

Modeling the influence of the optical fiber strain on the readiness performance of fiber-optic communication lines

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Abstract. A mathematical model for determining the readiness performance of the fiber-optic communication lines depending on the degree of optical fiber strain with different methods of influence. The model is based on the theory of Markov chains. The adequacy of the model is achieved by the false positive and false negative errors. The application of the developed model enables us to determine the allowable maintenance interval for the fiber-optic communication lines.

Index Terms. fiber-optic communication line, optical fiber strain, tensile load, mathematical model, real time, current time, readiness performance.

1. Introduction

The field experience of the fiber-optic communication lines (FOCLs) has shown that a life of optic cables (OCs) depends on mechanical strains in optic fibers (OFs) [1 – 6].

The early diagnostics and monitoring of the optical fibers (OFs) in the OCs are important at present due to the mass distribution of the FOCL.

The use of the automatic monitoring systems based on optical time domain reflectometers (OTDRs) is one of the solutions for the FOCL. Reflectometers well detect defects and troubles of the OF and allow attenuation at any point of the FOCL to be determined. Defects and troubles of the OFs include sections with high strain or fall of temperature, bends or microbends, violation of the OF integrity due to unauthorized access to it.

The underground OCs are subjected to high mechanical loads because of the ground deformations. The aerial optic cables also can be subjected to mechanical loads in case of icing the cable. This can lead to irreversible changes associated with high mechanical strains within the OF of the FOCL and reduce the OC life [2 – 5].

To provide a trouble-free operation of the FOCL, an ongoing monitoring of the OFs is needed for timely detection of sections with high OF strain [1 – 4]. The article describes the influence of tensile loads on the OC life.

2. Statement of the problem

We need to have the right information on the OF state in the FOCL to estimate the reliability of the FOCL. In addition, not every optical reflectometer detects OF sections with high strain. A method of Brillouin reflectometry should be applied to find such sections in the FOCL. Due to this, the monitoring system for the FOCL should necessarily include the Brillouin optical time-domain reflectometers (BOTDR).



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The absence of mechanical strains in the OFs is necessary to achieve a trouble-free operation of the FOCL during the life. The reliability of the FOCL and its durability are directly influenced by the increase in the OF strain.

There are several ranges of the OF strain at which various periods of trouble-free operation are possible according to the data from the “Fujikura” Ltd. A strain of less than 0.2% is a safe range which has no influence on the OF life. A strain range of more than 0.6 % is an unacceptable because it leads to destruction of the OF. The life of the optic cable is reduced in the range of tensile loads of 0.2-0.6 %. A guaranty period of the optic cable is 25 years. Tensile load should be less than 0.2% to maintain this guaranty period. If the OF strain is 0.45%, the optical fiber break will occur with a probability of 50%.

Detection and analysis of the distribution of the Mandelstam – Brillouin backscattering spectrum (MBBS) along the OF is carried out in the BOTDR [1 – 6]. We analyze the BOTDR reflectograms for OF sections with modified tensile loads.

Fig.1 – Fig. 4 show the examples of the BOTDR reflectograms obtained by investigation tests of the OFs containing sections with modified tensile loads [4 – 6].

The light pipe is composed of single mode optic fibers: G.652 OF (usual OF), welded with G.657 OF, which in turn is welded with G.653 (DSF– dispersion-shifted fiber) in the investigation tests, the data of which are given below [5, 6].

A BOTDR reflectogram with a modified OF section subjected to a strong tensile load is shown in Fig. 1. The place of the OF strain is clearly noticeable by the shift of the MBBS maximum (f_{Bs}) from 10.84 GHz (f_{B0}) to 11.08 GHz towards a higher frequency of f_B (F2).

