Model assessment of the lifetime of a composite overwrapped pressure vessel under creep conditions

N V Eremin\(^1,2\) and V V Moskvichev\(^1\)

\(^1\)Krasnoyarsk Branch of the Federal Research Center for Information and Computational Technologies, Krasnoyarsk, Russian Federation
\(^2\)Institute of Computational Modeling of the Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk, Russian Federation

Abstract. An approach has been developed to estimate the lifetime of a composite overwrapped pressure vessel under creep conditions. Creep tests of unidirectional composite material based on T1000 carbon fibers and epoxy resin were conducted at high temperatures. Experimental creep curves were obtained and the creep rate for each specimen was determined. A numerical analysis of creep of a composite overwrapped pressure vessel subjected to a constant pressure was carried out. Time-strain curves are obtained for each characteristic point in the composite shell. The strains range up to 12.5%. The curves of relaxation of tensile stress in a composite overwrapped pressure vessel are obtained. The stress gradually decreases from 926 to 564 MPa. The structure of the vessel considered remains stable without critical strains and stresses after 50 years of exploitation. Using the proposed modeling approach of a composite overwrapped pressure vessel, taking into account the effect of creep in the composite shell, it is possible to evaluate the lifetime of the structure.

1. Introduction

Layered composite materials (CM) based on carbon fibers and epoxy resin are widely used to manufacture composite overwrapped pressure vessels (COPV) for spacecraft applications. COPV is subjected to constant internal pressure during the active life of the spacecraft in orbit. COPV consists of a titanium liner and layered composite shell. During 15 years of exploitation, stress relaxation can occur and damage develops in the composite shell and liner. CMs are subject to changes in properties during prolonged mechanical and temperature loads. These processes can have a significant effect on the strength and geometric stability of the tank under load.

Long-term tests of COPV are expensive and difficult to put into practice, and in some cases impossible [1]. Since long-term tests of a COPV are expensive, there is a need to develop approaches based on extrapolation of experimental data (obtained using short-term testing) and implementation in numerical models.

Traditionally, the calculation of the structural life of components made of CM with long-term static loads are based on empirical models that determine the relationship between stress and time [2]. The authors in [3, 4] show that CM begins to creep at high temperatures, which requires a complete understanding of creep processes at micro and macro levels. It was determined that the creep behavior of unidirectional CMs depends on the viscoelastic properties of the matrix; the tensile strength of carbon fibers under creep conditions can be reduced by 30% [5].
The creep analysis of a COPV is a complex process, covering various stages of creep. In [6], the authors presented a multilevel model of the durability of composite vessels (based on carbon fibers) under pressure. However, these studies were devoted only to static mechanical tests of specimens, and the creep characteristics of CMs were not taken into account. Studies in [7-11] are devoted to the analysis of the effect of steady creep of a spherical vessel. It was determined that an increase in the fiber content leads to an increase in the tangential, axial and effective stresses near the inner radius, but decrease on the outer radius. Singh and Gupta [12] used the threshold creep law, in which creep parameters were estimated by linear extrapolation of the experimental results. Loghman and others [13] conducted studies of the dependence of stress on time for a spherical shell. The computations are restricted to small strains here. For a more general approach to viscoelastic composites the reader is referred to [14]. It was determined that under creep conditions, stress relaxation occurs in the vessels over time, and also after 50 years the creep rate reaches a stationary state.

Taking into account the results of previous studies, in this work, an assessment of a COPV lifetime under creep conditions was carried out. The goals of the research are:

- development of an approach to estimation of COPV lifetime under creep conditions;
- construction of experimental curves of strain-time and determination of the creep rate of CM at high temperatures;
- development of a numerical model for the analysis of creep of a COPV taking into account experimental data;
- lifetime assessment of a COPV by finite element analysis.

