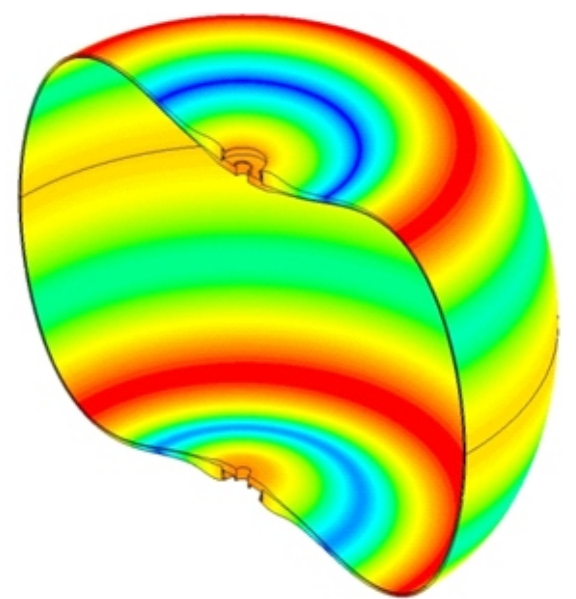




STRENGTH AND RELIABILITY ANALYSIS OF METAL-COMPOSITE OVERWRAPPED PRESSURE VESSEL



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Polymer composite materials (PCM) exhibit an attractive combination of remarkable mechanical and thermal properties and have found a wide application in aerospace and aeronautical industries for highly loaded structures. A particularly promising application is the use of fibrous PCM for fabrication of high pressure vessels. Such vessels should combine the required impermeability and high weight efficiency with enhanced long-term safety and durability. These requirements are met by metal-lined composite overwrapped pressure vessels (MCOPV) made by filament winding. The liner serves as a mandrel during the winding and provides an impermeable barrier to the stored gas or fluid, while the composite shell aims to ensure strength and stiffness of the structure.

Presented are the results of comprehensive studies on strength, lifetime and reliability of MCOPV. The investigated MCOPV were axisymmetric ellipsoid-like shells of revolution with the minor to major diameter ratio of about 0.6. The thin welded liner was made of VT1-0 titanium alloy and the composite shell was formed by helical winding of IMS-60 carbon fibers impregnated with a polymer matrix.

RESEARCH METHODS

The stress analysis of MCOPV under internal pressure was performed using the finite element method. The calculations were carried out with finite element models developed to reflect all significant geometric and deformation characteristics of the composites vessel (Fig. 1). The computational models coded with a parametric design language were used within a commercial package ANSYS. 3D simulation using a twenty-node element in the layered and homogeneous structural solid forms was employed to represent the composite shell and the liner, respectively (Fig. 2). Due to the geometrical and load symmetry only a one-twelfth of the vessel was modeled. The interaction between the liner and composite shell was simulated as a contact of two deformable bodies.

To calculate the lifetime of MCOPV, the classical models of low-cycle fatigue were applied for the metallic liner, while the effect of creep on the composite structural behavior was also considered. The lifetime was determined taking into account the results of numerical stress analysis. Two damaging factors - creep strains and fatigue damages were evaluated for the lifetime prediction of composite shell. The lifetime at the stage of creep was computed using empirical models that determine the durability as the dependence of creep strain on stress σ and loading time t in the following form:

$$e_f = A\sigma^\alpha t^\beta$$

The fatigue lifetime estimation of the composite shell was based on the nominal stress-life method and Palmgren-Miner linear damage hypothesis:

$$\sigma_a = \sigma_f N^b$$

The lifetime of the liner was determined considering elasto-plastic deformation of the metal. A low-cycle fatigue diagram expressed as the dependence of the strain range vs number of cycles to failure ($\Delta\epsilon$ -N) was computed:

$$\Delta\epsilon = 2 \left[\frac{e_f}{4\sqrt{N} + \{(1+r)/(1-r)\}} + \frac{R_1/E}{1 - (R_1/R_m)\{(1+r)/(1-r)\}} \right]$$

The calculation of reliability included the evaluation of two components: the reliability $R(0)$ at the beginning of service and the reliability $R(t, \sigma)$ during operation. The component $R(0)$ was estimated by means of a conventional "load-strength" model assuming the Gaussian law for load and strength values of MCOPV.

