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THE ANALYSIS OF THE IMPACT OF THE METHOD OF FASTENING ON STRAIN-STRESS BEHAVIOR OF COMPOSITE OVERWRAPPED PRESSURE VESSEL

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Currently, composite overwrapped pressure vessels (COPV), with high weight efficiency, are widely used in spacecraft (SC). In satellite construction COPVs provide necessary volume of working fluid for the realization of a highly efficient scheme of raising SC into geostationary orbit using standard electric propulsion engines. The issue of using such vessels in order to increase the period of active lifetime of SC and the implementation of deep-space exploration programs is relevant as well.

The urgent task is to ensure the reliability of COPVs. The study of foreign literature suggests that fastening elements in direct contact with the vessel, have an important impact on the strain-stress behavior (SSB) of the vessel. The paper discusses the basic methods of fastening large-sized COPVs having a spherical shape – an adapter module is made in the form of a "skirt" and a cable-stayed system. We have created a finite element model (FEM) of COPV to analyze the effect of fastening elements on SSB of COPV.

The analysis of the obtained results of the calculation shows that a cable-stayed system has almost no effect on SSB of COPV, in contrast to a composite "skirt", which reduces the effective stresses in the place of attachment to the vessel by two times or more, causing uneven distribution of stresses. The composite "skirt" directly transfers its buckling mode to the vessel, which reflects the significant effect of the "skirt" on the vessel's SSB. The use of a composite "skirt" in comparison with a cable-stayed system has high probability of COPV failure.

The obtained results show that a cable-stayed system is more effective way to fasten COPV than a composite "skirt".

Keywords: composite overwrapped pressure vessel, strain-stress behavior, cable-stayed system, spacecraft.

АНАЛИЗ ВЛИЯНИЯ СПОСОБА КРЕПЛЕНИЯ НА НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ КОМПОЗИТНОГО БАКА ВЫСОКОГО ДАВЛЕНИЯ

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В настоящее время композитные баки высокого давления (КБВД), обладающие высокой весовой эффективностью, находят широкое применение в космической технике. В спутникостроении КБВД обеспечивает необходимый объем рабочего тела для реализации высокоэффективной схемы довыведения космического аппарата (КА) на геостационарную орбиту с использованием штатных электрореактивных двигательных установок. Актуальным также является вопрос использования подобных баков в целях увеличения срока активного существования КА и реализации программ освоения дальнего космоса.

Актуальной задачей является обеспечение надежности КБВД. Изучение зарубежной литературы свидетельствует о том, что немаловажное влияние на напряженно-деформированное состояние (НДС) бака ока-

зывают их элементы крепления, находящиеся в непосредственном контакте с баком. Рассматриваются основные способы крепления крупногабаритных КБВД сферической формы: переходный отсек, выполненный в форме «юбки», и вантовая система. Создана конечно-элементная модель КБВД для проведения анализа влияния элементов крепления на НДС КБВД.

Анализ полученных результатов расчета показал, что вантовая система практически не оказывает влияния на НДС КБВД, в отличие от композитной «юбки», которая в два и более раза снижает действующие напряжения в районе крепления к баку, провоцируя неравномерное распределение напряжений. Композитная «юбка» напрямую передаёт свою форму потери устойчивости баку, что говорит о значительном влиянии «юбки» на НДС бака. Применение композитной «юбки», в сравнении с вантовой системой, характеризуется высокой вероятностью отказа КБВД.

Полученные результаты свидетельствуют о том, что вантовая система является более эффективным способом крепления КБВД.

Ключевые слова: композитный бак высокого давления, напряженно-деформированное состояние, вантовая система, космический аппарат.

Introduction. Currently, in order to increase the competitiveness of Russia in the international market, it is necessary to constantly increase the efficiency of telecommunication spacecraft, which means an increase in the capacity of data-transmission channels. In this regard, there is a tendency to increase the payload mass, and as a consequence, there is a high demand for heavy class telecommunication spacecraft [1].

Heavy class spacecraft being developed by JSC "Reshetnev Information Satellite Systems" (JSC "ISS") have the mass of more than 4000 kg, which significantly exceeds the carrying capacity of the traditional launch vehicle in Russia: the Proton-M launch vehicle with Briz-M booster unit [2]. To overcome current restrictions of the mass of the output payload, we have implemented an alternative scheme for launching spacecraft into an intended orbit using standard electrical propulsion engines located in spacecraft [3], this allows competing with world companies on the mass of the output payload. The developed COPV provides the necessary volume of the rocket propellant – xenon, which is necessary for the operation of propulsion engines [4].