2. Experimental studies of creep characteristics of the CM

Since the matrix and fibers in CMs can experience creep, each of these structural elements contributes to the total creep. However, in the case of carbon fibers and an epoxy resin, it is necessary to consider the effects of creep of the epoxy matrix. Specimens had a rectangular flat shape. The average width of the composite tape was 15.5 mm, thickness 0.3 and the gage length 42 mm. To determine the creep characteristics, it is necessary to test unidirectional CM, which consists of carbon fibers T1000 and the epoxy resin ED-I.

Creep tests were carried out on the ATS-2330 electromechanical testing machine (figure 1 (a)) equipped with the ATS-3710 oven (figure 1 (b)). Specimens were tested with constant static loading of 800; 1000; 1200 MPa and temperatures +70; +90; +110°C. The duration of one test was 250 hours.

![Figure 1](image)

**Figure 1.** Experimental equipment: (a) ATS Creep Tester 2330; (b) ATS-3710 oven.

Based on the results of test, creep curves were constructed (figure 2).
Figure 2. Strain-time curves of specimens: (a) constant stress of 1200 MPa at different temperatures; (b) constant temperature of 110°C at different stresses.

Figure 2 (a) shows that with increasing temperature, the strain in the specimens increases. However, the steady-state creep rate at temperatures of 70 and 90°C is insignificant. Figure 2 (b) shows the dependence of strain on stress at constant temperature of 110°C.

After data processing, creep rates at various temperatures were obtained (table 1).

Table 1. Creep rates of specimens at different temperatures.

| Temperature, °C | 70   | 90   | 110  |
|-----------------|------|------|------|
| Creep rate, 1/hr| 3·10^{-8} | 2.68·10^{-8} | 3.18·10^{-7} |

Since creep at temperatures of 70 and 90°C is not strongly manifested, we will simulate creep at a constant temperature of 110°C.

3. Numerical modeling of creep by finite element analysis

For a numerical simulation of the COPV lifetime, it is necessary to set the law of creep. Most finite element software has the ability to model creep using the Norton equation (1), which is used in the calculation of creep:

$$\dot{\epsilon}_{\text{creep}} = C_i \sigma e^{-C_3/T},$$

where $C_i$ is the coefficients determined from experimental creep data; $\sigma$ is the stress; $T$ is the temperature.

According to the obtained experimental data (figure 2 (b)), the coefficients for the Norton equation were determined (table 2).

Table 2. Coefficients for Norton’s law.

| Coefficient | $C_i$, 1/hr | $C_2$   | $C_3$ |
|-------------|-------------|---------|-------|
| Value       | 1.78·10^{22} | 4.95736 | 0     |

A numerical model of the COPV design was formed on the basis of the geometrical parameters of the liner and relations describing the shape and geometry of the composite shell [15]. Modeling only the symmetric part (figure 3) allows one to significantly reduce the number of degrees of freedom, while preserving the reliability of the results [16]. Composite shell consists of nine layers of composite tape (width 24 mm and thickness 0.2 mm) which is wound on a liner along a geodesic path. The radius
of the shell is 506 mm, the height of the liner from the equator 281 mm and radius of the pole hole 35 mm.

![Figure 3. COPV: (a) design scheme; (b) 3D solid finite element model.](image)

The mechanical properties for the liner and composite shell are presented in table 3.

| Structural material | $E_1$, MPa | $E_2 = E_3$, MPa | $v_{12} = v_{13}$ | $v_{23}$ | $G_{12} = G_{13}$, MPa | $G_{23}$, MPa |
|---------------------|-------------|------------------|------------------|---------|---------------------|-------------|
| Liner, VT1-0 alloy  | 110000      | –                | 0.32             | –       | –                   | –           |
| Composite shell, IMS60(T1000)/ED-I | 165000 | 7700             | 0.32             | 0.45    | 3400                | 3800        |

The operating pressure of the COPV was set on the inner surface of the liner of 7.8 MPa. The contact interaction between the liner and the composite shell was set with the friction ratio of 0.2

4. Results and discussion

Since the composite shell takes the major part of the load, and the liner serves to ensure hermiticity, in this article we will consider the stress-strain state of the composite shell. Based on the analysis of the stress-strain state of the COPV, three characteristic points were identified for further consideration (figure 4 (a)). The first point is the zone of the pole hole, second point is the zone of the hump of the composite shell, and the third is the equator.
Figure 4. The results of strain calculations: (a) strain field distribution after 15 years of exploitation; (b) strain-time curves.

