

MACHINE BUILDING

МАШИНОСТРОЕНИЕ



UDC 629

Original Theoretical Research

<https://doi.org/10.23947/2541-9129-2026-10-1-32-46>

Predicting the Reliability of Steel Ropes at the Design Stage

Anatoly A. Kotesov 

Don State Technical University, Rostov-on-Don, Russian Federation

✉ a.kotesov@yandex.ru

EDN: CEJWGJ

Abstract

Introduction. Ensuring the safety of lifting equipment is closely linked to the reliability of steel ropes operating under variable loads and in aggressive environments. Increased design complexity, higher operational intensity, and larger machine lifting capacities lead to increased human-made risks and economic losses. Traditional methods, such as static safety factors and visual inspections, are ineffective in the face of digitalization and increased operational intensity. According to regulatory authorities, 20% of accidents involving lifting equipment are caused by rope defects, with more than 5,000 injury incidents recorded annually. The literature describes statistical defect analysis, tribological models of wire wear that take into account friction and lubricant degradation, and hierarchical modeling of rope as a system. However, there are still some serious systemic problems: models are not fully integrated into practice, theoretical knowledge is not always applied in engineering methods, and predictive models do not allow for a comprehensive analysis of operational factors. To address these issues, the aim of this work is to develop a predictive model for assessing the reliability of steel ropes at the design stage. This model takes into account regulatory requirements in order to prevent sudden failures and optimize operations.

Materials and Methods. The study was based on the proposed hierarchical decomposition of rope reliability by degradation levels, which allowed for the algorithmic implementation of the “weakest link” principle for sequential systems. The modeling object was a 6×36 WS FC (two lay rope type) steel rope according to GOST 7668–80 used in gantry crane mechanisms. RD ROSEK 012–97 standards were adapted to the design tasks using a polynomial approximation method of discrete criteria into continuous limit state functions. To assess reliability at various hierarchical levels, a combination of Kelvin-Voigt, Archard, and Weller models, as well as the Weibull, Poisson, and normal distributions, was applied. Mathematical data processing and probability calculations were implemented in MS Excel and Mathcad. The model was verified by comparing predicted curves with the estimated service life according to the ISO 16625 methodology for M5 and M6 modes.

Results. Based on the RD ROSEK 012–97 rejection standards, generalized limit states for 6×36 WS FC rope (GOST 7668) were determined. Analytical functions were derived for the relationship between the permissible number of breaks, wear, and corrosion, as well as the dependence of cross-sectional area loss on accumulated defects for M1–M8 modes. A comprehensive predictive reliability model was developed that integrates probabilistic processes of wire breakage accumulation, wear kinetics, and rheological degradation of the core into a single calculation model.

Discussion. The proposed approach aims to bridge the gap between theoretical knowledge and operational practice, by considering the synergy of degradation mechanisms. It resolves the contradiction between the parallel development of defects and the sequential approach (“weakest link model”), using the principle of criticality in any limit state. Unlike additive methods, this approach incorporates the concept of dynamically dependent parameters. The rheology of the material alters the contact conditions between wires, accelerating fatigue damage accumulation. Using this approach as an analytical tool during design ensures high accuracy in predictions. However, due to the heterogeneity of models, it is necessary to develop a specific criterion for assessing overall error.

Conclusion. The model is designed to be used during the design phase of lifting equipment to predictively assess reliability and minimize the risk of sudden rope failure in accordance with GOST 7668–80. It takes into account regulatory requirements and provides a 37% more conservative forecast compared to ISO 16625. Future development plans include extending the model to other rope design groups and integrating it into engineering practice.

Keywords: steel rope, reliability, failure-free operation, predictive model, hierarchical decomposition, wear and corrosion, rheological degradation of the core

Acknowledgements. The author would like to express their gratitude to the reviewers for their critical assessment of the submitted materials and their constructive suggestions for improvement. These comments have significantly contributed to the enhancement of the quality of the research presentation.

For Citation. Kotesov AA. Predicting the Reliability of Steel Ropes at the Design Stage. *Safety of Technogenic and Natural Systems*. 2026;10(1):32–46. <https://doi.org/10.23947/2541-9129-2026-10-1-32-46>

Оригинальное теоретическое исследование

Прогнозирование надежности стальных канатов на этапе проектирования

А.А. Котесов 

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ a.kotesov@yandex.ru

Аннотация

Введение. Обеспечение безопасности грузоподъемных машин тесно связано с надежностью стальных канатов, работающих под переменными нагрузками и в агрессивных средах. Рост сложности конструкций, высокая интенсивность эксплуатации и увеличение грузоподъемности машин приводят к росту техногенных рисков и экономическим потерям. Традиционные методы — статические коэффициенты запаса и визуальный контроль — неэффективны при цифровизации и росте интенсивности эксплуатации. По данным надзорных органов, 20 % аварий на подъемных сооружениях вызваны дефектами канатов, а ежегодно фиксируется свыше 5000 инцидентов с травматизмом. В литературе описаны статистический анализ дефектов, трибологические модели износа проволок с учетом трения и деградации смазки, иерархическое моделирование каната как системы. Однако сохраняются серьезные системные проблемы: модели слабо интегрированы в практику, теория отделена от инженерных методов и предиктивные модели не предусматривают комплексного анализа динамики эксплуатационных факторов. Поэтому целью данной работы явилась разработка предиктивной модели оценки надежности стального каната на этапе проектирования с учетом нормативных требований для исключения внезапных отказов и оптимизации эксплуатации.

Материалы и методы. В основе исследования — предложенная иерархическая декомпозиция надежности каната по уровням деградации, позволившая алгоритмизировать принцип «слабого звена» для последовательных систем. Объект моделирования — стальной канат 6×36 ЛК-РО по ГОСТ 7668-80 в составе механизмов портального крана. Адаптация норм РД РОСЭК 012-97 к задачам проектирования выполнена методом полиномиальной аппроксимации дискретных критериев в непрерывные функции предельных состояний. Для оценки безотказности на различных уровнях иерархии использован комплекс моделей Кельвина–Фойгта, Арчарда, Веллера, а также распределения Вейбулла, Пуассона и нормальный закон. Математическая обработка данных и расчеты вероятностных показателей реализованы в средах MS Excel и Mathcad. Верификация модели проведена сопоставлением прогнозных кривых с расчетным ресурсом по методике ISO 16625 для режимов М5 и М6.

Результаты исследования. На основе норм браковки РД РОСЭК 012–97 определены обобщенные предельные состояния каната 6×36 ЛК-РО (ГОСТ 7668). Получены аналитические зависимости допустимого числа обрывов от износа и коррозии, а также функции связи потери площади сечения с накопленными дефектами для режимов М1–М8. Разработана комплексная предиктивная модель надежности, объединяющая вероятностные процессы накопления обрывов проволок, кинетику износа и реологическую деградацию сердечника в единую вычислительную схему.

Обсуждение. Предложенный подход сокращает разрыв между теорией и практикой эксплуатации за счёт учета синергии механизмов деградации. Противоречие между параллельным развитием дефектов и последовательной «моделью слабого звена» разрешено через принцип критичности каждого предельного состояния. В отличие от аддитивных методов реализована концепция динамически зависимых параметров — реологические изменения сердечника трансформируют условия контакта проволок и тем самым ускоряют накопление усталостных повреждений. Применение разработанного аппарата в проектировании повышает точность прогноза. В то же время гетерогенность используемых моделей диктует необходимость создания специфического критерия достоверности для оценки суммарной погрешности.

Заключение. Модель предназначена для применения на этапе проектирования грузоподъёмных машин с целью предиктивной оценки безотказности и минимизации рисков внезапных отказов канатов по ГОСТ 7668–80. Модель позволяет учесть нормативные требования и обеспечивает на 37 % более консервативный прогноз по сравнению с ISO 16625. Дальнейшее развитие предполагает распространение модели на другие конструктивные группы канатов и внедрение в инженерную практику.

Ключевые слова: стальной канат, надёжность, безотказность, предиктивная модель, иерархическая декомпозиция, износ и коррозия, реологическая деградация сердечника

Благодарности. Автор выражает благодарность рецензентам, чья критическая оценка представленных материалов и конструктивные предложения по их совершенствованию способствовали существенному повышению качества изложения результатов исследования.