At present time, COPVs with high weight efficiency are widely used in space-system engineering. The issue of using such vessels in order to increase the active life of SC and to implement deep-space exploration programs is rather relevant.

The loss of operability of COPV is a single failure point of entire spacecraft – the reservation of such a heavy and bulky block in the design of spacecraft is impossible, therefore, ensuring the reliability of COPV is an important task. To date, the work on the definition of bearing capacity and stiffness and the study of SSB of COPV [5–9] have been carried out; the results of this work guarantee the reliability of the pressure vessel. However, the study of foreign literature suggests that fastening elements in direct contact with the vessel, have an important impact on the strain-stress behavior (SSB) of the vessel.

In this article, we have presented the description of the analysis of SSB of COPV with various fastening methods and the results obtained. The aim of the work is to determine the most effective fastening method of COPV.

Description of COPVs and methods of their fastening. Initially, we conducted a review of COPVs and the methods of their attachment among the following manufacturing companies: Cobham Inc., ARDE Inc., ATK Space Systems (USA); EADS Astrium, Thales Alenia Space, MT-Aerospace (Europe); JSC R&DIME, JSC CRISM jointly with JSC ISS (Russia).

We identified two main methods of fastening large-sized COPVs of spherical shape, one of which is implemented by foreign manufacturing companies through the connecting compartment in the form of a "skirt" [10–14]. Fig. 1 presents, as an example, COPV with the composite "skirt", developed by NASA's Global Precipitation Measurement (GPM) program by Cobham Inc. A detailed report of the program is presented in the scientific article of the American Institute of Aeronautics and Astronautics [15], which materials are used in this work. We took this vessel as the basis for the study.

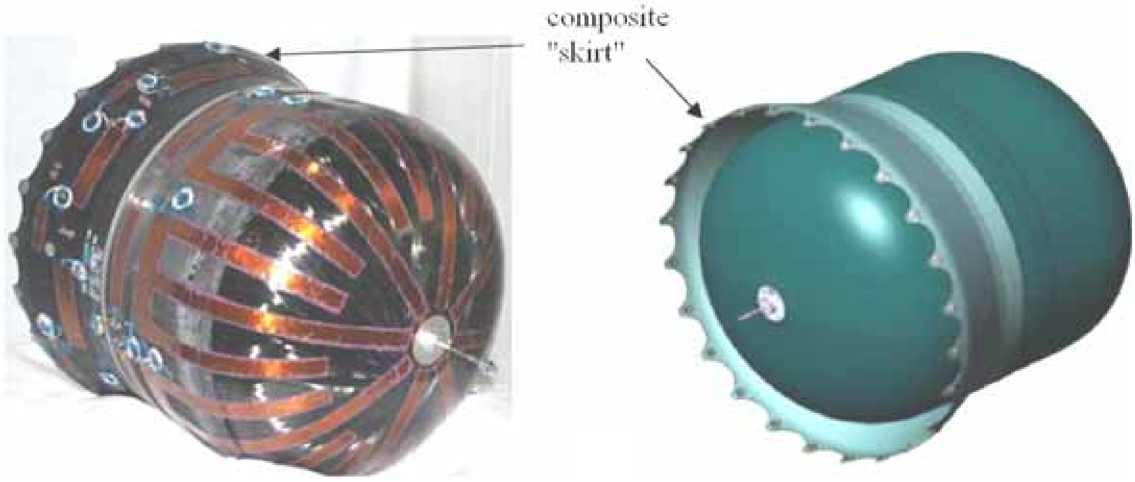
The second method is a cable-stayed system, implemented for the first time in world practice on COPV coproduced by joint-stock company the Central Research Institute for Special Machinery, Khotkovo (JSC CRISM) and JSC ISS (fig. 2). The cable-stayed system is made simultaneously with the vessel by the method of winding of organic plastic. The pair interweaving of the platform for attachment to the frame of spacecraft body forms cables wound along geodesic lines with uniform pitch.

When comparing the parameters of COPVs in tab. 1, we revealed a unique mass superiority of the cable-stayed system – it is lighter than the composite "skirt" by more than 65 %.