The Phoenix approach based on the Weibull reliability model was used to determine the term $R(t, \sigma)$. To account the influence of structural-mechanical heterogeneity of MCOPV, a reference measure M_0 was introduced. It is assumed that within M_0 the deformation of material is uniform. The probability of failure-free operation (PFFO) can be expressed as following:

$$R(t, \sigma) = \exp \left\{ - \frac{M}{M_0} \left[\frac{t}{t_c} \left(\frac{\sigma}{\sigma_c} \right)^\alpha \right]^\beta \right\}$$

Experimental investigations were carried out on full-scale samples of MCOPV fabricated according to requirements of the design documentation. The studies included the burst (static failure) tests and lifetime tests under long-term static and cyclic loading. Fifteen MCOPV samples were explored in burst tests and one sample in long-term static and cyclic loading tests. Eighty two cycles (according to a safety factor of 4.0 for cycling loading) of 3.9-7.8 MPa pressure were applied during cyclic testing. The long-term testing was performed at the maximum design pressure (7.8 MPa). All tests were performed using pneumatic pressure. Acoustic emission, impermeability and displacement control were employed throughout the testing.

RESULTS AND CONCLUSIONS

The computational models described above were applied for the stress analysis of 200, 350 and 500 liters MCOPV. The following mechanical properties were used in calculations: titanium alloy – $E=110$ GPa, $\nu=0.32$, $\sigma_{02}=360$ MPa, $\sigma_{01}=450$ MPa, unidirectional fibrous tape – $E1=165$ GPa, $E2=E3=7.7$ GPa, $G12=G13=3.8$ GPa, $G23=3.4$ GPa, $\nu12=\nu13=0.32$, $\nu23=0.45$.

The stress analysis of the liner as a separated structure shows a non-uniform distribution of meridional, circumferential and radial strain r induced by internal pressure (Fig. 3). The magnitude of ϵ_r is significantly higher than that of ϵ_θ while the latter turns negative near the liner equator. Such strain distribution results in a significant displacement in the meridional direction close to the polar fitting of the liner. The calculation predicted the failure of liner at pressure of 2.4 MPa due to a local buckling of the wall that was confirmed by the test.

The stress-strain state of the composite shell is also featured by non-uniformity in meridional and through the thickness directions (Fig. 4). The highest stress and strain gradients along the fiber direction are observed near the polar opening where the shell thickening is formed.

The MCOPV lifetime calculation considering the creep effect was performed for $\pm\varphi$ angle-ply composites ($\varphi=0+450$) at the stress of 400, 500, 600 and 700 MPa. The results indicate that the composite shell stressed up to 500 MPa exhibits the lifetime no less than the specified value of 15000 hours.

The cyclic lifetime calculation for the composite shell was carried out using the following parameters of equation 3: $b = -0.0951$; $\sigma_f = 1600$ MPa (when fibers are oriented along the principal stress axis); $\sigma_f = 800$ MPa (fibers are oriented at 450); $\sigma_f = 530$ MPa (fibers are oriented at 900). The results show that the lifetime is not less than 300 cycles if the nominal stress in composite does not exceed 500 MPa.

The computed low-cyclic lifetime of the liner amounts to 130 cycles for the operating pressure of 7.8 MPa and about 70 cycles for the proof pressure of 9.8 MPa. However, taking into account a combination of pressures that the vessel can bear during the whole testing program, the allowable number of loading cycles should not exceed 60. If the safety factor for strain $n_e = 1.25$ is applied, the allowable number decreases to 50 cycles.