Для цитирования. Котесов А.А. Прогнозирование надёжности стальных канатов на этапе проектирования. *Безопасность техногенных и природных систем.* 2026;10(1):32–46. <https://doi.org/10.23947/2541-9129-2026-10-1-32-46>

Introduction. Steel ropes are critically important load-bearing elements of lifting machines that determine their safety and operational efficiency. According to Rostechnadzor and global industry research, up to 20% of lifting accidents are related to critical rope defects. Rope failure can lead to economic losses due to downtime and disruptions of logistics cycles, as well as man-made consequences. Statistics show that over 5,000 incidents occur annually due to broken traction and load-bearing elements, with approximately 30% having consequences for human life and health [1].

A steel rope is a complex mechanical and technical system that distributes the load between interconnected elements that operate in different conditions and are subject to aging, corrosion, wear, and fatigue damage. This makes it difficult to assess the reliability of the entire system. Existing design methods compensate for uncertainty through significant safety factors. However, practice shows that this approach does not provide the required reliability for modern high-power lifting machines with high work intensity—it does not exclude sudden failures and is economically inefficient. In these conditions, in order to reduce man-made risks and improve operational efficiency, it is necessary to move from the use of stock coefficients and visual control to predictive design and analytics that provide an estimated level of reliability based on predictive failure models.

Research on steel ropes reliability has been conducted for decades and covers the stages of design, production and operation. In 1963, with the support of OITAF and RILEM organizations, the international organization for the study of rope fatigue, OIPEEC, was established.

Modern development of artificial intelligence and digital vision has significantly advanced the issues of predictive analytics of steel ropes. The developed methods and automated digital control systems described in the works of M.N. Khalfin [2, 3], A.A. Korotkov [4, 5], A.V. Panfilov [6, 7] and A.A. Kulchitskiy [8] are being actively implemented in operational practice.

An important stage for the development of predictive design is the updating of ISO 16625, which involves determining the margin coefficient and evaluating fatigue life, taking into account a variety of factors, which marks the transition from simplified calculations to deep modeling of real-world operating conditions.

The complexity of distribution of mechanical properties and loads between the elements is a determining factor in the reliability of a steel rope. The multilayer structure of the rope is hierarchical in nature: the internal elements serve as a support for the external ones. The violation of these supporting links leads to degradation of the rope structure and changes in the working conditions of its elements. Wahid A. [9, 10] designates this phenomenon as the effect of “systemic wear” that occurs when core stability is lost.

The basis for the implementation of predictive design is the consideration of the rope as a system. Mouradi H. [11] proposed a method for predicting durability using majority logic, where the key aspect is the mathematical relationship between the probability of trouble-free operation and the degree of accumulated damage. Bassir Y. [12] notes that the analysis of the hierarchical structure makes it possible to transform the failure statistics of the basic elements into an accurate forecast of the reliability of the entire rope. Xia Y. [13] suggests conducting finite element analysis at three hierarchical levels: at the micro level—wire contact, at the meso level—the interaction of strands, and at the macro level—the behavior of the entire rope. This approach takes into account local friction and intermittent sliding during bending, described in the Han Y. model [14], as well as the loss of cross-sectional area from wear over time, considered by Salleh S. [15]. Studies by Peng Y. [16] and Xu C. [17] focus on the processes of internal friction and inter-wire wear, confirming that the degradation rate directly depends on lay parameters and lubrication rate. V.P. Golovin [18] demonstrates the effectiveness of synthetic thickeners of rope lubricants, and Peng H. [19] emphasizes the need to take into account the degradation of lubricant properties as a key factor in rope durability. V.Yu. Volokhovskiy [20] examines the effect of thermal cycles on the ropes of metallurgical cranes and suggests a transition from deterministic calculations to risk assessment as the probability of a random event in which the diagnostic indicator of the rope exceeds the established rejection level.

The analysis of modern research shows that, despite the in-depth study of certain aspects of rope operation, the issue of assessing their reliability as machine elements remains insufficiently studied. The gap between theoretical degradation models and practical design methods prevents the full realization of the potential of the predictive approach. As a result, reliability rationing becomes an urgent task, requiring the establishment of quantitative normative values and the selection of adequate evaluation criteria. There is an objective need to create comprehensive reliability forecasting models that take into account the design features of the rope, the expected operating conditions and the requirements of regulatory and technical documentation.

The aim of this research is to develop a model for predicting the reliability of a steel rope, taking into account the multicomponent structure, operating conditions and requirements of regulatory and technical documentation (using the example of a two lay rope GOST 7668 as part of gantry crane mechanisms).

Research objectives:

- perform the analysis of the requirements of regulatory and technical documentation and determine the limits of the steel rope's operability;
- determine boundary values of indicators corresponding to the transition of the system to the limiting state, taking into account the dominant mechanisms of destruction;
- integrate regulatory criteria into the reliability forecasting model;
- develop a comprehensive mathematical model for reliability assessment.

Materials and Methods. The research was based on the proposed hierarchical decomposition of steel rope reliability by degradation levels and algorithmization of the “weak link” principle for sequential systems according to the principles of calculating the probability of trouble-free operation of elements of lifting cranes RTM 24.090.25–76. The object of the simulation was a two lay steel rope with a diameter of 27 mm. 6×36(1+7+7/7+14)+1 WS FC according to GOST 7668–80 as part of lifting mechanism of Kirovets gantry crane 16/20 (Fig. 1, Table 1).

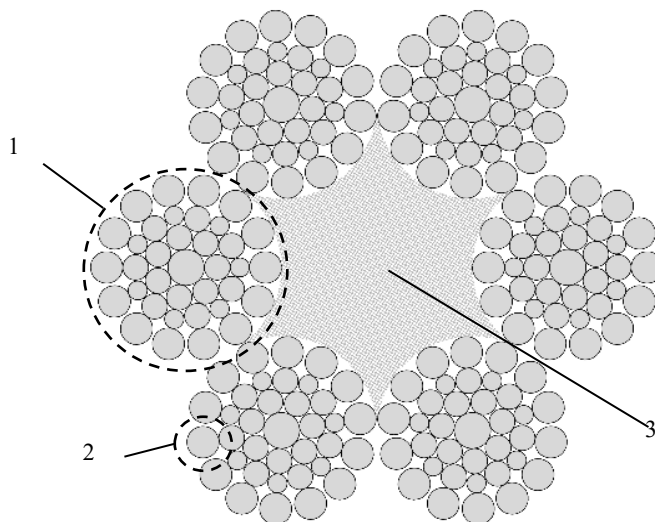


Fig. 1. Cross section of a steel rope 6×36(1+7+7/7+14)+1 WS FC according to GOST 7668–80:
1 — strand; 2 — wire; 3 — fiber core

Table 1

Scheme of a strand of steel rope 27 mm 6×36 WS FC according to GOST 7668–80

	Central	1-st layer	2nd layer A	2-nd layer B	3-d layer (outer)
Group of wire strands					
Number, pcs.	1	7	7	7	14
Wire diameter, mm	1.70	1.20	1.20	0.90	1.50

Reliability was accepted as an indicator of the failure-free operation of a steel rope in accordance with GOST R 27.102–2021¹. The choice of the indicator was due to the unmaintainability of the rope as a separate element of the lifting machine and the continuous nature of the processes of corrosion of wires and aging (decomposition) of the core, which could occur regardless of the intensity of operation.

To establish the limits of the working capacity of a steel rope, an analysis of RD ROSEC 012–97² rejection standards was performed, which took into account defects caused by natural wear and aging of the rope material (Table 2) and the acceptable number of wire breaks, taking into account the wear rate and the classification group (operating mode) of the mechanism (Table 3). The analyzed defects were systematized by the nature of degradation: A — wire breaks, B — wire wear, C — fiber core degradation. Taking into account the discrete nature of the damage accumulation process, the calculated values of the number of breaks were rounded upward. Critical defects that occurred instantly, such as creases, kinks, electric arc damage, lightning, fire, etc., were excluded from consideration.