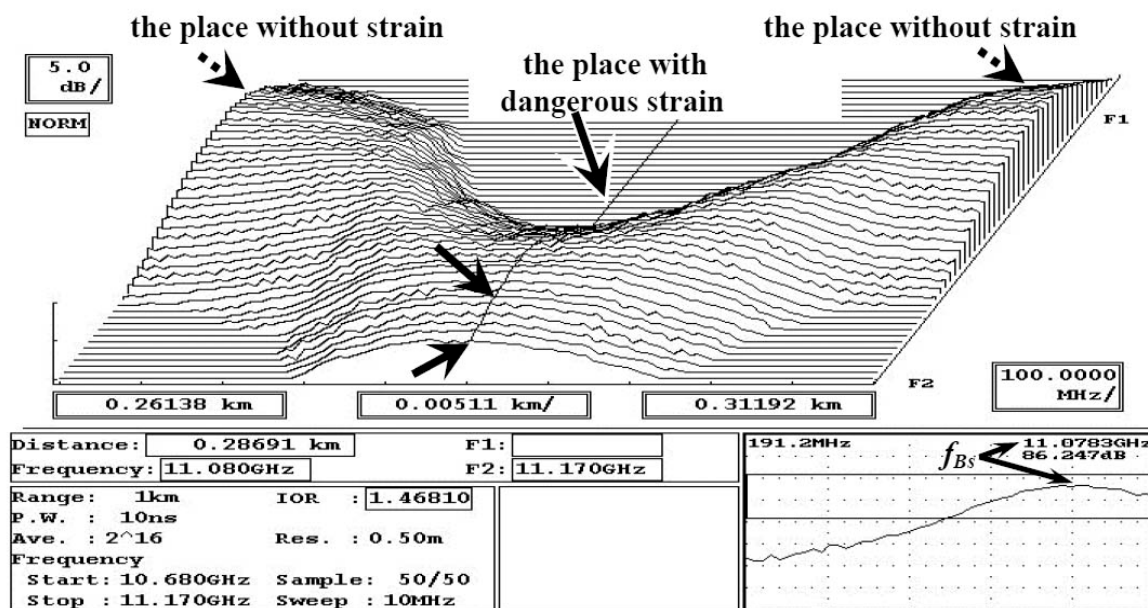


Figure 1. BOTDR reflectogram for the “problem” OF section

The comprehensive picture of the OF strain conforming to the distribution of the MBBS (Fig. 1) is shown in Fig. 2. The graph demonstrates that the strain increases in the place of mechanical load on the OC by more than 0.45 %, which is dangerous for the OF.