The results of reliability calculation for MCOPV with 7 composite layers have revealed that the high PFFO values (>0.999) are provided if the stress does not exceed 650 MPa. For MCOPV over-wrapped with 9 layers the indicated level of PFFO is achieved if the stress is less than 800 MPa. In all the studied structures of MCOPV loaded with the given operating pressure, the stress values were not exceeded 400-500 MPa. This indicates that the target level of structural reliability is provided by the taken design and technology solutions. The computed reliability functions $R(t, \sigma)$ are presented in Fig. 5. As it follows from the graph, for a homogeneous composite shell under stress not exceeding 0.5 of strength, the PFFO value more than 0.999 is provided at the end of the service life. The stress level of 0.6 and higher is not allowable for the specified reliability requirements.

In general, the experimental results confirm the estimates presented above. The full-scale samples of MCOPV tested at static conditions showed an excellent strength with the safety factor higher than it was specified by the design documentation. MCOPV sustained the specified number of cycles without damage and detrimental deformation. Long-term static testing (during 2.5 years) also revealed no noticeable effects of creep, changes in the stress-strain state or leakage. Thus, the analysis performed using the developed models and experimental results indicate a high performance of the studied MCOPV. The taken design concept and structure of MCOPV can be considered as basis for manufacturing a new line of pressure vessels to be used in space vehicles of different classes.

REFERENCES

1. V. V. Vasiliev, *Composite Pressure Vessels: Analysis, Design, and Manufacturing* (Ridge Publishing, Blacksburg, VA, 2009).
2. V. Vasiliev, A. Krikanov and A. Razin, *Composite Structures*, 62, 449-459 (2003).
3. A. M. Lepikhin, A. E. Burov and V. V. Moskvichev, *J. Mach. Manufact. Reliab.* 44, 344-349 (2015).
4. E. V. Amelina, A. E. Burov, S. K. Golushko, A. M. Lepikhin, V. V. Moskvichev and A. V. Yurchenko, *Computational technologies*, 21, No 5, 3-21 (2016).
5. ANSYS Academic Research, Release 14.5, Help System, ANSYS, Inc.
6. Oak Ridge National Laboratory, ORNL/TM-2009/29 (2009).
7. A. Derewońko and R. Gieleta, *Journal of KONES Powertrain and Transport*, 19, No. 3, 103-110 (2012).
8. *Strength of Structures at Low-Cycle Loading* / edited by N. A. Makhutov (Nauka, Moscow, 1983).
9. K. Kapur and L. Lamberson, *System reliability and design: Translated from English* (Mir, Moscow, 1980).
10. P. Murthy, J. Thesken and S. Phoenix, *AIAA, Paper 2007-2145* (2007).