Table 2

Rejection standards of steel rope 6×36(1+7+7/7+14) +1 WS FC GOST 7668 when operating on lifting cranes according to RD ROSEK 012–97

Defect designation	Defect description	Rejection standards	Mechanism (cause) of the defect
A1	External wire breaks in 6d section	Acceptable number of breaks is shown in Table 3	Fatigue wear, mechanical wear, corrosion (oxygen, electrochemical, chemical)
A2	External wire breaks in 30d section	Acceptable number of breaks is shown in Table 3	
A3	Local wire breaks concentrated on a single rope strand	Three or more broken wires	
B1	Surface wear of the rope	Outer wires diameter reduction by 40% or more	Mechanical wear and corrosion (oxygen, electrochemical, chemical)
B2	Loss of the metal part of the rope cross-section (loss of the inner section)	Loss of the metal part of the rope cross-section by 17.5% or more	Breakages, mechanical wear and corrosion (oxygen, electrochemical, chemical) of the wires of inner layers
B3	Surface wear and corrosion	Rope diameter reduction by 7% or more	Mechanical wear, corrosion (oxygen, electrochemical, chemical)
B1	Reduction of rope diameter as a result of core damage	Rope diameter reduction by 10%	Wear, crumpling, tearing, aging of fibers or complete destruction (breakage) of the core
B2	Local increase in rope diameter	Rope diameter increase by 7 %	Exposure to moisture and low temperatures leads to expansion (swelling) of the core. Uneven redistribution of core fibers along the length (rolling area)

¹ GOST R 27.102-2021. *Dependability in Technics. Dependability of Item. Terms and Definitions.* (In Russ.) URL: https://rosgos.ru/file/gost/21/020/gost_r_27.102-2021.pdf (accessed: 20.10.2025)

² RD ROSEC 012-97. *Regulatory Document. Steel Ropes. Control and Rejection Standards.* (In Russ.) URL: <https://files.stroyinf.ru/Data2/1/4293850/4293850134.pdf> (accessed: 20.10.2025)

Table 3

Number of wire breaks in the presence of which steel ropes of lifting cranes working with steel and cast-iron blocks of 6×36(1+7+7/7+14)+1 WS FC design are rejected according to GOST 7668 in accordance with RD ROSEC 012–97

Reduction of wire diameter as a result of surface wear or corrosion, %	Percentage of acceptable wire breaks depending on wear and tear, %	Mechanism classification (mode) group	Number of wire breaks N^*			
			Cross lay		Long lay	
			In a section of length			
			6d	30d	6d	30d
0	100	M1 – M4	7	14	4	7
		M5 – M8	14	29	7	14
10	85	M1 – M4	5	11	3	5
		M5 – M8	11	24	5	11
15	75	M1 – M4	5	10	3	5
		M5 – M8	10	21	5	10
20	70	M1 – M4	4	9	2	4
		M5 – M8	9	20	4	9
25	60	M1 – M4	4	8	2	4
		M5 – M8	8	17	4	8
30 и более	50	M1 – M4	3	7	2	3
		M5 – M8	7	14	3	7

Note: * N — number of wire breaks in the 3rd (outer) layer; d — rope diameter, mm

To synthesize the forecasting model, we decomposed the steel rope's reliability by degradation levels and determined generalized limiting states for groups A, B, and C (Table 4). We implemented a hierarchical relationship between degradation levels through a system of dynamically dependent parameters. In this system, the predicted values of wear and deformation at the current time step acted as variable boundary conditions for evaluating the subsequent states of the system. The method of calculating losses of metal cross-section was based on a combined consideration of mechanical wear of wires and atmospheric corrosion. We introduced the parameters of medium aggressiveness into the model as an additive degradation factor that determined the rate of decrease in wire diameter in the outer layer of the rope.

The methodology for substantiating the generalized limit state for group B was implemented through the calculation of the total loss of metal section area as a function of surface wear of wires, taking into account the dynamic breakage threshold N_{lim} , which determined the point of joint achievement of the limit state according to criteria B1 (wear) and B2 (loss of cross-sectional area) (Fig. 2, 3).

The dynamically changing threshold for the acceptable number of N_{lim} breaks was determined based on the approximation of discrete dependencies presented in Table 3 (Fig. 4, 5).

To verify the results, a comparative analysis of the predicted reliability curves with the calculated value of the median service life for M6 operating mode according to ISO 16625 was applied. Mathematical data processing was performed using MS Excel 14.0.4760.1000 and Mathcad 14.0.0.163. The dependencies were approximated by a polynomial function of 3–4 orders of magnitude; the coefficient of determination was in the range 0.9425–0.9998.

Results. During the study, we obtained the dependencies of the total loss of cross-sectional area of the rope metal part on the amount of surface wear of wires in the outer layer (Fig. 2, 3). Based on the curves obtained, we found that, considering the contribution of the dynamic number of wire breaks N_{lim} and formal compliance with regulatory requirements for wear (Table 2), a critical threshold of 17.5% (defect B2) was achieved with surface wear values less than 40% (defect B1).

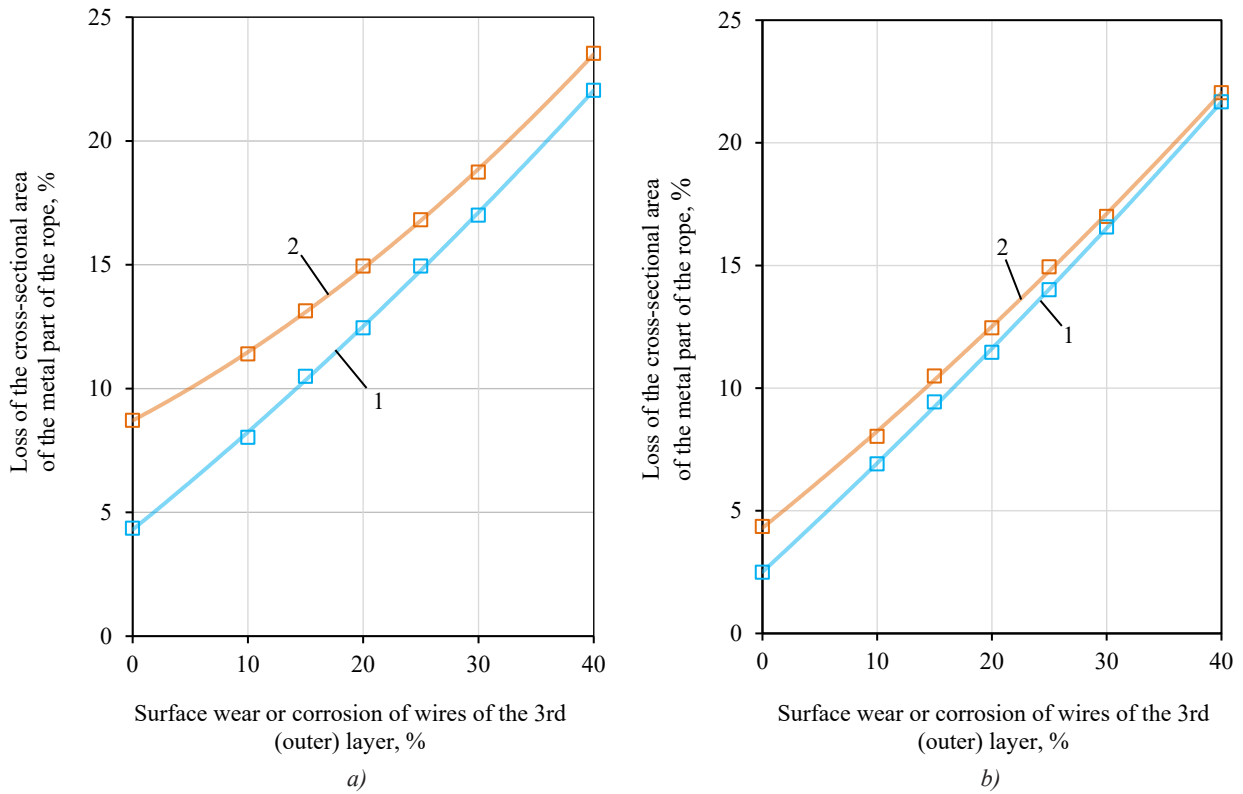


Fig. 2. Dependence of the loss of cross-sectional area of the metal part of the rope on the number of breaks, surface wear or corrosion of the wires of the 3rd (outer) layer for the classification group (mode) of M1–M4 mechanism: *a* — cross lay; *b* — long lay; 1 — in a section with a length of $6d$; 2 — in a section with a length of $30d$; d — rope diameter