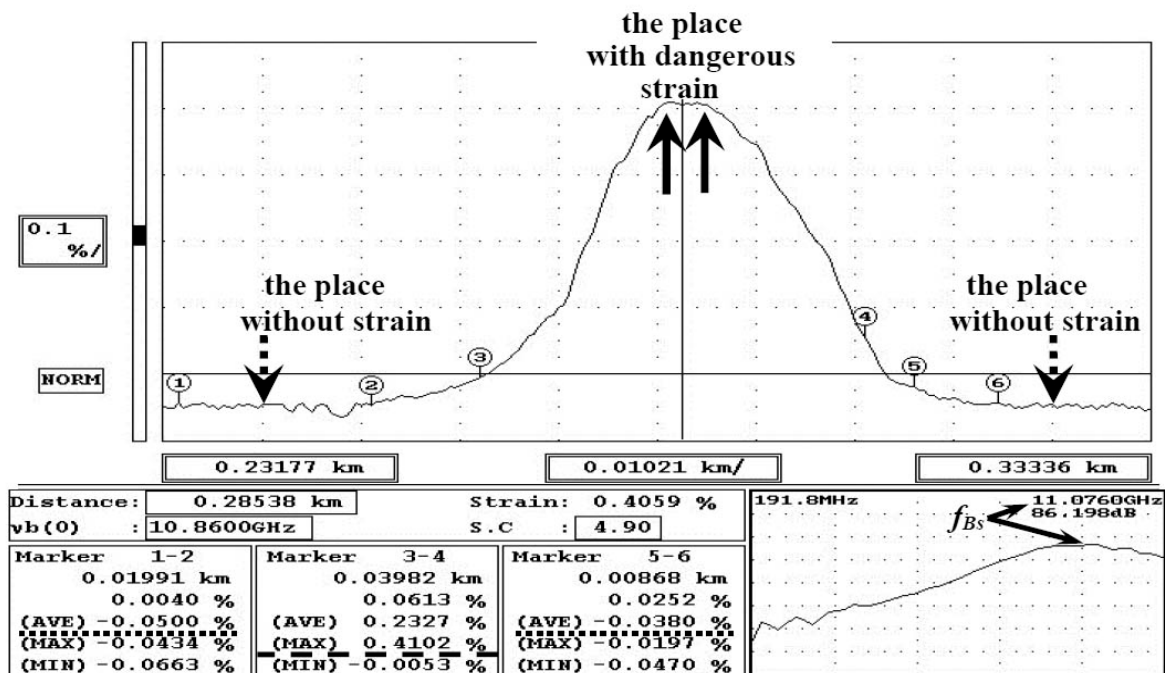


Figure 2. Comprehensive picture of the OF strain

Fig. 3 shows the BOTDR reflectogram at point strain in the longitudinal direction of the "problem" section of the same light pipe (the longitudinal tensile load was 0.5 N, the protective sheath of the OF was not removed).

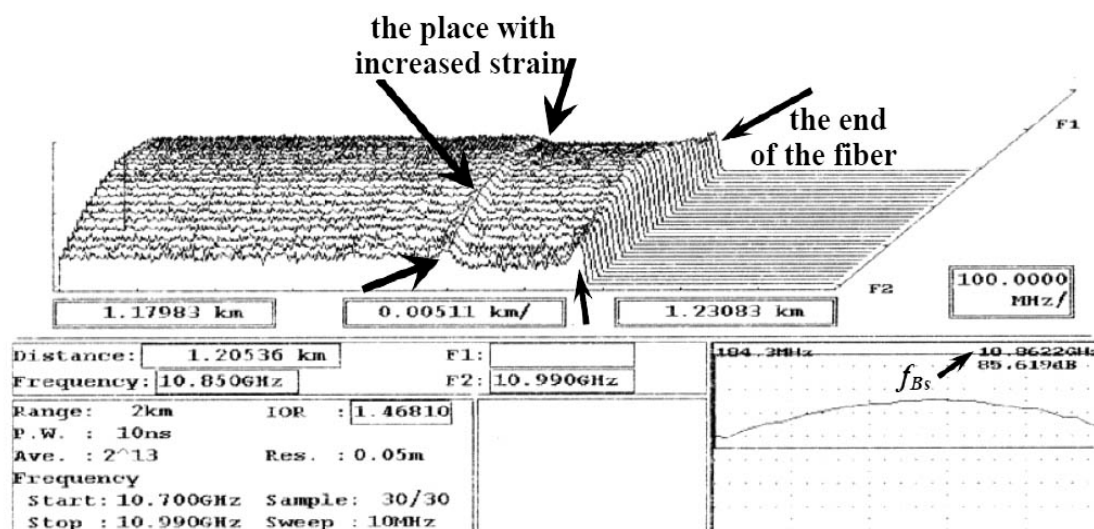


Figure 3. BOTDR reflectogram at the tensile load on the OF section

The f_{B0} is 10.84 GHz at normal conditions. A slight shift of the MBBS (f_{Bs}) towards a higher f_B (F2) is observed at the optic fiber under strain and the f_{Bs} is equal to 10.86 GHz. (The profile of MBBS is shown in the bottom right corner of the Brillouin reflectogram and the peak frequency of the MBBS is selected).

Fig. 4 shows a strain distribution graph (for the same light pipe) conforming to the distribution of the MBBS with strain section as demonstrated in Fig. 3.

