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Prediction of the service life of reinforced concrete bridge super-structures on high-speed rail lines

Dmitry A. Shestovitskiy^{1✉}, Gleb A. Efremov², Nikolay V. Kozak³

^{1,2} Emperor Alexander I St. Petersburg State Transport University; St. Petersburg, Russian Federation

³ Saint Petersburg State University of Architecture and Civil Engineering; St. Petersburg, Russian Federation

¹ shestovitskiy@mail.ru[✉]; <https://orcid.org/0000-0002-2828-4290>

² frost0077@mail.ru; <https://orcid.org/0000-0001-9311-3765>

³ kozak.spbgasu@gmail.com; <https://orcid.org/0000-0002-7707-4388>

ABSTRACT The design standards for artificial structures of high-speed rail lines set the service life of bridge structures in a prescriptive way at 100 years. However, the actual average service life of railway bridges ranges from 40 to 70 years. The service life is one of the key general-purpose characteristics that determine the main parameters of a bridge structure. However, there are no methods or algorithms for predicting and justifying service lives of bridges in the design stage. The limit state equations do not contain a time variable, and the factors of safety take into account the probabilistic variation of the initial parameters, but not their change over time. This study proposes a method for predicting and justifying the service life of unified reinforced concrete bridge structures developed for the High-speed Rail Line No. 1, taking into account the simultaneous influence of climatic degradation factors and high dynamic loads in high-speed conditions. All the initial parameters are random, which is why it is proposed to calculate the service life in a stochastic form, where the calculation results are used to generate a histogram of service life distribution. Based on this distribution histogram, it is possible to determine the service life with a specified probability by using target reliability indexes.

KEYWORDS: service life; superstructure; high-speed traffic; reinforced concrete; reliability; stochastic approach; Monte Carlo method

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Научная статья

Прогнозирование срока службы железобетонных пролетных строений мостов на высокоскоростных железнодорожных магистралях

Д.А. Шестовицкий^{1✉}, Г.А. Ефремов², Н.В. Козак³

^{1,2} Петербургский государственный университет путей сообщения Императора Александра I; г. Санкт-Петербург, Россия

³ Санкт-Петербургский государственный архитектурно-строительный университет; г. Санкт-Петербург, Россия

¹ shestovitskiy@mail.ru[✉]; <https://orcid.org/0000-0002-2828-4290>

² frost0077@mail.ru; <https://orcid.org/0000-0001-9311-3765>

³ kozak.spbgasu@gmail.com; <https://orcid.org/0000-0002-7707-4388>

АННОТАЦИЯ В нормах проектирования искусственных сооружений высокоскоростных железнодорожных линий срок службы мостовых сооружений назначается директивно и составляет 100 лет. При этом фактический средний срок службы железнодорожных мостов находится в диапазоне 40–70 лет. Срок службы является одной из определяющих универсальных характеристик, отвечающих за основные параметры мостовой конструкции. Нормы проектирования не содержат методик и алгоритмов прогнозирования и обоснования срока службы проектируемых мостов. Уравнения предельных состояний не содержат переменной времени, а коэффициенты надежности учитывают вероятностный разброс исходных параметров, но не их изменение во времени. В данном исследовании предлагается

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метод прогнозирования и обоснования срока службы унифицированных железобетонных пролетных строений железнодорожных мостов, разработанных для Высокоскоростной железнодорожной магистрали № 1, с учетом одновременного влияния климатических факторов деградации и больших динамических нагрузок в условиях высокоскоростного движения. Все исходные параметры имеют случайный характер, ввиду чего расчет срока службы предлагается вести в стохастической форме, где по результатам расчета получается гистограмма распределения срока службы. По данной гистограмме распределения можно определить срок службы с заданной обеспеченностью через целевые индексы надежности.

КЛЮЧЕВЫЕ СЛОВА: срок службы; пролетное строение; высокоскоростное движение; железобетон; надежность; стохастический подход; метод Монте-Карло

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INTRODUCTION

High-speed rail (HSR) lines are an effective tool for promoting economic growth, regional development, and introduction of technical innovation. This is so because HSR projects yield economic returns, increase human mobility, improve territorial connections, and induce the development of related industries. Cur-

rently, HSR lines are widely in use in Japan, France, Italy, Germany, Spain, South Korea, and China.