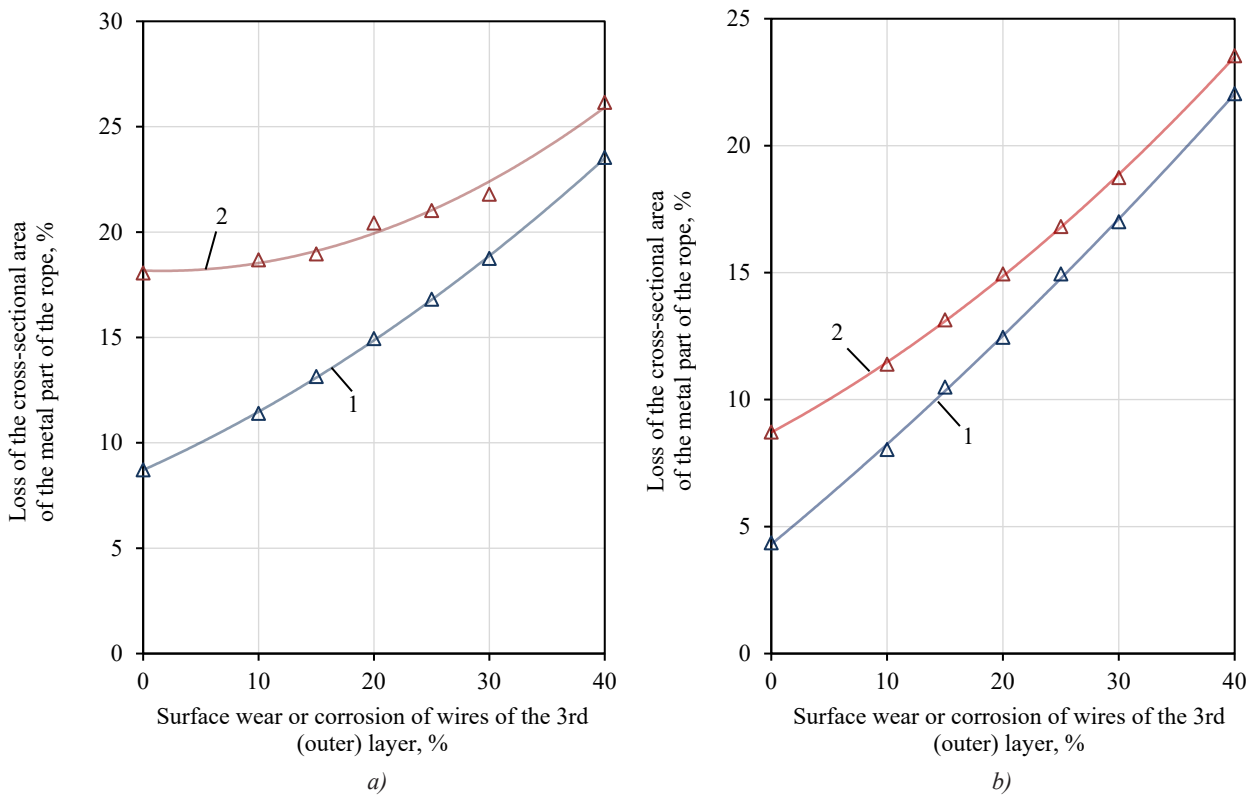


Fig. 3. Dependence of the loss of cross-sectional area of the metal part of the rope on the number of breaks, surface wear or corrosion of the wires of the 3rd (outer) layer for the classification group (mode) of M5–M8 mechanism: *a* — cross lay; *b* — long lay;

As a result of hierarchical decomposition of rope reliability by degradation levels, a generalization of regulatory defects was performed (Tables 2, 3) and a selection of mathematical models for predicting reliability was made. The formulated generalized criteria for limit states and the corresponding calculation apparatus were systematized and described in Table 4.

Generalized limiting conditions and models for predicting the reliability of $6 \times 36(1+7+7/7+14)+1$ WS FC steel rope by groups of defects according to GOST 7668

Group of defects	Combined private defects	Generalized limit state of the group	Reliability assessment model
A	A1, A2 (distributed breaks), A3 (local breaks on strands)	Reaching the threshold number of N_{lim} breaks, dynamically dependent on current wear or the presence of ≥ 3 breaks in one strand	Inhomogeneous Poisson process combined with a “weak link” model (estimates the probability that a discrete number of breaks will not exceed the safety threshold)
B	B1 (wire wear), B2 (internal cross section), B3 (nominal diameter)	Reduction of the metal cross-sectional area below the acceptable one (17.5%) as a result of cumulative wear of external and internal wires	Kinetic model of Archard degradation with a corrosion additive (determines the probability of maintaining the bearing capacity above a critical level)
C	C1 (shrinkage or destruction of the core), C2 (core swelling)	Nominal diameter of the rope goes beyond the range $[-10\%; +7\%]$, leading to the loss of radial support of the strands	Rheological model of Kelvin-Voigt structure stability (estimates the probability of non-destruction of the core and maintenance of the geometric shape of the rope)

Based on the data in Table 3, analytical dependencies of the acceptable number of N_{lim} wire breaks on the degree of surface wear and corrosion of the outer layer of wires (expressed as a percentage of the nominal diameter of wires) were obtained, determining the dynamically changing limits of rope operability in the reliability model (Fig. 4, 5).

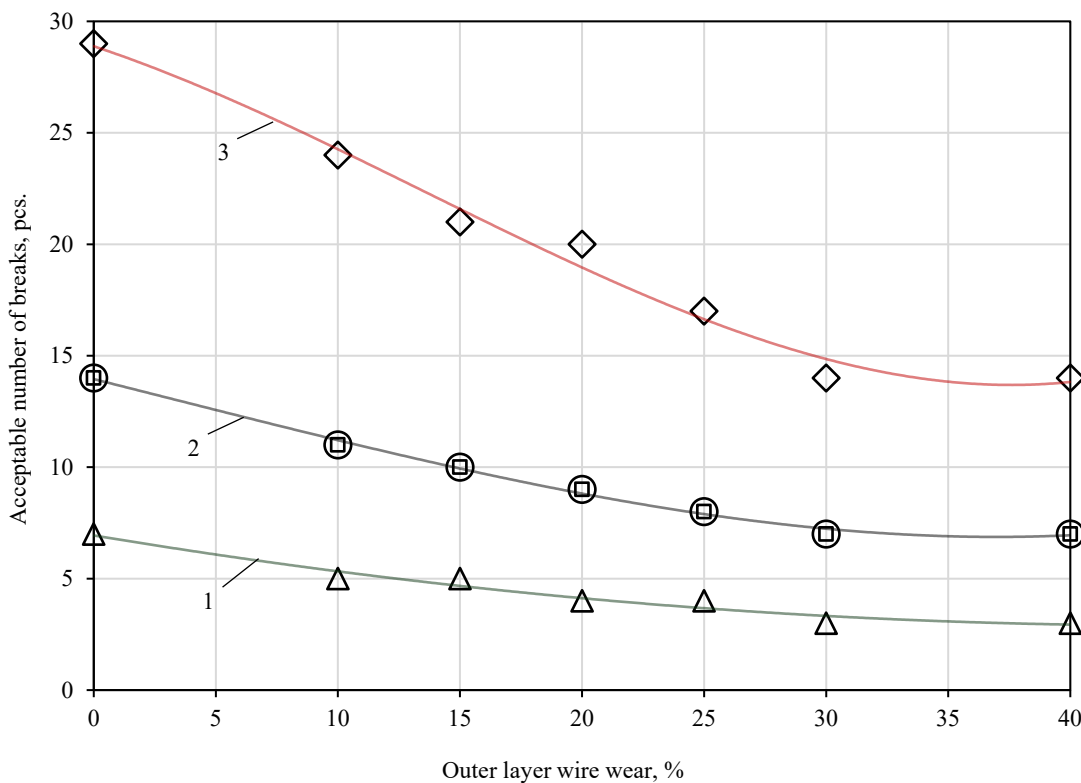


Fig. 4. Dependence of the acceptable number of breaks on wear and corrosion of wires of the outer layer for the classification group (mode) of M1-M4 mechanism for $6 \times 36(1+7+7/7+14)+1$ WS FC GOST 7668 rope structure: 1 — long lay at section $6d$ ($R^2 = 0.9617$); 2 — cross lay in section $6d$ and long lay in section $30d$ ($R^2 = 0.9959$); 3 — cross lay in section $30d$ ($R^2 = 0.9866$); d — rope diameter