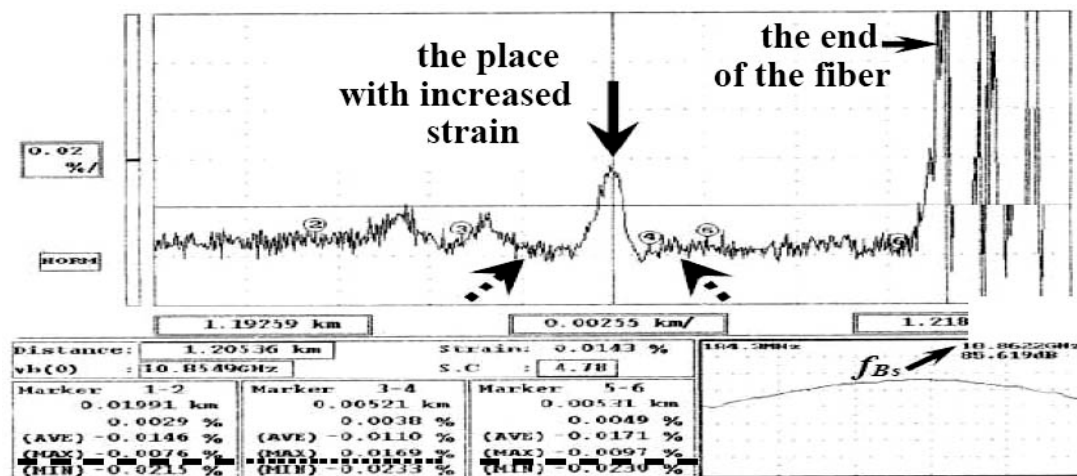


Figure 4. Graph of the strain under the influence of tensile load on the OF section

A slight increase in strain by 0.03 % is observed in the tensile section (solid arrow) relative to the section without strain (dashed arrows in Fig. 4).

Evaluation of the influence of optic fiber strain on the reliability of the FOCL is of particular interest. We analyze the dependence of the readiness performance of the FOCL on the OF strain.

3. The theory

The transmission path is ready to operate if both of its ways are in readiness. There are the following performances of readiness in the G.821 recommendation: a readiness performance of K_{AF} and an unreadiness performance of K_U . The readiness performance is the ratio of time during which the transmission path is in readiness to the overall observation time. The unreadiness performance is the ratio between the time during which the transmission path is in unreadiness and the overall observation time. The Markov chain theory and probabilistic modeling are used to estimate the readiness performance [4 – 9].

The development of the mathematical model was carried out in several stages. These stages are described in [4 – 9].

The investigated system (FOCL) has the following states:

- S_0 – operational state;
- S_1 – state under tensile load on an optic cable (OC);
- S_2 – detectable failure state;
- S_3 – nondetectable failure state;
- S_4 – fictitious failure state;
- S_{TO} – technical operation (TO) (maintenance) of an operational system.
- S_{ITO} – TO at tensile load on an OC;
- S_{3TO} – TO in case of a nondetectable failure.

The graph of states used in the model is shown in Fig. 5.

The system is in the state of S_0 at the time of $t = 0$. The system continuously operates the time of T (periodicity time or cycle). The operability check and technical operation (TO) (maintenance) of the system are possible only at the end of time of T [10–12]. External factors (various influences on the OF, leading to its strain) affect the OF during an exploitation time of T . In this case the system passes into a state of S_1 . The failure loads influence on the system at the state of S_1 and it passes into a state of S_2 . The system can go from the state of S_1 to the state of S_{ITO} , which means that one takes

scheduled technical maintenance. The system is in the state of S_{ITO} for the time t_n required to check it. If the system fails during the check it will go from the state of S_{ITO} to the S_2 .