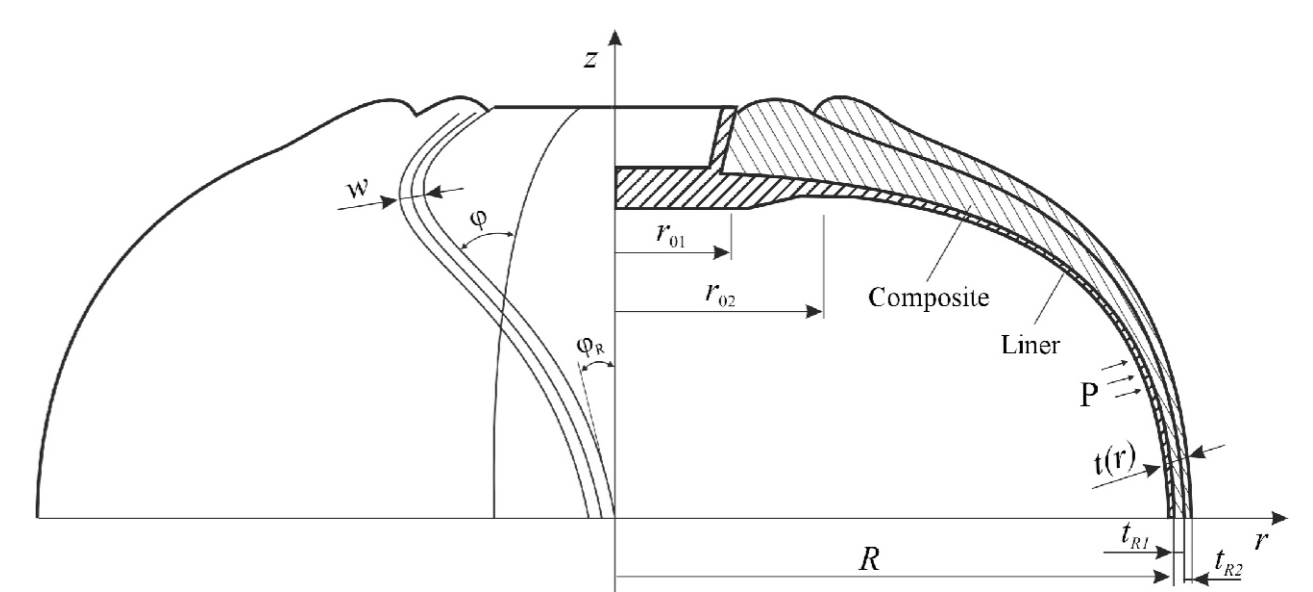


Fig. 1 - A metal-lined composite pressure vessel

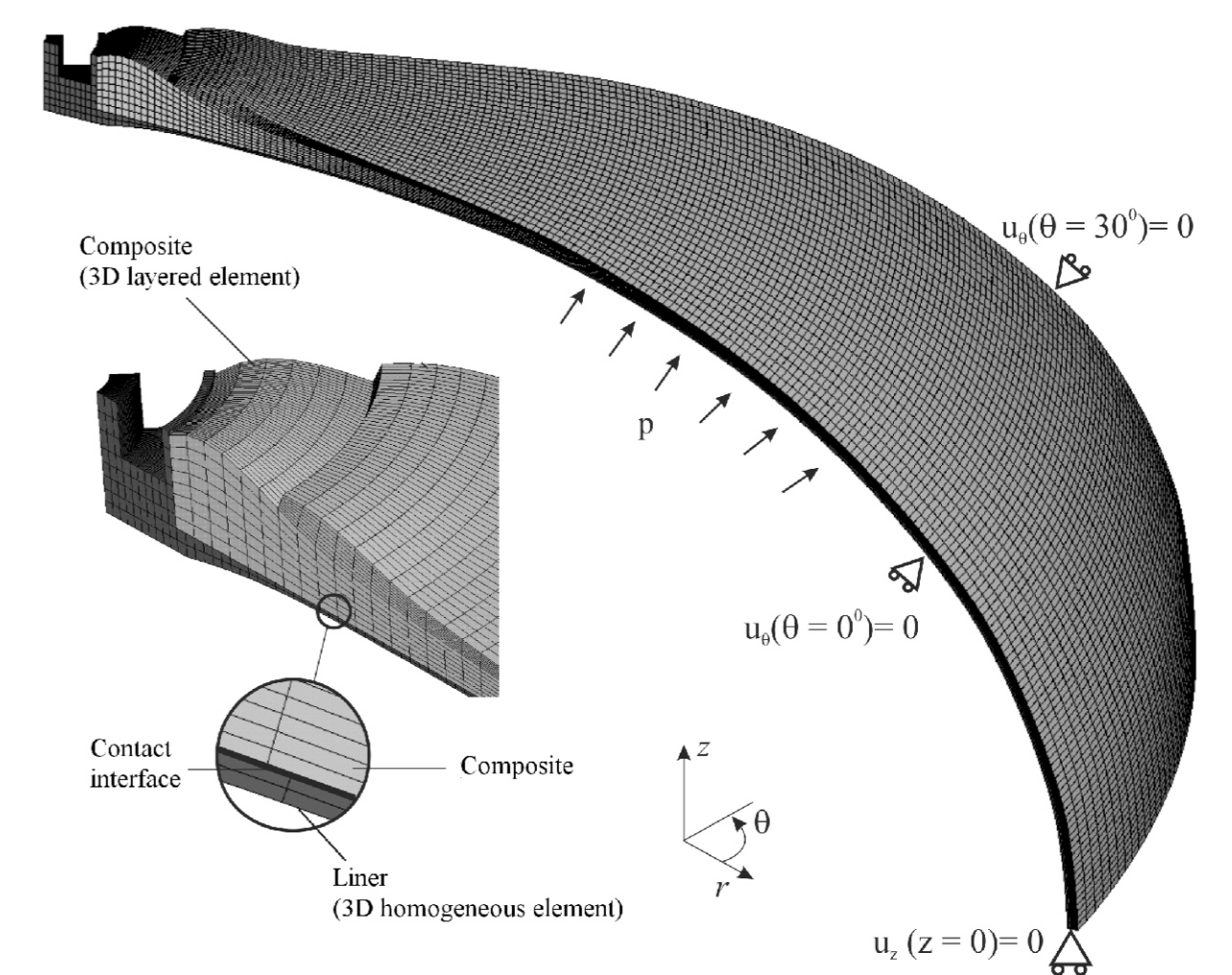