In August 2023, a decision was made to design and build Russia's first 679 km-long high-speed rail line between Moscow and St. Petersburg with train speeds of at least 350 km/h. The line will be the first in the HSR network planned to be built in Russia (Fig. 1).

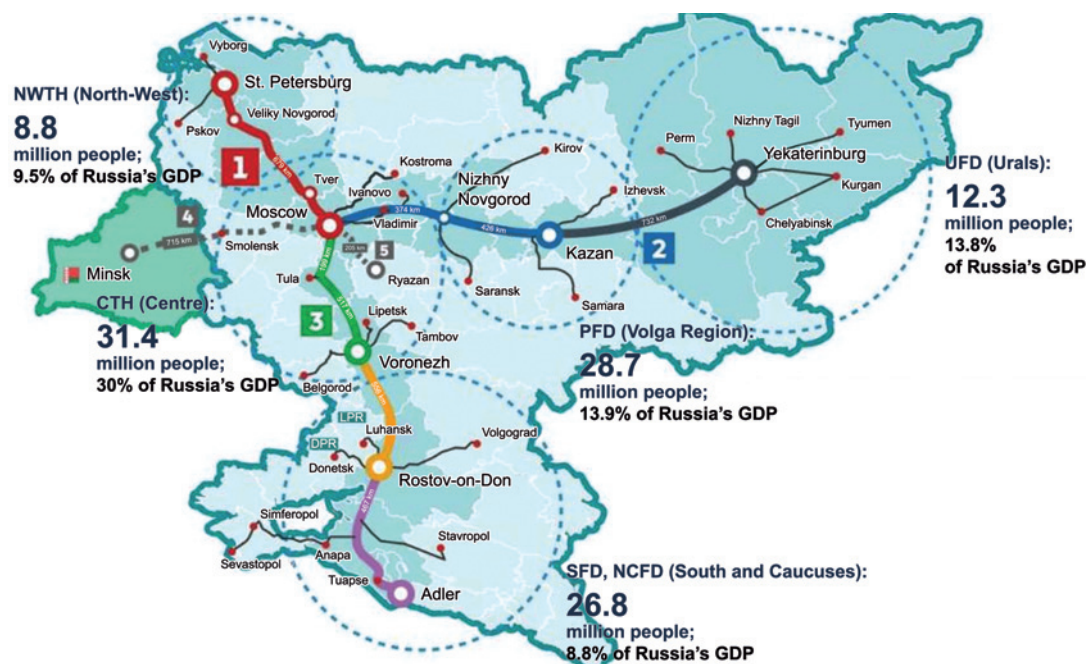


Fig. 1. The planned high-speed rail network in Russia¹

A large number of artificial structures, including bridges, flyovers and viaducts, are designed on the line.

Two modifications of new standard unified reinforced concrete simply supported superstructures (types IA and IB) have been designed (Fig. 2).

In accordance with the Terms of Reference for design documentation development and requirements of applicable regulations^{2, 3, 4}, the estimated service life of the main structures of bridges and tunnels on high-speed rail lines is taken equal to 100 years.

¹ https://ya.ru/images/search?img_url=https%3A%2F%2Fcs13.pikabu.ru%2Fpost_img%2F2024%2F02%2F20%2F9%2Fog_1708438458259017481.jpg&lr=2&pos=0&rpt=simage&text=карта%20всех%20россии

² SP 453.1325800.2019. Engineering structures for high-speed railway lines. Rules for design and construction (approved by Order of the Ministry of Construction and Housing of the Russian Federation No. 809/pr, dated December 16, 2019; effective as of June 17, 2020).

³ GOST 27751-2014. Reliability for constructions and foundations. General principles (put into force by Order of the Federal Agency for Technical Regulation and Metrology No. 1974-st, dated December 11, 2014).

⁴ SP 259.1325800.2016. Bridges in dense urban areas. Design rules. Official publication. Moscow, 2016.