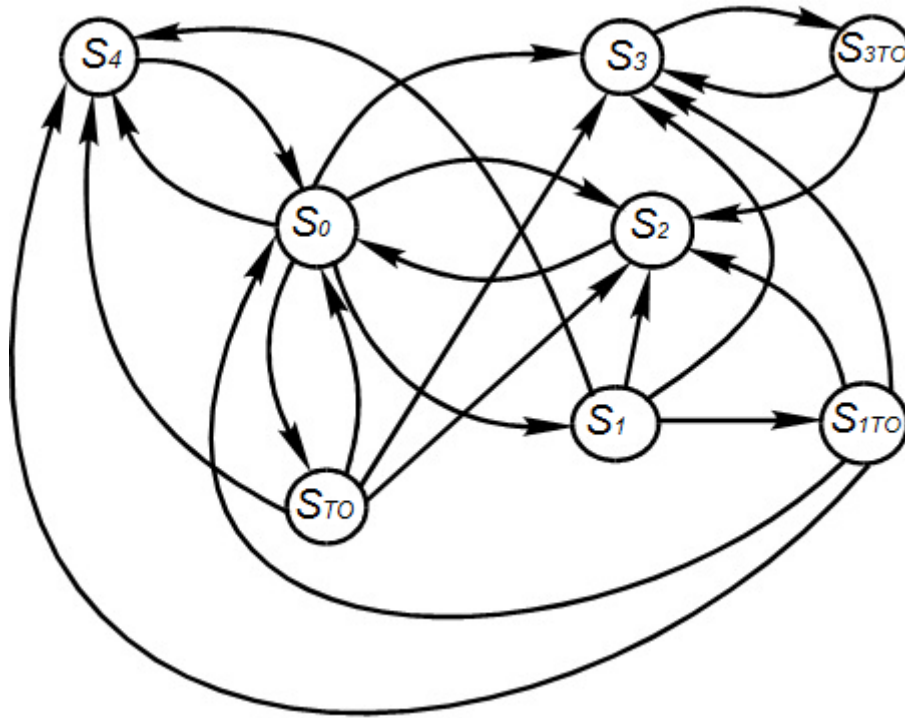


Figure 5. Graph of states for FOCL

The system transition into the nondetectable failure state is possible because of the false positive and false negative errors (type I error and type II error respectively). A possible reason for the system transition from the S_{ITO} to the S_3 is an incorrect choice of performances in the test module (in reflectometer) of the OF monitoring system, leading to a formation of non-fixed irregularities. If there is no failure in the S_{ITO} state, the system passes into the operational state of S_0 . Then the operating cycle is repeated.

If the system is in the state of S_0 for a time no more than T , the system failure may occur. It is characterized by the transition of the system to the state of S_2 . If the system operates without troubles the time of T in the state of S_0 , it will pass into the technical maintenance of S_{ITO} . The system is checked in this state. The duration of the test is t_p .

The system goes into the state of S_3 only during the check and stays here until the next system control. Unconditional transition of the system to the state of S_{3TO} occurs from the S_3 state. In case of transition from the state of S_{3TO} to the failure state due to failure detection, the system returns into the operational state. If the failure is unfound, the system will return into the nondetectable failure state (S_3). The return cause of the system to the state S_3 is false negative error (β_2).

The system can go to a fictitious failure state of S_4 . Fictitious failure occurs because of the false positive error of built-in diagnostic equipment. Timely detection of the fictitious failure returns the system to its operational state. The operating cycle is repeated each time when the system returns to the state of S_0 .

The detailed procedure of determination of the readiness performance is given in [7 – 11].

The readiness performance is determined by the following algorithm:

1. The matrix of transition probabilities (P) is written in accordance with the graph of system states (Fig. 5).

The matrix of transition probabilities is given in [7 – 9].

We wrote the probabilities of the system transition from the state of S_i to the state of S_j . The probabilities are presented in table 1.