COPV of JSC CRISM and JSC ISS is not as good as COPV of Cobham Inc. in working volume which is partially compensated by the maximum allowable design pressure and high safety factor. Low safety factor of the vessel of Cobham Inc. is caused by relatively short active life (5 years against 15 years) and by low reliability requirements in order to meet the requirements for disposal – complete burning in dense layers of the atmosphere [15].

The description of the calculated model. In the accounting module Femap with NX NASTRAN, we created FEM of the vessel with the averaged technical characteristics of two vessels listed above for comparing the methods of fastening COPVs in terms of their effect on SSB of the vessel.

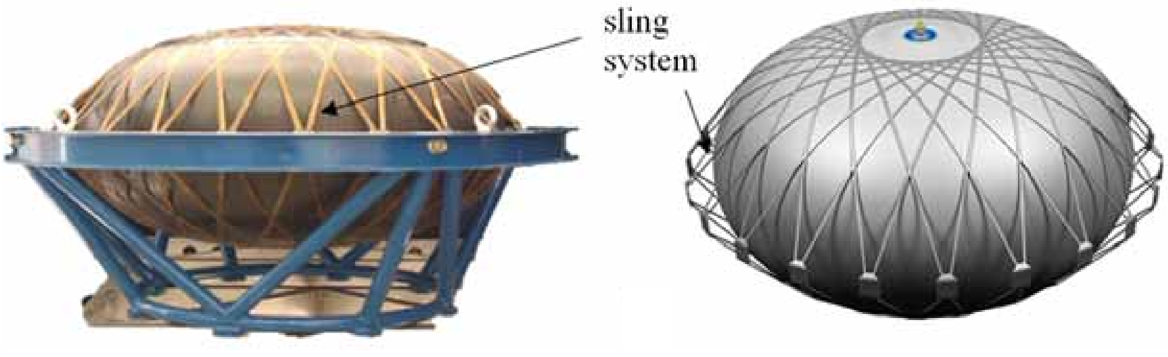
The geometrical parameters of FEM are similar to the vessel's flight model of Cobham Inc. – the diameter of the vessel in the cylindrical part is 1 m, the maximum length from dome to dome is 1.3 m (fig. 3). A metal liner was not modeled. We described the composite layer of the vessel with elements of the "plate" type, modeling a shell with equivalent stiffness 8 mm thick and elasticity modulus E = 90 GPa. We assigned the density of the equivalent material so that the total weight of the filled vessel (without the fastening interface) was 760 kg.



a *b*

Fig. 1. COPV with composite "skirt": *a* – manufactured model; *b* – 3D model

Рис. 1. КБВД с композитной «юбкой»: *а* – изготовленный образец; *б* – 3D-модель



a *b*

Fig. 2. COPV with cable-stayed system: *a* – manufactured model; *b* – 3D model

Рис. 2. КБВД с вантовой системой крепления: *а* – изготовленный образец; *б* – 3D-модель

Table 1

Main technical characteristics of COPVs and their interfaces

№	Parameter	COPV of JSC CRISM and JSC "ISS"	COPV of Cobham Inc.
1	Vessel size, mm	Ø1015x666	Ø1028x1348
2	Vessel mass (without fastening interface), kg	37.5	34.6
3	Swept volume, l	347	772
4	Working fluid	Xenon	Hydrazine hydrate
5	Mass of working fluid, kg	570	727
6	Maximum allowable design pressure, kgf/m^2	95	56
7	Safety factor	3.6	2
8	Fastening interface	cable-stayed system	"skirt"
9	Mass of fastening interface, kg	1.3	12.45