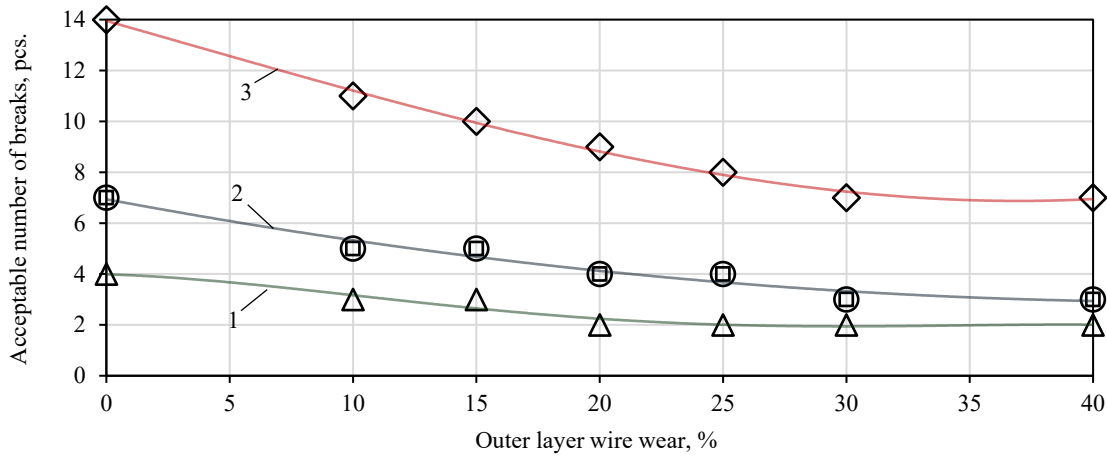


Fig. 5. Dependence of the acceptable number of breaks on wear and corrosion of wires of the outer layer for the classification group of the mechanism M5-M8 for $6 \times 36(1+7+7/7+14) + 1$ WS FC GOST 7668 rope structure: 1 — long lay in $6d$ section ($R^2 = 0,9959$); 2 — cross lay in section $6d$ and long lay in section $30d$ ($R^2 = 0,9617$); 3 — cross lay in section $30d$ ($R^2 = 0,9425$); d — rope diameter

To determine the acceptable number of wire breaks $N_{lim}(x)$, we obtained the following expressions for ropes:

– long lay in sections $6d$ in M1-M4 mode and $30d$ in M5-M8 mode, as well as cross lay in section $6d$ in M5–M8 mode:

$$N_{lim}(x) = (-3.0 \cdot 10^{-18})x^3 + (2.0 \cdot 10^{-3})x^2 - 0.18x + 6.94; \quad (1)$$

– cross lay in sections $6d$ in M1-M4 mode and $30d$ in M5-M8 mode, as well as long lay in in section $30d$ in M1-M4 mod:

$$N_{lim}(x) = (8.0 \cdot 10^{-5})x^3 - (6.0 \cdot 10^{-4})x^2 - 0.28x + 13.95; \quad (2)$$

– cross lay in section $30d$ in M1–M4 mode:

$$N_{lim}(x) = (3.0 \cdot 10^{-4})x^3 - (1.28 \cdot 10^{-2})x^2 - 0.37x + 28.88; \quad (3)$$

– long lay in section $6d$ in M5–M8 mode:

$$N_{lim}(x) = (-4.0 \cdot 10^{-6})x^4 + (4.0 \cdot 10^{-4})x^3 - (8.7 \cdot 10^{-3})x^2 - (2.81 \cdot 10^{-2})x + 3.99. \quad (4)$$

Based on reasonable criteria for limiting conditions (Table 4), an algorithm for predictive reliability modeling has been developed, presented as a flowchart in Figure 6.

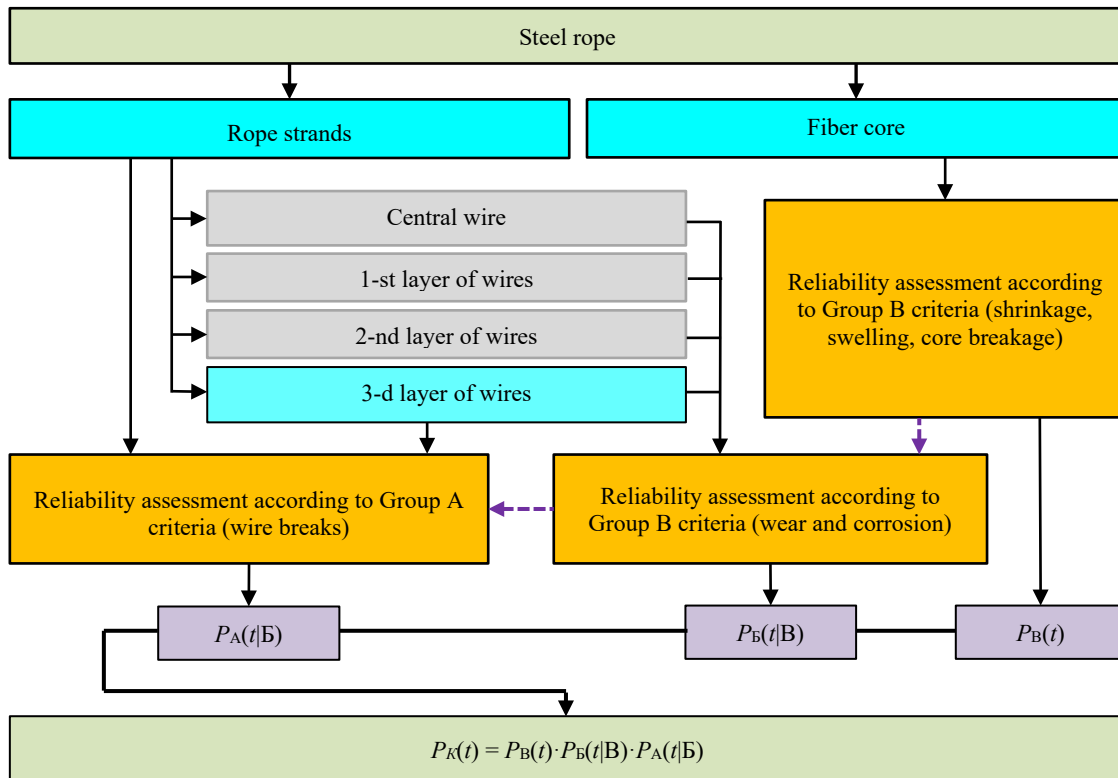


Fig. 6. Flowchart of a model for predicting the reliability of a steel rope structure $6 \times 36(1+7+7/7+14) + 1$ WS FC according to GOST 7668

Description of the model. The following is an analytical description of the reliability assessment models according to criteria groups C, B, and A according to Table 4 and the flowchart in Figure 6.

I. Reliability assessment in accordance with the limiting condition of group C:

$$P_B(t) = \exp\left(-\left(\frac{t}{T_B}\right)^{\beta_B}\right), \quad (5)$$

where T_B — fiber core characteristic resource, h; β_B — parameter that determines the intensity of core aging;

$$T_B = \frac{1}{k_{\text{дег.}}} \cdot \ln\left(1 - \frac{\varepsilon_{\text{lim}} \cdot E_B}{q}\right),$$

where $k_{\text{дег.}}$ — constant of the core degradation process, h⁻¹; E_B — core elasticity modulus, MPa; q — radial pressure of the strands, MPa.