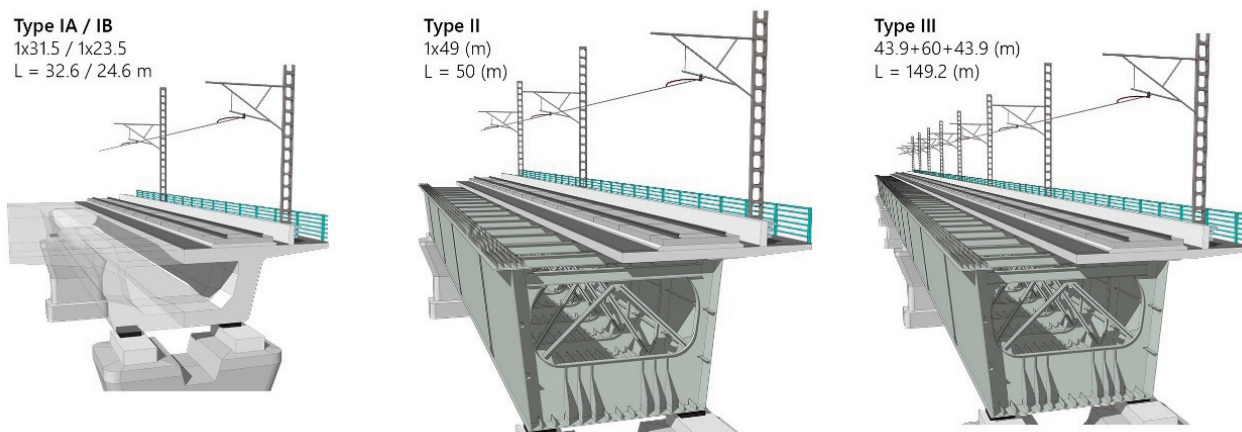


Fig. 2. Variants of bridge spans for HSR: *a* – standard unified reinforced concrete split spans in two versions with a length of 24.6 m and 32.6 m; *b* – split steel-reinforced concrete span with a length of 50 m; *c* – continuous steel-reinforced concrete span according to the scheme 43,9 + 60 + 43,9 m

Based on the available statistics and data on service lives of bridges all over the world, we can conclude that the 100-year service life before an overhaul or reconstruction of a bridge can be met in isolated instances, mostly for out-of-class bridges. The service life of a superstructure designed for a C14 load (54.1 %) usually does not exceed 50 years [1]. Paper [2] states that in Japan, the average lifecycle of reinforced concrete bridges is set by the Ministry of Transport at 60 years.

Regulatory documents stipulate that in order to provide the required durability, the following should be taken into account during the design phase:

- Operation conditions; environmental exposure;
- Properties of materials used;
- Possible protections against adverse impacts of the environment;
- Possible degradation of their properties;
- Possible impact of an aggressive environment or other adverse operation conditions (freeze/thaw activity, exposure to deicing chemicals, exposure to seawater, industrial emissions, etc.).

At the same time, there is no methodological framework for forecasting, calculation and justification of service lives taking into account the above listed affecting factors. The design dependencies for cross-section inspections provided in the standards do not include a time variable, and the reliability factors account for the probabilistic random nature of values used in calculations, but not their change over time. Since the actual service lives of bridge structures differ from those prescribed by the regulations, it becomes necessary to justify these service lives as early as during the design phase, when it is possible to change the design to ensure that the required service life stated in the standards is met. Predicting and justifying the durability of transport structures is one of the most important tasks to be addressed during the design phase.

In this study, the authors present the scientific approaches and methods for predicting and justifying service lives of superstructures of artificial structures

taking into account the peculiarities of their operation in high-speed conditions that are used in the implementation of the Moscow–St. Petersburg HSR1 project to justify the stipulated service life of 100 years.

IDENTIFYING DEGRADATION FACTORS

The number of factors influencing the durability of reinforced concrete bridge superstructures throughout the service life goes to infinity [3–9]. The original task was to identify the most significant factors having the strongest impact on the service life and to develop the most accurate mathematic models to describe the influence of these factors on the durability of reinforced concrete superstructures over time.

Some of the most significant factors contributing to degradation and reduction of the service life include the following:

- Carbonation of concrete in the protective layer by carbon dioxide;
- Corrosion of reinforcement steel;
- Dynamic loading by trains, leading to fatigue processes (Fig. 3, 4).

We did not consider the influence of chlorides, because this is not a determining factor for railway bridges outside coastal areas of seas and oceans.