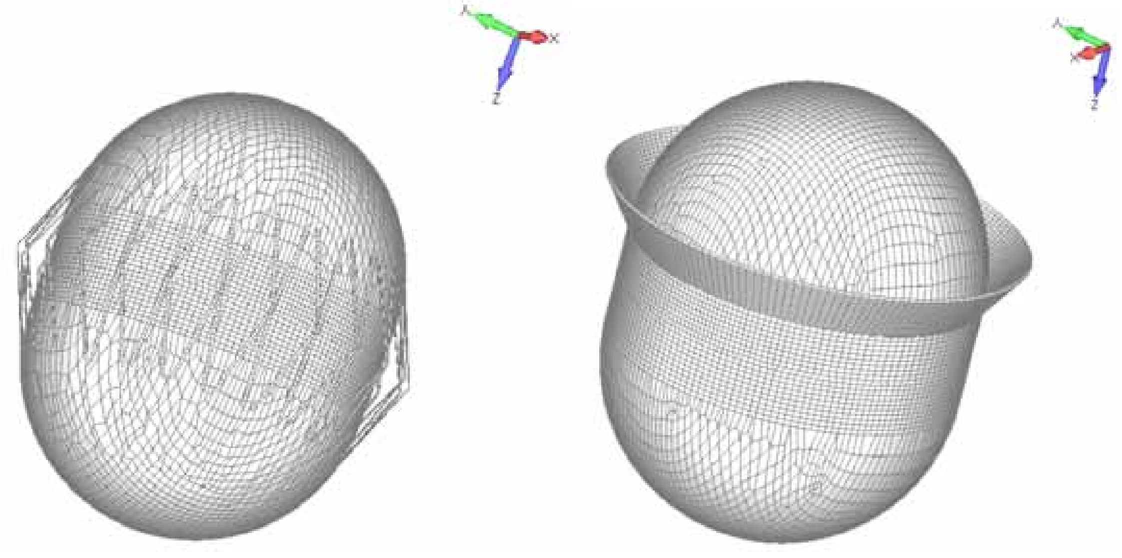


Fig. 3. FEM of COPV with a cable-stayed system (*left*) and with a composite “skirt” (*right*)

Рис. 3. КЭМ КБВД с вантовой системой (*слева*) и композитной «юбкой» (*справа*)

Table 2

The first frequencies of natural oscillation

Type	Vessel with a cable-stayed system	Vessel with a composite “skirt”
Transverse, Hz	60.67	208.06
Longitudinal, Hz	235.82	340.57

The cable-stayed system has the following geometrical parameters: the diameter in the place of attachment to the spacecraft body is 1.2 m, the angle of inclination of each cable relative to the generatrix of the cone formed by them is 15 °, the number of pairs of ribs is 24, the section of a cable is 5x10 mm.

The composite “skirt” has the following geometrical parameters: wall thickness is 10 mm, the height of the area of contact with the vessel is 75 mm, the angle of inclination of the “skirt” is 33.7°, the diameter in the place of attachment to the spacecraft body is 1.2 m

The masses of fastening interfaces, according to the calculation model (excluding manufacturing technology):

– cable-stayed system – 4.4 kg;

– composite “skirt” – 13.3 kg.

The fasteners have hard contact with the vessel.

The description of the experiment. Based on the existing experience of working with the vessel of Cobham Inc., described in the source [15], we decided to carry out the following calculations:

– frequency analysis;

– analysis of SSB from uniform internal pressure 2 MPa. We assumed the pressure conditionally and applied to the inner surfaces of the “plate”-type elements;

– quasistatic analysis. The main design case is the combined effect of longitudinal overload of 11g and a transverse overload of 3.5 g in the spacecraft launch phase. These overloads are applied to the vessel with internal pressure.

The results of frequency analysis. The results of the first natural frequencies in the longitudinal and transverse directions are presented in tab. 2.

The results of the analysis of SSB from internal pressure. The character of SSB for COPVs and fastening interfaces under the influence of internal pressure of the vessel is shown in fig. 4, 5, respectively. All voltage values are in Pa.

The results of the quasistatic analysis. We evaluated SSB of the vessel and the stability of the cable-stayed system and the “skirt”. The cable-stayed system has a stability margin-1.5. The “skirt” has a sustainability margin-2.8. The forms of buckling of fastening interfaces are shown in fig. 6.

The analysis of the results obtained. The results of the first natural frequencies in the longitudinal and transverse directions (tab. 2) meet the requirements (not less than 50 Hz).

According to the results of calculating the effect of internal pressure (fig. 4, 5), it can be concluded that fastening with the help of a cable-stayed system has almost no effect on SSB of COPV, in contrast to a composite “skirt”, which two or more times reduces actual stress in the place of attachment to the vessel, causing uneven distribution of stress.

While assessing the nature of the influence of fastening method on SSB of COPVs under the influence of overloads, it is advisable to evaluate the form of buckling (fig. 6). A cable-stayed system has no significant effect on

SSB of the vessel under the action of overloads while launching spacecraft. Buckling of a cable-stayed system is expressed in buckling of individual cables, without affecting the shape and SSB of COPVs. Moreover, the efforts from a buckled cable are redistributed between neighboring cables, allowing the structure to continue working without leading to its complete destruction.