Table 1

Initial state (S_i)	Transition probability	Final state (S_j)
S_0	$[1 - F_{02}(T)]F_{01}(T)$	S_1
	$(1 - \beta_1)F_{02}(T)$	S_2
	$\beta_1 F_{02}(T)$	S_3
	$\alpha_1 [1 - F_{02}(T)][1 - F_{01}(T)]$	S_4
	$(1 - \alpha_1)[1 - F_{02}(T)][1 - F_{01}(T)]$	S_{TO}
S_1	$(1 - \beta_1)F_{12}(T)$	S_2
	$\beta_1 F_{12}(T)$	S_3
	$(1 - \alpha_1)[1 - F_{12}(T)]$	S_{ITO}
	$\alpha_1 [1 - F_{12}(T)]$	S_4
S_2	1	S_0
S_3	1	S_{3TO}
S_4	1	S_0
S_{TO}	$(1 - \beta_2)F_{TO}(t_p)$	S_2
	$\beta_2 F_{TO}(t_p)$	S_3
	$\alpha_2 [1 - F_{TO}(t_p)]$	S_4
S_{ITO}	$(1 - \alpha_2)[1 - F_{TO}(t_p)]$	S_0
	$(1 - \beta_2)F_{TO}(t_p)$	S_2
	$\beta_2 F_{TO}(t_p)$	S_3
	$\alpha_2 [1 - F_{TO}(t_p)]$	S_4
S_{3TO}	$1 - \beta_2$	S_2
	β_2	S_3

2. A row matrix of final probabilities is written [7 – 9].

$$\pi = [\pi_0(T), \pi_1(T), \pi_2(T), \pi_3(T), \pi_4(T), \pi_{TO}(T), \pi_{ITO}(T), \pi_{3TO}(T)], \quad (1)$$

3. The final probabilities of the system are determined in each state. To find ones we need to multiply the matrix of transition probabilities by the row matrix of final probabilities and execute the necessary transformations [9 – 12].

$$\begin{cases} \pi = \pi \cdot P \\ \sum \pi_i = 1 \end{cases} \quad (2)$$

4. To find the readiness performance of the FOCL is necessary to identify the real time of $\omega_i(T)$ and the current time of $\nu_i(T)$ for the system in specific states.

The real time is determined for the following states: S_0 , S_1 and S_4 .

$$\omega_i(T) = \sum_j p_{ij} \int_0^T \tau_{ij} dF_{ij}(\tau_{ij}), \quad (3)$$

where p_{ij} is the transition probability from this state,

τ_{ij} is the time for a system in this state,

$F_{ij}(\tau_{ij})$ is the distribution function for this stage of process [8 – 10].

As an example, we write an equation to find the real time for the state of S_0 :

$$\omega_0(T) = \int_0^T [1 - F_{02}(\tau)][1 - F_{01}(\tau)] d\tau.$$

The current time is estimated for the following states: S_0 , S_1 , S_2 , S_3 and S_4 .

$$\nu_i(T) = \sum_j p_{ij} \int_0^T \tau_{ij} dF_{ij}(\tau_{ij}). \quad (4)$$

We write an equation to find the current time for the state of S_0 :

$$\nu_0(T) = \int_0^T [1 - F_{02}(T)][1 - F_{01}(T)] d\tau + \beta_1 \int_0^T F_{02}(\tau) d\tau.$$

The first component of this equation is equal to the real residence time of the system in the state of S_0 .

Diagnostics error of the type II of built-in diagnostic equipment influences on the second component.

Then we can write this equation as follows:

$$\nu_0(T) = \omega_0(T) + \beta_1 \int_0^T F_{02}(\tau) d\tau.$$

To find the readiness performance of $K_{AF}(T)$ we apply the above equations for the final probabilities of $\pi_i(T)$ (1) – (2), for the real $\omega_i(T)$ (3) and the current $\nu_i(T)$ (4) time.

An equation for the readiness performance of $K_{AF}(T)$ is given by:

$$K_{AF}(T) = \frac{\pi_0(T)\omega_0(T) + \pi_1(T)\omega_1(T) + \pi_4(T)\omega_4(T)}{\pi_0(T)\nu_0(T) + \pi_1(T)\nu_1(T) + \pi_2(T)\nu_2(T) + \pi_3(T)\nu_3(T) + \pi_4(T)\nu_4(T)}. \quad (5)$$

To solve this task is possible with the help of mathematical programs (MathCAD), because they are suited both for numerical and symbolic solutions to many problems. Ones also have a mathematical apparatus to find solutions to linear algebraic equations [7 – 12].