Fig. 2 - Finite element model of MCOPV

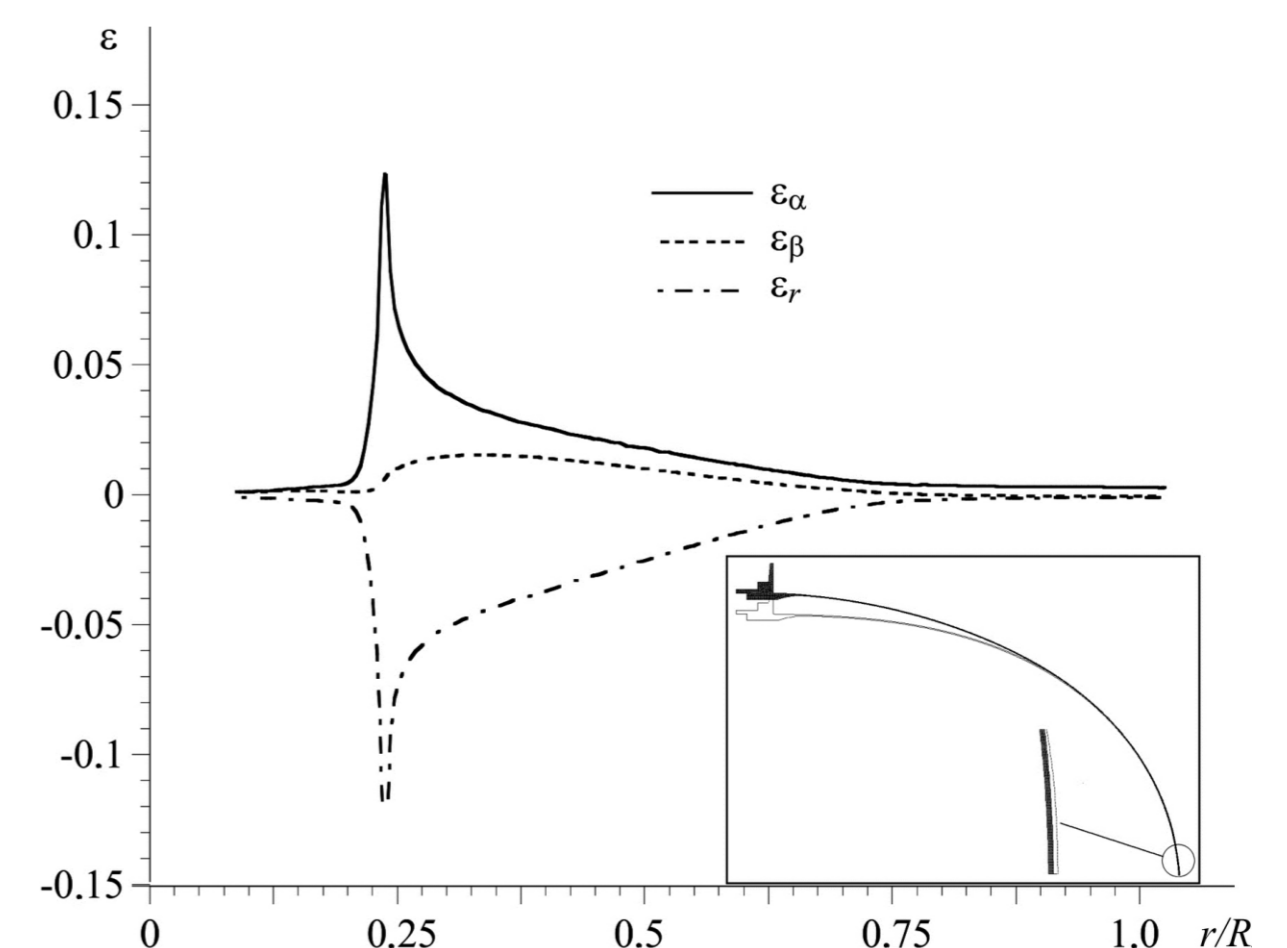


Fig. 3 - Strain distribution in the liner