Based on the results of numerical simulation, the strain-time curves were constructed for each characteristic point (figure 4 (b)). The creep is most noticeable at the first point, however, at two and three points strains increase slightly over time.

Figure 5 shows the distribution of total strains depending of the radius in the composite shell. The distribution of the stress-strain state in the composite shell depends on changes in the angle of reinforcement of the composite tape. It can be observed that in the first and third points, the strain level increased by 12.5% after 50 years.

Figure 5. The distribution of total strain in the composite shell.

During the 50 years of exploitation of the COPV at pressure 7.8 MPa, the relaxation of tensile stresses in the composite shell occurs (figure 6), the stresses in the COPV are gradually reduced from 926 to 564 MPa, by 39% of the initial value.
Figure 6. Stress-time curves.

The results of the data obtained allow us to conclude that the considered design of the COPV at a temperature of 110°C, taking into account the effects of creep, retains its bearing capacity without the occurrence of critical strains (more than 0.08) or damage in the composite shell for 50 years of exploitation.

5. Conclusions
In this article, an approach was developed to estimate the lifetime of a COPV taking into account experimental creep data. Experimental studies of creep of CM were carried out to determine the coefficients in the Norton equation. The stress-strain behavior of the COPV over 50 years of exploitation is considered. Based on the results obtained, the considered design of the COPV has a sufficient lifetime under pressure in the expected operating conditions (15 years) without unacceptable strains. It is important to note that the operating pressure is the highest overpressure that the COPV must withstand over the life of its exploitation and maintain its functionality.

References
[1] Vasiliev V V 2009 Composite Pressure Vessels: Analysis, Design, and Manufacturing (Virginia: Bull Ridge Pub)
[2] Guedes R M 2011 Creep and Fatigue in Polymer Matrix Composites (Cambridge: Woodhead)
[3] Reeder J R 2010 A Critique of a Phenomenological Fiber Breakage Model for Stress Rupture of Composites Materials (Virginia: NASA Langley Research Center)
[4] Jensen E M and Fertig III R S 2015 (56th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference) pp 1–9
[5] Goertzen W K and Kessler M R 2006 Mat. Sci. Eng. 421 (1) 217–25
[6] Camara S and Bunsell A R 2011 Int. J. Hydrogen Energ. 36 (10) 6031–8
[7] You L H and Ou H 2007 Compos. Struct. 78 (2) 285–91
[8] You L H and Ou H 2008 J. Press. Vess.-T. ASME 130 (1) 14501–5
[9] Gupta V K and Singh T 2009 J. Strain Anal. Eng. 44 (7) 583–94
[10] Singh T and Gupta V K 2010 J. Compos. Mater. 44 (11) 1317–33
[11] Sandhu S S and Singh T 2019 Mater Today-Proc. 18 (7) 3401–8
[12] S Singh T and Gupta V K 2011 Compos. Struct. 93 (2) 747–58
[13] Loghman A A and Ghorbanpour Arani A 2011 Mech. Time-Depend. Mat. 15 (4) 353–65
[14] Tagiltsev I I, Laktionov P P and Shutov A V 2018 Meccanica 53 (15) 3779–94
[15] Eremin N V and Moskvichev E V 2017 Konst. Kompozit. Mater. 147 (3) 3–7 (in Russian)
[16] Moskvichev E V 2016 Procedia Structural Integrity 2 2512–8