Fig. 6 shows that the composite "skirt", despite the internal pressure of the vessel, directly transmits to its form of buckling. In turn, the vessel receives a completely different form of buckling, which indicates significant effect of the "skirt" on the vessel's SSB. This fact is confirmed by the results of the calculations of the GPM vessel set that is presented in the source [15]: "As a result of the quasistatic acceleration and internal pressure loads, the composite "skirt" was an area of critical stress. The project was improved several times until positive reserves were reached for all mutually perpendicular axes."

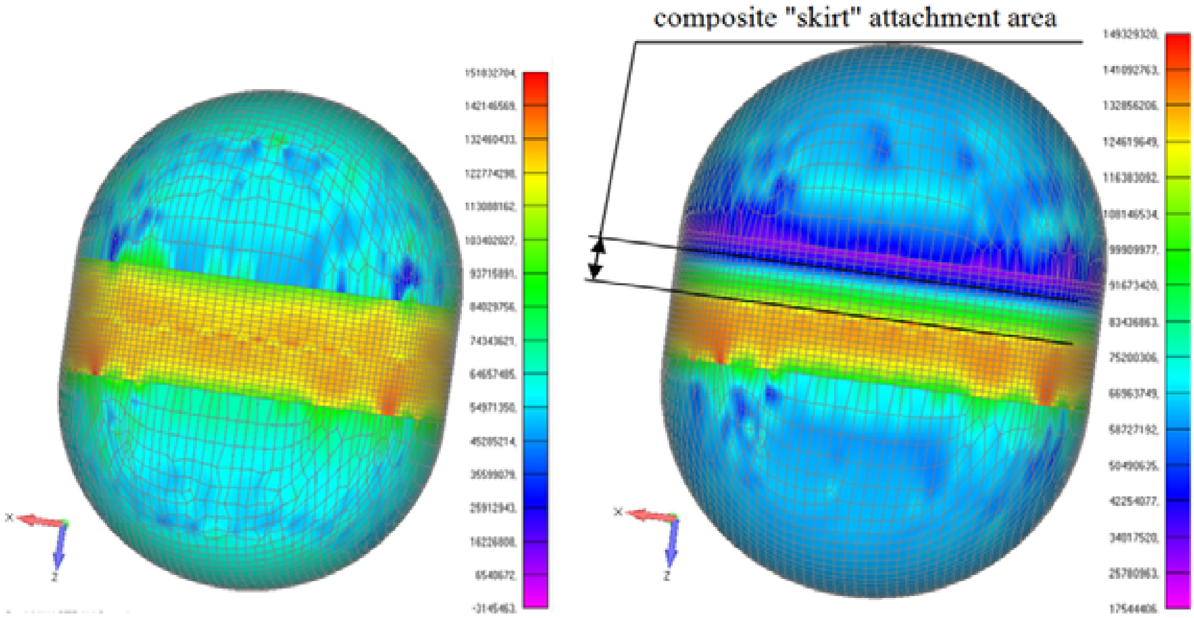


Fig. 4. SSB of FEM of COPVs with a cable-stayed system (*left*) and with a composite "skirt" (*right*) and when exposed to internal pressure

Рис. 4. НДС расчетной модели КБВД с вантовой системой (*слева*) и композитной «юбкой» (*справа*) и при воздействии внутреннего давления