Deformation of the core under load at time t according to the Kelvin-Voigt model:

$$\varepsilon(t) = \frac{q}{E_B} \left(1 - e^{-\frac{E_B \cdot t}{\eta_B}}\right),$$

where η_B — dynamic viscosity of the rope lubricant, MPa · h; t — estimated time, h.

To account for changes in the structural stability of the core when assessing reliability according to the limiting state of group B, it is proposed to determine the coefficient of wear intensification in case of structural instability of the core:

$$K_{\text{стр.}} = 1 + \frac{\varepsilon(t)}{\varepsilon_{\text{lim}}},$$

where ε_{lim} — maximum acceptable deformation.

II. Reliability assessment in accordance with the limiting condition of group B:

$$P_B(t) = \Phi\left(\frac{k_A \cdot A_0 - E[\Delta A_{\Sigma}(t)]}{\sqrt{D[\Delta A_{\Sigma}(t)]}}\right), \quad (6)$$

where k_A — coefficient of acceptable loss of metal section of the rope; A_0 — nominal cross-sectional area of the metal part of the rope, mm²; ΔA_{Σ} — cumulative loss of the cross-sectional area of wires of outer and inner layers, mm²; $E[\Delta A_{\Sigma}]$ and $D[\Delta A_{\Sigma}]$ — mathematical expectation and variance of a random value of cumulative loss of cross-sectional area of the metal part of the rope.

The mathematical expectation of the cumulative loss of cross-sectional area of the metal part of the rope is determined by the expression:

$$E[\Delta A_{\Sigma}(t)] = E[\Delta A_{\text{внеш.}}(t)] + E[\Delta A_{\text{внут.}}(t)],$$

where $\Delta A_{\text{внеш.}}(t)$ and $\Delta A_{\text{внут.}}(t)$ — cumulative loss of cross-sectional area of outer and inner wires at time t .

$$\Delta A_{\text{внеш.}}(t) = Z_{\text{внеш.}} \cdot f_{\Delta A}(E[h_{\text{внеш.}}(t)]) \quad \text{and} \quad \Delta A_{\text{внут.}}(t) = Z_{\text{внут.}} \cdot f_{\Delta A}(E[h_{\text{внут.}}(t)]),$$

where $Z_{\text{внеш.}}$ and $Z_{\text{внут.}}$ — number of wires in outer and inner layers; $f_{\Delta A}(h(t))$ — function that determines the area loss depending on the amount of wear $h(t)$.

Mathematical expectations of the amount of wear on outer and inner wires are determined by the Archard model of wear kinetics with a corrosion additive:

$$E(h_{\text{внеш.}}(t)) = \left(\frac{K_{\omega} \cdot p \cdot v}{H} \cdot K_{\text{стр.}} + v_{\text{кор.}}\right) \cdot t \quad \text{and} \quad E(h_{\text{внут.}}(t)) = (K_f \cdot K_{\text{стр.}} \cdot \sigma_{\text{кон.}} \cdot \delta + v_{\text{кор.}}) \cdot t,$$

where K_{ω} — coefficient of wear rate (depends on the conditions of friction and lubrication); p — average contact pressure in the “wire — block groove” pair, MPa; v — average relative sliding speed of the rope in the groove, mm/h; $v_{\text{кор.}}$ — average corrosion rate for a specific category of medium, mm/h; H — hardness of the wire material, MPa; K_f — coefficient of fretting wear of wires (determined from reference data); $K_{\text{стр.}}$ — coefficient of wear intensification with structural instability of the core; $\sigma_{\text{кон.}}$ — contact stress between the wires inside the strand, MPa; δ — amplitude of wire slippage during bending, mm; $h_{\text{внеш.}}(t)$ — amount of wear on the outer wires, mm; $h_{\text{внут.}}(t)$ — amount of wear on the inner wires, mm; t — estimated time, h.

The average corrosion rate for a specific category of medium is proposed to be determined according to GOST ISO 9226³.

³ GOST ISO 9226 – 2022. *Corrosion of Metals and Alloys. Corrosivity of Atmospheres. Determination of Corrosion Rate of Standard Specimens for the Evaluation of Corrosivity, IDT*. (In Russ.)

The dispersion of the cumulative cross-sectional area losses of the metal part of the rope is determined by the expression:

$$D[\Delta A_{\Sigma}(t)] = D[A_{\text{внеш.}}(t)] + D[A_{\text{внут.}}(t)] + 2 \text{cov}[A_{\text{внеш.}}(t), A_{\text{внут.}}(t)].$$

Accordingly, the expression includes variances of the random value of the loss of the cross-sectional area of the outer and inner wires:

$$D[\Delta A_{\text{внеш.}}(t)] = (E[\Delta A_{\text{внеш.}}(t)] \cdot v_{\text{внеш.}})^2 \quad \text{and} \quad D[\Delta A_{\text{внут.}}(t)] = (E[\Delta A_{\text{внут.}}(t)] \cdot v_{\text{внут.}})^2,$$

where $v_{\text{внеш.}}$ — coefficient of variation of loss of the cross-sectional area of outer wires; $v_{\text{внут.}}$ — coefficient of variation of loss of the cross-sectional area of inner wires.

As well as the covariance matrix:

$$\text{cov}[A_{\text{внеш.}}(t), A_{\text{внут.}}(t)] = \rho \sqrt{D[\Delta A_{\text{внеш.}}(t)] \cdot D[\Delta A_{\text{внут.}}(t)]},$$

where ρ — correlation coefficient.

III. Reliability assessment in accordance with the limiting condition of group A. The model assumes the use of Poisson distribution, where the intensity of defects is modeled by Weibull's law and increases with wear:

$$P_A(t) = \left[\sum_{k=0}^{N_{lim}-1} \frac{(\Lambda(t))^k e^{-\Lambda(t)}}{k!} \right] \cdot \left[e^{-\Lambda(t)} \left(1 + \frac{\Lambda(t)}{n_{np}} + \frac{\Lambda(t)^2}{2n_{np}^2} \right) \right]^{n_{np}}, \quad (7)$$

where N_{lim} — safety threshold for the number of breaks (decreasing with wear); k — accumulated number of breaks over time; $\Lambda(t)$ — mathematical expectation of the number of breaks at time t ; n_{np} — number of strands; t — estimated time, h.

To take into account the predicted wear when estimating the probability of trouble-free operation under limiting conditions of group B, you should determine $A(t)$ using function $f_{\Delta A}(h(t))$ (see part II), and the maximum number of breaks N_{lim} using dependencies 1–4, assuming $x = 100 (A_0 - A(t)) / A_0$.

The frequency of breaks, considering the accumulation of fatigue damage:

$$\Lambda(t) = \left(\frac{t}{\eta(A(t))} \right)^{\beta_A},$$

where β_A — shape parameter that determines the wear rate; $\eta(A(t))$ — scale parameter that determines the resource, h.

The scale parameter defines the following dependency:

$$\eta(A(t)) = \eta_0 \left(\frac{A(t)}{A_0} \right)^m,$$

where m — indicator of sensitivity of the characteristic resource to overstress (indicator of the angle of inclination of the fatigue curve); η_0 — characteristic resource of the new rope with nominal cross-section A_0 , h; A_0 — nominal cross-sectional area of the steel rope wire without wear, mm²; $A(t)$ — cross-sectional area of the steel rope wire at time t , mm².

The scale parameter assumes that the equivalent stress in the wire section increases as the wire cross-sectional area decreases:

$$\sigma(t) = \frac{S}{A(t)},$$

where S — equivalent load on the wire, N.

It should be noted that this model uses the dependence of the resource on the cross-sectional area, which corresponds to the Weller model:

$$\sigma^m \cdot N_{\text{циклов}} = \text{const}.$$

Since stresses $\sigma(t)$ are inversely proportional to cross-sectional area of wire $A(t)$, the following expression can be derived:

$$\left(\frac{1}{A} \right)^m \cdot N_{\text{циклов}} = \text{const}.$$

In this case, indicator of the inclination angle of fatigue curve m in this model is equivalent to the indicator of the slope of the fatigue curve of the wire material.

$$\eta_0 = \frac{N_{\text{циклов}}}{\omega \cdot n_{\sigma} \cdot k_p},$$

where $N_{\text{циклов}}$ — number of cycles before cracks appear, ω — frequency of operation — the number of work cycles per hour, h⁻¹; n_{σ} — number of blocks; k_p — multiplicity of work per cycle.