Fig. 3. Destruction of concrete protective layer and intense corrosion of primary reinforcement steel

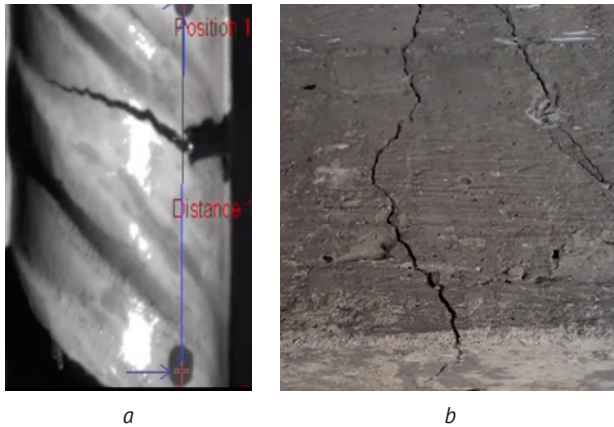


Fig. 4. Fatigue cracking: *a* – in reinforcement steel; *b* – in concrete

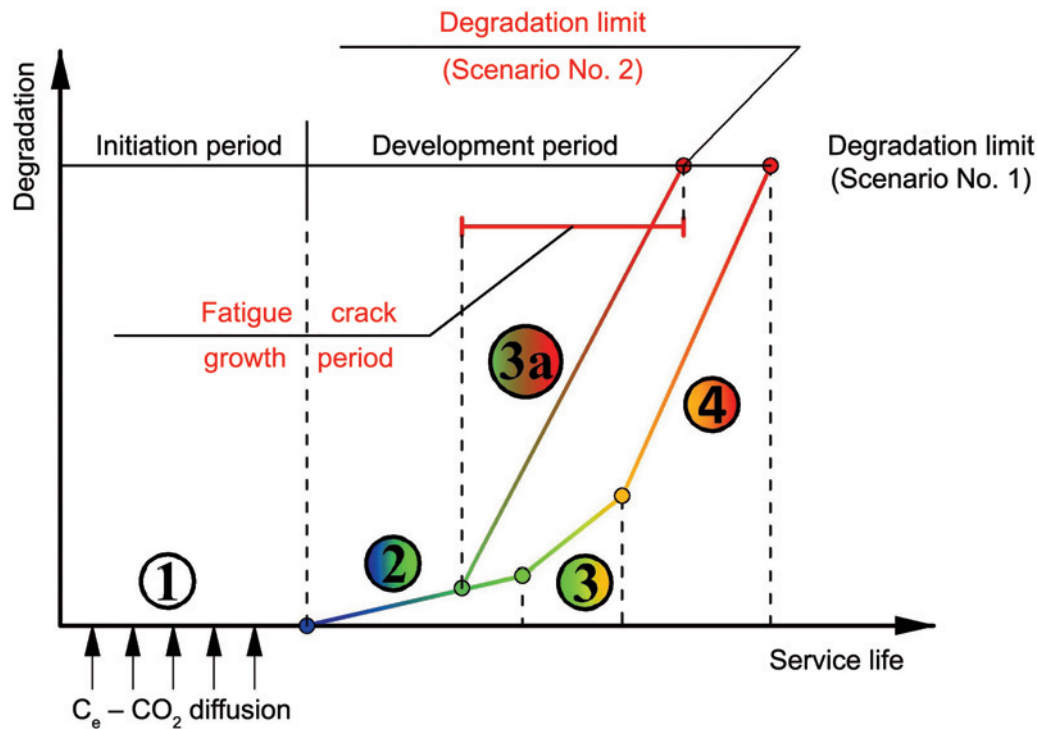
In the existing durability prediction approaches and models, effects of climate and forces are usually considered separately and independently; corrosion processes are modelled without taking material fatigue

into account; and fatigue effects from dynamic loading are calculated without considering corrosion of reinforcement steel. In high-speed conditions and given a large number of dynamic effects, the method proposed in this study integrates effects of both climate and forces into a single mathematic model, taking into account their reciprocal influences.

ADOPTED METHOD FOR PREDICTING AND JUSTIFYING SERVICE LIVES

The model description is based on a hypothesis that the service life of a reinforced concrete beam consists of a sum of periods shown in Fig. 5.

A flow chart of the developed and adopted method for predicting the service life of unified reinforced concrete 32.6- and 24.6-metre long superstructures is given below (Fig. 6).