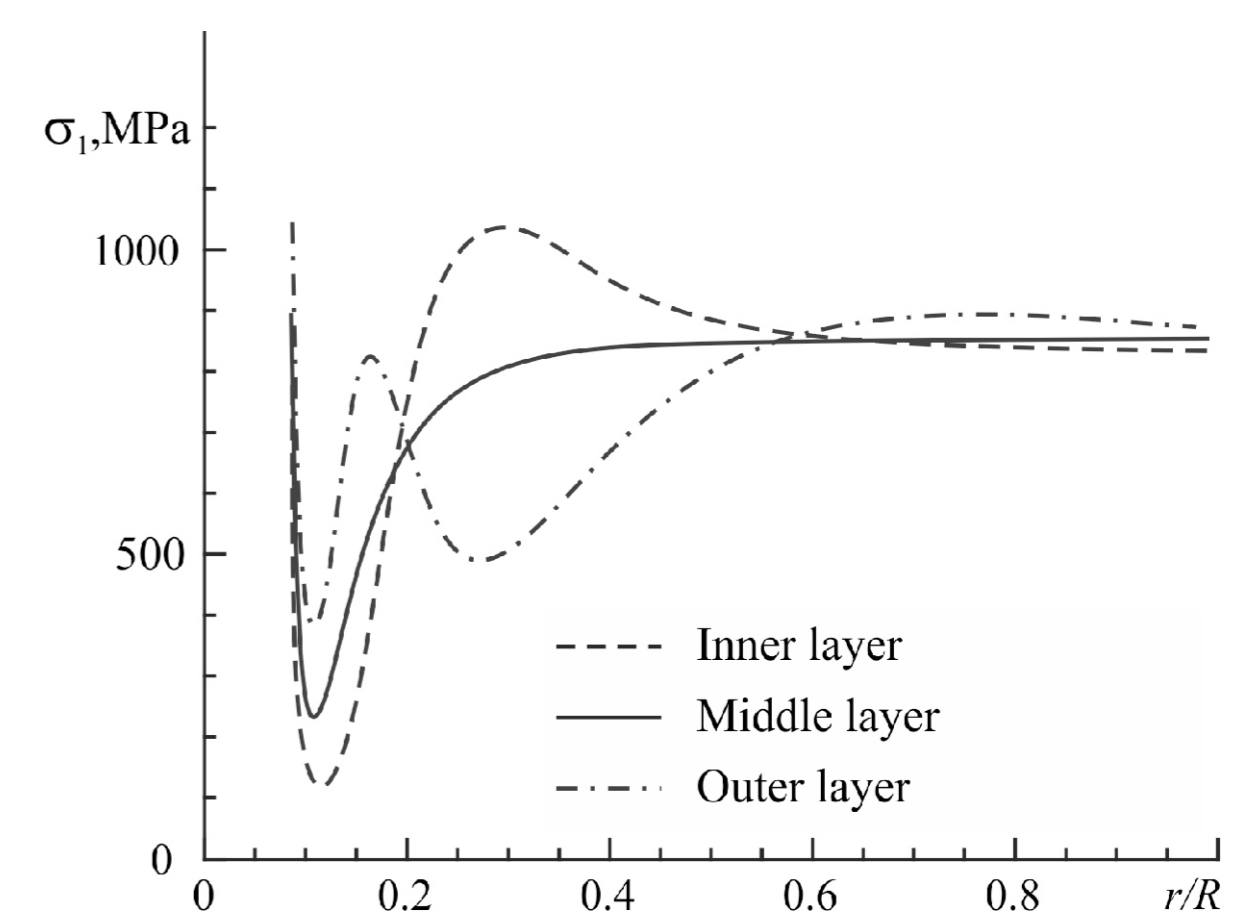


Fig. 4 - Stress distribution in the composite shell