4. Experimental results

The achieved results are applied to construct the graph of dependence of the OF durability on the magnitude of the tensile load. The graph is shown in Fig. 6.

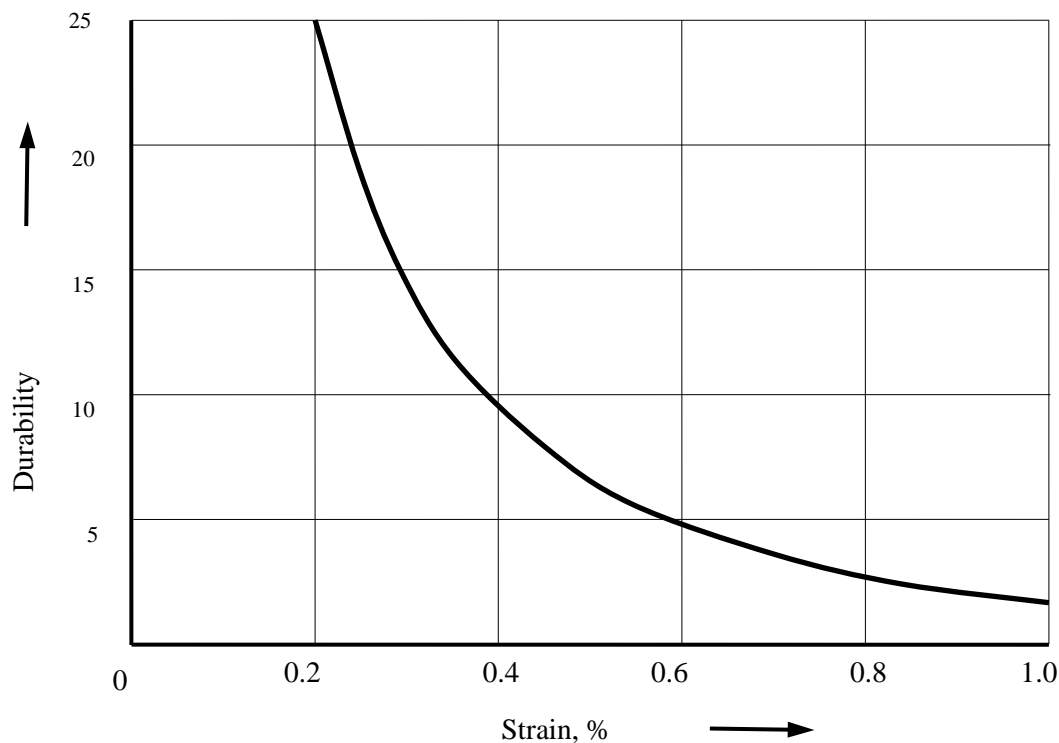


Figure 6. Graph of dependence of the OF durability on the magnitude of the tensile load

The graph helps to determine the dependence of the OF durability on the strain, and find the necessary value of the OF strain for given durability.

5. Result discussion

A permitted value of readiness performance is $K_{AF}(T) = 0.999$. We determine the life of the FOCL by this value. If the OF strain is not more than 0.2%, the service life of the FOCL will be 25 years. If the strain of the OF increases to the level of 0.33 %, the service life of the OF will be 13 years. A further increase in strain to 0.45 % leads to reduction of the FOCL life up to 8 years.

6. Conclusion

The performed tests show that strain changes of the OFs influence on the readiness performances of the FOCL.

Process modeling of optical signal propagation in the OF enables the performance of the FOCL reliability by the above equations to be determined.

The use of BOTDR in the monitoring system for the FOCL significantly increases its reliability, because it allows “problem” sections in the OF to be detected in advance.

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