- ① Protective layer depassivation
- ② Corrosion initiation and pore space filling
- ③ Initiation and growth of a crack in concrete; acceleration of corrosion
- ③a Initiation of a fatigue crack in reinforcement steel and its growth to a critical level (Scenario No. 1)
- ④ Decrease in the bearing capacity to a critical level (Scenario No. 2)

Fig. 5. Periods of the service life of reinforced concrete superstructures

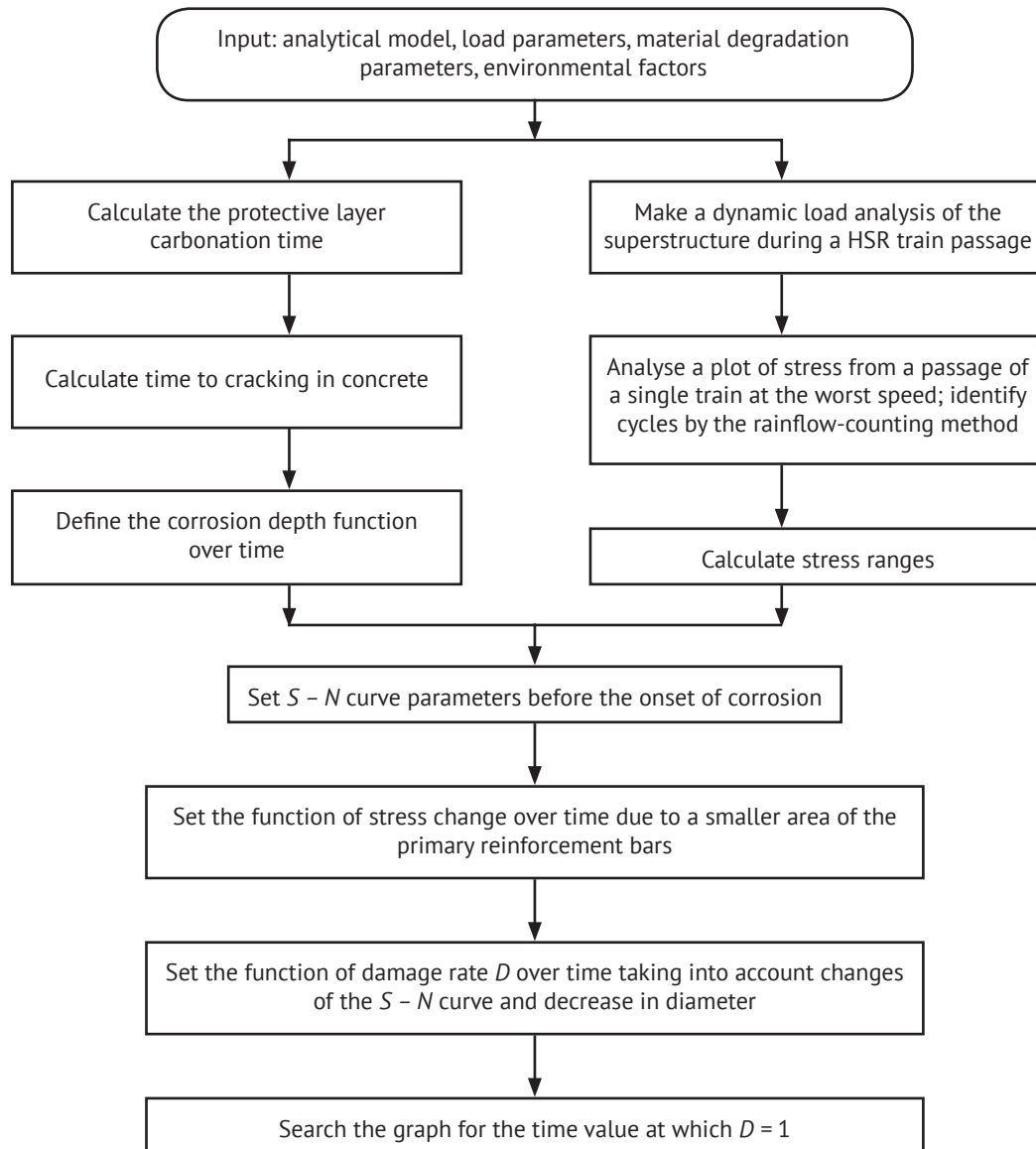


Fig. 6. Flow chart for calculating the service life of a reinforced concrete beam taking into account degradation and effects of dynamic loading

TAKING INTO ACCOUNT DYNAMIC LOADING FROM HIGH-SPEED TRAINS

Regular dynamic effects from high-speed trains lead to the gradual accumulation of fatigue damage. The total damage is estimated by the linear summation of accumulated damage based on the Palmgren-Miner Rule:

$$D_t = \sum_{i=1} \frac{n_i}{N_i} = \frac{1}{C} \sum_{i=1} n_i \cdot \Delta \sigma_i^m$$

When D_t reaches 1, the ultimate limit state is reached.

