості. Хвостовий відсік складається із корпусу та опірного кільця. Корпус є зварною конструкцією, яку виготовлено із двох вафельних оболонок то двох торцевих шпангоутів. На верхньому та нижньому торцевих шпангоутах є отвір під болт та направляючі штирі для стикування із баком горючого та опірним кільцем. Матеріалом обичайок є сплав із алюмінію АМг6НПП, а шпангоутів – сплав алюмінію АМг6М. Навантаження корпусу хвостового відсіку здійснюється за допомогою чотирьох опірних кронштейнів силового кільця, яке вводиться до складу випробувального збирання. У статті описуються результати експериментального аналізу статичного НДС оптимізованого корпусу хвостового відсіку під дією зусиль, що є наближеними до натурних. Внаслідок проведення експериментальних досліджень досягнуто такі цілі: отримано дані з міцності корпусу хвостового відсіку з урахуванням особливостей конструкцій, технологій виготовлення та механічних характеристик матеріалу; перевірено теоретичні методи розрахунку на міцність конструкцій; досліджено напруження у місцях, де вони вірогідно знаходяться тільки експериментально; виявлено перерізи конструкцій з надміром міцності для наступного полегшення. До хвостового відсіку прикладаються різні статичні силові навантаження. Статичне навантаження конструкцій проводилось поетапно без динамічних складових. Під час дослідження корпусу хвостового відсіку проводилось вимірювання переміщень та деформацій. Деформацій вимірювались для трьох значень повздовжньої координати оболонки та різних точках вздовж колової координати конструкцій. У кожній точці наклеювалась розетка із двох тензодатчиків. Один тензодатчик наклеювався у повздовжньому напрямі, а другий – у коловому. З використанням запропонованого методу досліджено напружено-деформований стан хвостового відсіку, котрий спроектовано на ДП КБ «Південне».

***Ключові слова:** хвостовий відсік, вафельна циліндрична оболонка, датчик деформацій, навантаження.*

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