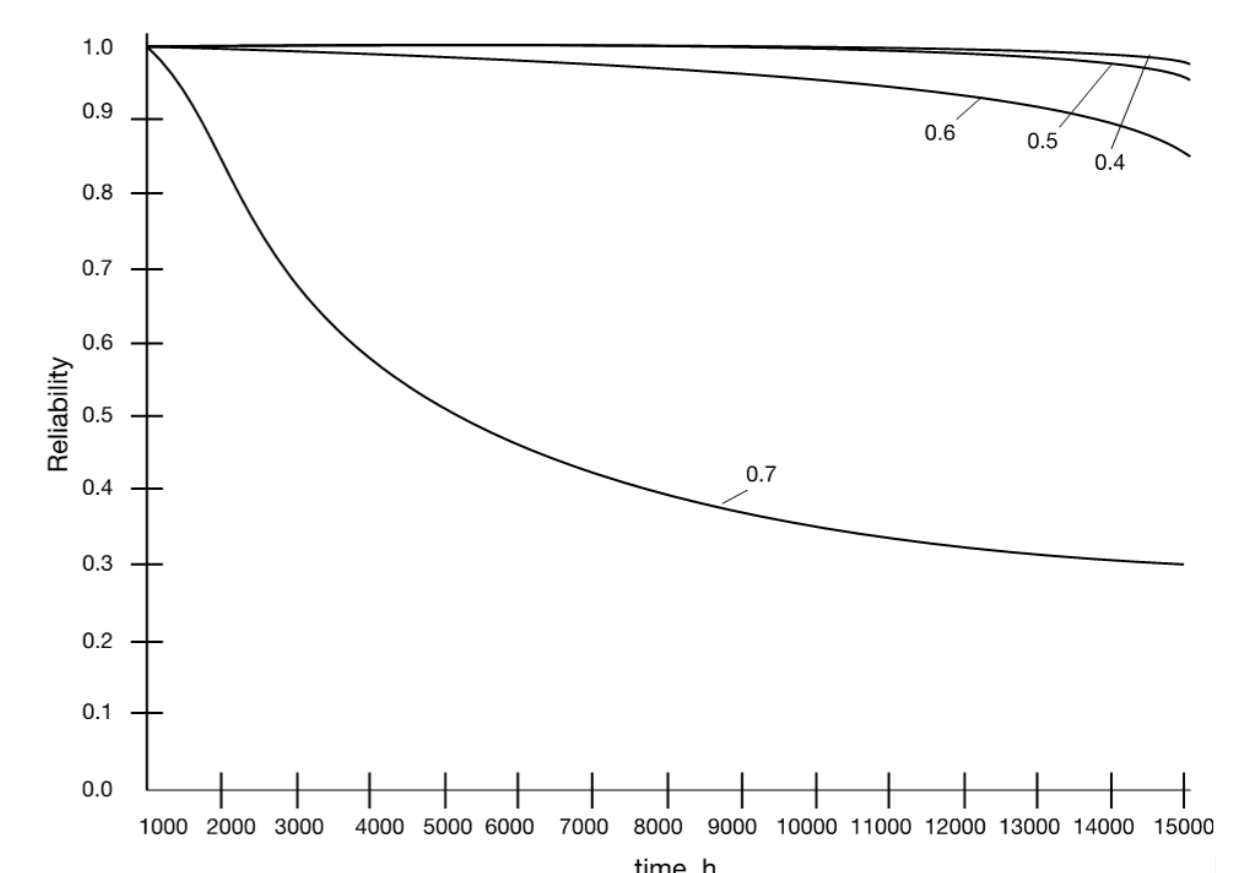


Fig. 5 - Functions of the probability of failure-free operation depending on the stress level