To predict the number of cycles before the appearance of cracks $N_{циклов}$, it is proposed to use the empirical formula of Professor K. Feirer:

$$LgN_{циклов} = b_0 + \left(b_1 + b_3 \cdot l g \frac{D}{d} \right) \cdot \left(l g \frac{S}{d^2} - 0.41 \cdot l g \frac{R_0}{1770} \right) + b_2 \cdot l g \frac{D}{d},$$

where D/d — ratio of the diameter of the carriage rollers to the diameter of the rope. S — rope tension, N; R_0 — marking group of wire strength, N/mm²; b_0, b_1, b_2, b_3 — empirical constants that take into account lay density and the shape of wires ($b_0 = 2.634; b_1 = 4.375; b_2 = -1.72; b_3 = -0.4$).

According to the proposed model, the predicted rope failure is a consequence of the parallel development of several degradation mechanisms. Despite the fact that the processes of wear, corrosion and fatigue occur simultaneously in the rope, the principle of sequential connection of the system elements is embedded in the structure of the model. The model assumes that the system's performance stops when any of the three established failure criteria is reached — the “weak link model”. The mutual influence of degradation processes in the proposed model is realized through dependent parameters and coefficients. Therefore, the overall reliability of a steel rope is determined by the probability of trouble-free operation of a sequential system with dynamically dependent parameters:

$$R_K(t) = P_B(t) \cdot P_B(t|B) \cdot P_A(t|B), \tag{8}$$

where $P_B(t)$ — probability of failure free operation within a given time interval t according to the criteria of group C; $P_B(t|B)$ — probability of failure free operation within a given time interval t according to the criteria of group B, taking into account the coefficient obtained based on the forecast of the model of group C; $P_A(t|B)$ — probability of failure free operation within a specified time interval t according to the criteria of group A, taking into account the forecast of the dependent parameters of models of Group B.

Example of calculation and verification of the model. As an example, the calculation of the probability of trouble-free operation of a steel rope was performed during operation as part of the lifting mechanism of the Kirovets gantry crane 16/20 (operating mode group M6). The calculated parameters of the rope and operating modes are presented in Table 5. Based on the calculation results, a graph of the dependence of the probability of trouble-free operation on time is shown in Figure 7.

For verification, the graph shows the calculated value of the median service life of a steel rope according to ISO 16625 — $T_{M6} = 3200$ hours for a given operating mode M6.

Table 5

Initial data for assessing the reliability of a steel rope

Probability of failure free operation	Parameter designation	Value	Unit of measurement
$P_B(t)$	β_B	3	—
	q	68	MPa
	η_B	0.36	MPa·h
	$k_{дег.}$	0.0004	h ⁻¹
	E_B	110	MPa
	ε_{lim}	0.25	—
$P_B(t B)$	δ	0.05	—
	H	5100	MPa
	$\sigma_{кон.}$	850	MPa
	k_f	$5.0 \cdot 10^{-7}$	—
	k_ω	$4.1 \cdot 10^{-8}$	—
	k_A	0.175	—
	p	7.0	MPa
	$v_{вар.}$	0.15	—
$P_A(t B)$	β_A	4	—
	η_0	3200	h
	A_0	283.79	mm ²
	m	6	—

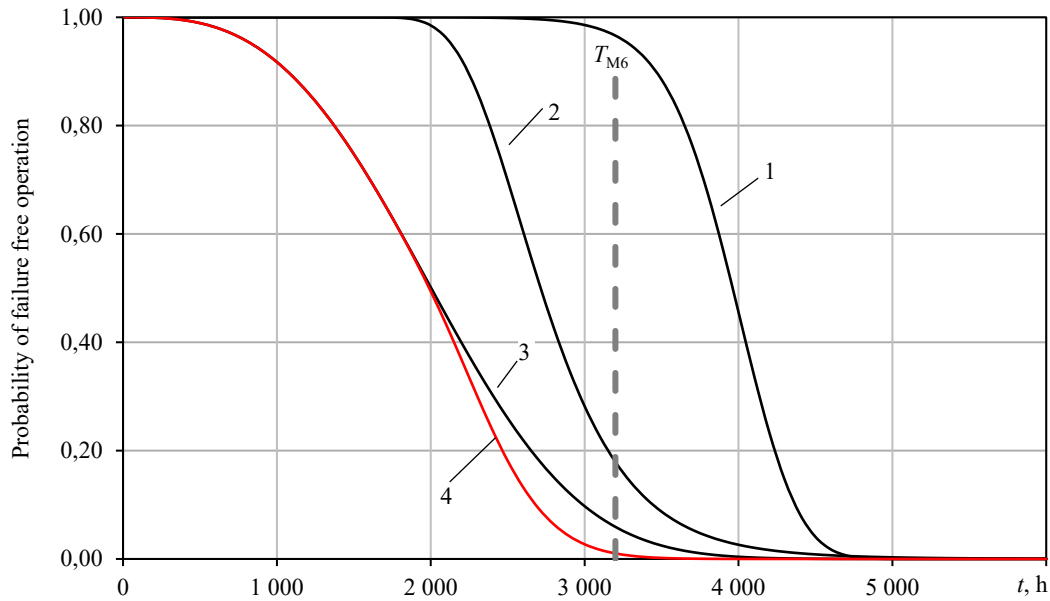


Fig. 7. Comparison of the predictive reliability assessment of a steel rope of 6x36 WS FC GOST 7668-80 construction with the calculated values of the median resource according to ISO 16625: 1 — assessment of reliability according to the criteria of group A — dependence $P_A(t|B)$; 2 — assessment of reliability according to the criteria of group B — dependence $P_B(t|B)$; 3 — assessment of reliability according to the criteria of group C — dependence $P_C(t)$; 4 — probability of failure of the rope $R_K(t)$; T_{M6} — life of the steel rope in the M6 mode, h

Discussion. The analysis of the results shows that the proposed set of models consistently bridges the gap between the theoretical assessment of reliability and operational documentation regulations. A key feature of the proposed interpretation of failures is the consideration of the synergetic interaction of several degradation mechanisms that form an integral picture of wear and damage. When modeling rope survivability, the central methodological issue is the contradiction between the physical nature of the processes and the mathematical scheme used. Within the framework of the proposed concept, the predicted rope failure is interpreted as the result of the parallel development of several degradation mechanisms — wear, corrosion and fatigue — despite the fact that the mathematical model purposefully includes the principle of sequential connection of elements (“weak link model”). Such a statement is justified by the fact that achieving any of the limiting criteria leads to a loss of performance of the system as a whole.

An essential feature of the model is the realization of the mutual influence of degradation processes through a system of dependent parameters and coefficients. Rheological degradation of the core and wear kinetics change the stress-strain state of wires, thereby modifying the rate of accumulation of fatigue damage and the redistribution of local loads. As a result, the overall reliability of the rope is determined by the probability of failure-free operation of a sequential system with dynamically dependent parameters, which provides higher forecast accuracy compared to additive approaches that ignore interprocess communications.

Unlike common studies, where degradation factors are treated as independent variables, this paper implements the concept of dynamic parameter dependence, reflecting the actual connectivity of mechanisms. The applicability of the developed apparatus as an analytical tool for design calculations of rope reliability in order to prevent critical defects and optimize design solutions is shown. At the same time, the heterogeneity of the apparatus used complicates the assessment of the total error by standard methods, which necessitates the development of a special reliability criterion that takes into account the particular errors of each component of the model and their possible correlation.