To calculate a degree of damage of the superstructure, a dynamic load analysis of the superstructure during a high-speed train passage was performed (Fig. 7).

The stress plot was recorded for the speed at which the maximum stress in the superstructure slab was registered (Fig. 8).

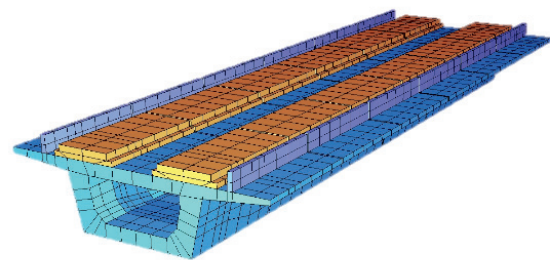


Fig. 7. 3D finite-element model of the superstructure

The rainflow-counting method was used to convert the resulting strain gauge records into the stress plot.

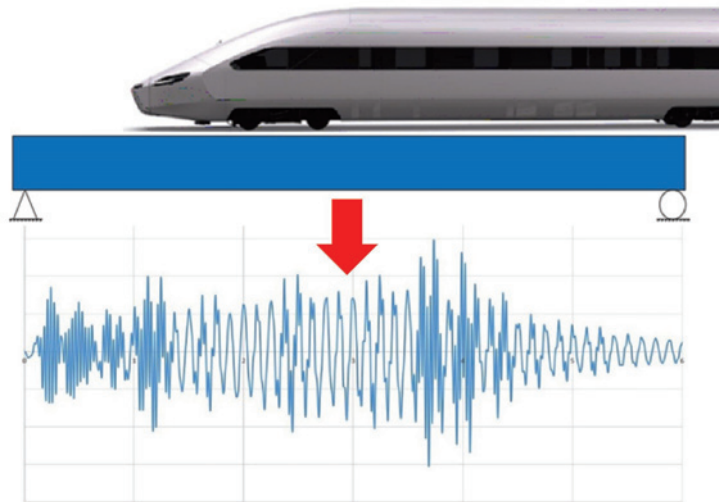


Fig. 8. Changes in stress in the superstructure slab caused by train passage

STOCHASTIC APPROACH

The service lives were calculated in a probabilistic setting using the Monte Carlo method which produced the functions of service life distribution density for various variations of climatic parameters and daily train traffic intensity. The estimated service life was determined with a given probability which is related to the design reliability level expressed by reliability index β . In accordance with the log-normal distribution, the

estimated service life was determined using the following formula:

$$t^g = t^d \cdot e^{-\beta \cdot v_t}$$

where t^g is the estimated service life; t^d is the service life expected value; e is the natural logarithm base; β is the target reliability index; and v_t is the service life variation coefficient (Fig. 9).

The target reliability level was selected in accordance with applicable regulations at $\beta = 4.3$; 3.8, and 3.0.

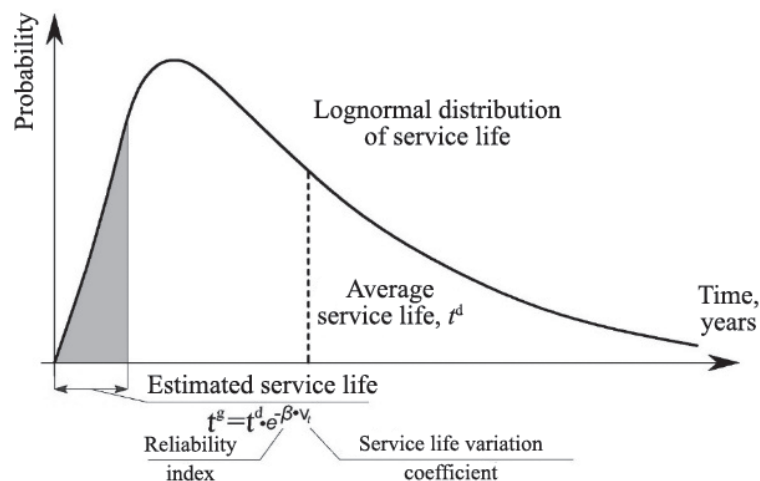


Fig. 9. Determining the estimated service life with a lognormal distribution

INPUT DATA AND CALCULATION RESULTS

In order to calculate service lives by the method developed, we used the input data listed below (Fig. 1–3). Since the calculation was made in a probabilistic setting using the Monte Carlo method, the initial parameters were adopted in the probabilistic form as expected value, coefficient of variation, or

standard deviation. All the input parameters were nominally divided into three groups: structural parameters and characteristics of materials; climatic parameters of the region of operation; and load parameters.