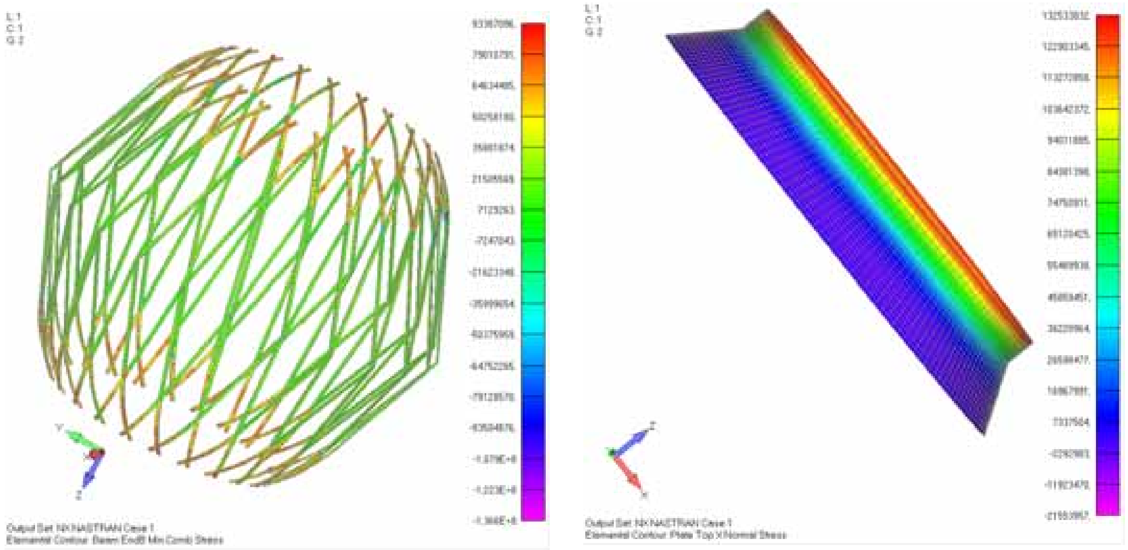


Fig. 5. SSB of a cable-stayed system (*left*) and a composite "skirt" (*right*) when exposed to internal pressure

Рис. 5. НДС вантовой системы (*слева*) и композитной «юбки» (*справа*) при воздействии внутреннего давления

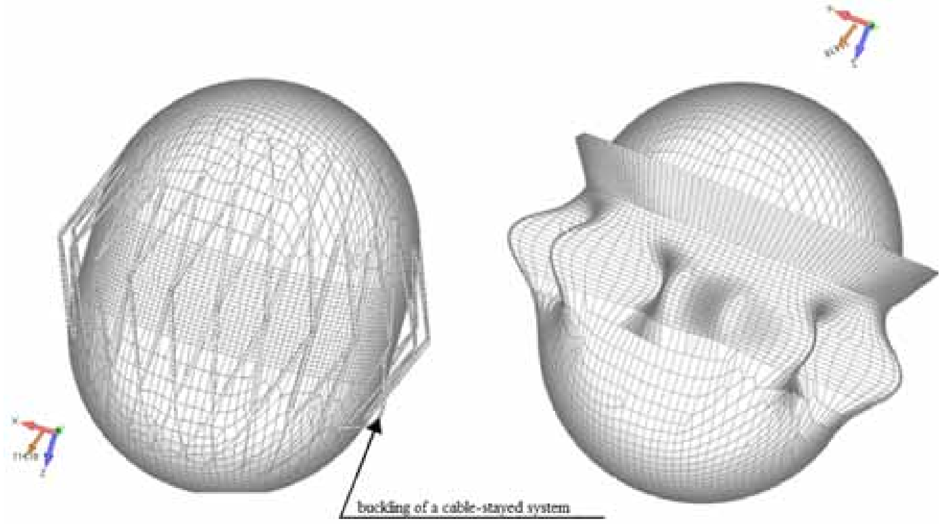


Fig. 6. The form of buckling of a cable-stayed system (*left*) and of a composite “skirt” (*right*) caused by overloads

Рис. 6. Форма потери устойчивости вантовой системы (*слева*) и композитной «юбки» (*справа*) под воздействием перегрузок

Therefore, when designing a cable-stayed system for a vessel, one can easily vary the number and geometry of cables without re-calculating COPVs as a pressure cylinder. The design of a composite “skirt”, on the contrary, should be carried out in parallel with the design of COPVs as a pressure cylinder, taking into account their mutual influence. The use of a composite “skirt”, in comparison with a cable system, is characterized by high probability of failure of COPVs and the complexity of its forecasting.

The stability margin of a composite “skirt” is significantly higher than that of a cable-stayed system, which is explained by the weight of a composite “skirt”. A cable-stayed system has an obvious mass advantage (67 % lighter).

A critical factor when choosing in favor of a cable-stayed system is the requirement for stiffness (frequency of natural oscillations), the rigidity of which can be reduced by varying the angle of cables at the design stage.

Conclusion. We carried out the calculation of natural frequencies, investigated the nature of SSB of COPVs depending on the fastening method under the internal pressure and overloads. The results indicate that a cable-stayed system has no significant effect on SSB of COPVs and it is more effective way to fasten COPVs than a composite “skirt”.

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