Conclusion. In the course of the research, we developed a comprehensive predictive mathematical model for steel rope reliability, which describes the combined effects of wire breaks, wear, atmospheric corrosion, and core rheological degradation. The hierarchical decomposition of rope reliability allows us to justify the calculation scheme with interdependent parameters and take into account synergistic effects of degradation, reducing the risk of sudden failure. The proposed calculation apparatus incorporates regulatory requirements into the forecasting process. Verification confirmed the consistency of predicted reliability curves with calculated values of median resource according to ISO 16625. At the same time, estimated median resource turned out to be 37% more conservative compared to traditional methods. The scope of applicability is limited to the assessment of the reliability of double lay ropes with an organic core according to GOST 7668–80 at the design stage and assumes the availability of statistical parameters of degradation models, as well as data on the strength and load of rope elements. Further research will focus on the development and experimental verification of models for ropes of different design groups, taking into account the specifics of operation, and their application in engineering practice for the reasonable selection of parameters and optimization of maintenance regulations.

References

1. Sukhorukov VV, Kotelnikov VS. Monitoring of Steel Ropes Condition with Technical Diagnostics Automated Means. *Occupational Safety in Industry*. 2019;9:72–81. (In Russ.) <https://doi.org/10.24000/0409-2961-2019-9-72-81>
2. Halfin MN, Al-Jumaili AKh. To Improve the Reliability Operation of Hoisting Ropes in the Metal Manufacturing. *Bulletin of Higher Educational Institutions. North Caucasian Region. Technical Sciences*. 2015;3(184):68–71. (In Russ.) <https://doi.org/10.17213/0321-2653-2015-3-68-71>
3. Halfin MN, Korotkiy AA, Ivanov BF. To a Question of the Choice of the Bearing Ropes of Passenger Cableways. *News of the Tula State University. Technical Sciences*. 2019;6:397–402. (In Russ.)
4. Korotkiy AA, Ivanov BF, Panfilova EA. On the Issue of Monitoring the Actual Condition of Steel Ropes of Passenger Cable Cars. *Scientific and Technical Journal of Bryansk State University*. 2025;1:67–74. (In Russ.) <https://doi.org/10.22281/2413-9920-2025-11-01-67-74>
5. Korotkiy AA, Panfilov AV, Khvan RV, Yusupov AR. Integral Method of Assessing Defects on the Operability of Steel Rope Using Artificial Neural Networks. *Transport, Mining and Construction Engineering: Science and Production*. 2023;18:73–79. (In Russ.)
6. Panfilov AV, Yusupov AR, Korotkiy AA, Ivanov BF. On the Control of the Technical Condition of Elevator Ropes Based on Artificial Intelligence and Computer Vision Technology. *Advanced Engineering Research (Rostov-on-Don)*. 2022;22(4):323–330. <https://doi.org/10.23947/2687-1653-2022-22-4-323-330>
7. Panfilov AV, Korotkiy AA, Ivanov BF, Yusupov AR. Control of Ropes during the Operation of Machines with Rope Traction. *Scientific and Technical Journal of Bryansk State University*. 2022;4:330–338. (In Russ.) <https://doi.org/10.22281/2413-9920-2022-08-04-330-338>
8. Kulchitskiy AA, Mansurova OK, Nikolaev MYu. Recognition of Defects in Hoisting Ropes of Metallurgical Equipment by an Optical Method Using Neural Networks. *Chernye Metally*. 2023;3:81–88. (In Russ.) <https://doi.org/10.17580/chm.2023.03.13>
9. Wahid Achraf, Mouhib Nadia, Sabah Fatima, Chakir Hamid, Ghorba MEL. Analytical Estimation of the Reliability of Wire Rope Based on Cumulative Damage. *MATEC Web of Conferences*. 2019;286(3):05001. <https://doi.org/10.1051/mateconf/201928605001>
10. Wahid Achraf, Bassir Youssef, Mouhib Nadia, Hamid Chakir, Mohamed Elghorba. Analytical Approach for Damage Reliability Assessment of Wire Rope. *International Journal of Performability Engineering*. 2020;16(8):1151–1158. <https://doi.org/10.23940/ijpe.20.08.p2.11511158>
11. Mouradi H, El Barkany Abdallah, Biyaali A. A Probabilistic Approach to Reliability Evaluation of Lifting Wire Ropes. *ARPJN Journal of Engineering and Applied Sciences*. 2014;9:923–928. <https://www.researchgate.net/publication/289468988>
12. Bassir Youssef, Wahid Achraf, Kartouni Abdelkarim, ELghorba Mohamed. Estimation of Wire Rope Reliability by Two Analytical Approach. *International Journal of Performability Engineering*. 2021;17(7):619. <https://doi.org/10.23940/ijpe.21.07.p6.619626>
13. Yifan Xia, Lu Deng, Xiangjun Chen, Tengyuan Liu, Zhendan Yang, Chunni Jia, et al. A Multi-Scale Finite Element Analysis Method for Dynamic Simulation of the Wire Rope. *Structures*. 2025;71:108136. <https://doi.org/10.1016/j.istruc.2024.108136>
14. Yuchen Han, Jingshan Hao, Huadong Yong, Youhe Zhou. The Stick-Slip Bending Behavior of the Multilevel Helical Structures: A 3D Thin Rod Model with Frictional Contact. *International Journal of Solids and Structures*. 2024;303:113005. <https://doi.org/10.1016/j.ijsolstr.2024.113005>
15. Salleh S, Abdullah MA, Abdulhamid MF, Tamin MN. Methodology for Reliability Assessment of Steel Wire Ropes under Fretting Fatigue Conditions. *Journal of Mechanical Engineering and Sciences*. 2017;11(1):2488–2502. <https://doi.org/10.15282/jmes.11.1.2017.8.0229>
16. Yuxing Peng, Kun Huang, Chenbo Ma, Zhencai Zhu, Xiangdong Chang, Hao Lu, et al. Friction and Wear of Multiple Steel Wires in a Wire Rope. *Friction*. 2023;11:763–784. <https://doi.org/10.1007/s40544-022-0665-y>
17. Chun-ming Xu, Yu-xing Peng, Zhen-cai Zhu, Wei Tang, Kun Huang. Fretting Behaviors of Steel Wires with Tensile-Torsional Coupling Force under Different Wire Diameters and Crossing Angles. *Tribology Letters*. 2020;68:91. <https://doi.org/10.1007/s11249-020-01331-8>
18. Golovin VP. Methods for Evaluating the Effect of Lubricants on the Wear Resistance of Steel Rope. *Vestnik Rostovskogo Gosudarstvennogo Universiteta Putej Soobshcheniya (Vestnik RGUPS)*. 2025;3:197–204. (In Russ.) https://doi.org/10.46973/0201-727X_2025_3_197
19. Han Peng, Yihao Zhang, Linjian Shangguan, Minzhang Zhao, Bing Li, Leijing Yang, Yannan Liu. Review of Failure Mechanisms of Steel Wire Ropes under Heavy-Load Conditions and the Anti-Friction Effects of Gel-Like Grease. *Gels*. 2025;11(11):900. <https://doi.org/10.3390/gels1111090>

20. Volokhovskiy VYu, Vorontsov AN, Shpakov II, Goncharov VV. Analysis of the Operational Reliability of the Hot-Metal Crane Cargo Ropes in Steelmaking. *Occupational Safety in Industry*. 2020;5:7–16. (In Russ.) <https://doi.org/10.24000/0409-2961-2020-5-7-16>

About the Author:

Anatoly A. Kotesov, Cand. Sci. (Eng.), Associate Professor of the Department of Operation of Transport Systems and Logistics, Don State Technical University (1, Gagarin Sq., Rostov-on-Don, 344003, Russian Federation), [SPIN-code](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), a.kotesov@yandex.ru

Conflict of Interest Statement: the author declares no conflict of interest.

The author has read and approved the final version of manuscript.

Об авторах:

Анатолий Анатольевич Котесов, кандидат технических наук, доцент кафедры «Эксплуатация транспортных систем и логистика» Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [SPIN-код](#), [ORCID](#), [ScopusID](#), [ResearcherID](#), a.kotesov@yandex.ru

Конфликт интересов: автор заявляет об отсутствии конфликта интересов.

Автор прочитал и одобрил окончательный вариант рукописи.

Received / Поступила в редакцию 17.11.2025

Reviewed / Поступила после рецензирования 18.12.2025

Accepted / Принята к публикации 30.12.2025