The calculation results are given below (Fig. 10–12, Tables 4–5).

Table 1

Structural parameters and characteristics of materials

Parameter	Expected value	Variation coefficient	Distribution
Beam concrete class	50	–	
Water-to-cement ratio, w/c	~ 0.342	0.1	Normal
Protective layer thickness, mm	40	0.2	Normal
Characteristic compressive strength of concrete (with a probability of 0.95), MPa	25	–	
Average strength of concrete, MPa	30.58	0.111	Normal
CaO content in cement, %	0.75	0.07	Normal
Cement amount, C_e , kg/m ³	~ 525	0.03	Normal
Diameter of reinforcement mesh bars in the slab, mm	Ø12 AIII	–	

Table 2

Climate parameters in the region of operation

Parameter	Expected value			Standard deviation (SD)	Distribution
	Moscow	Klin	Dmitrov		
Average temperature of warmest month, C°	19,1	17,4	18,3	1,0 C°	Normal
Average temperature of coldest month, C°	–7.8	–10.6	–8.9	1.0 C°	Normal
Average humidity of most humid month, C°	84	85	83	5 %	Normal
Average humidity of driest month, C°	73	66	70	5 %	Normal
Atmospheric carbon dioxide concentration, ppm	450	420	420	20 ppm	Normal

Table 3

Load parameters

Parameter	Value
Rolling stock	EVS ITsZhT
Axle load, KN	176.52
Trains per day	20/40/60

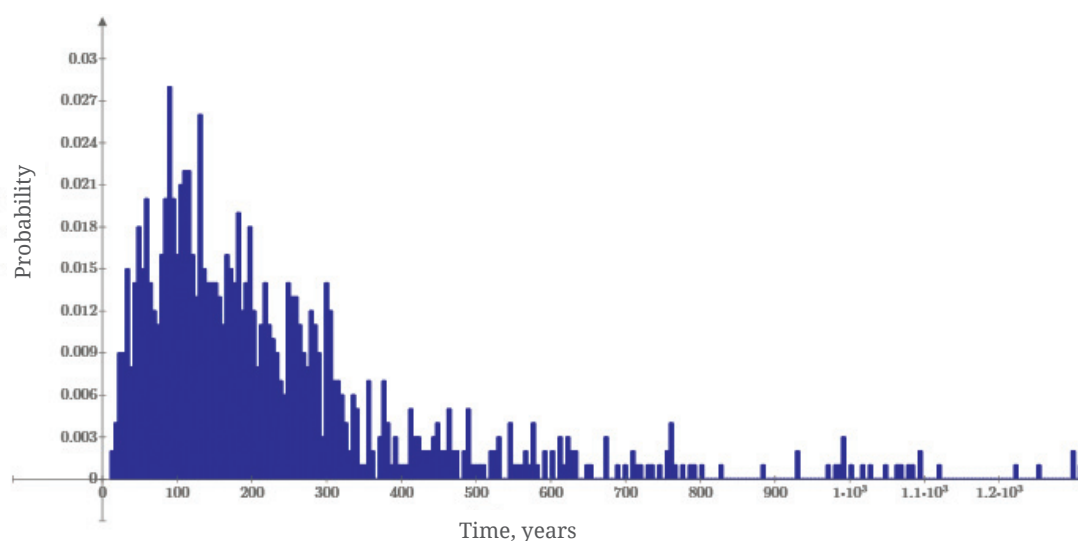


Fig. 10. Bar chart for distribution of 24.6-metre long superstructure protective layer carbonation time

Table 4

Calculation results for service life of 24.6-metre long superstructure slab (reliability index $\beta = 4.3$)

Region	Number of trains per day	Distribution parameters			Reliability index, β	Estimated service life, years
		type	μ	σ		
Moscow	20	Lognormal	410	126.1	4.3	109.3
	40		404.7	125		107.2
	60		399.1	124.9		103.9
Klin	20		435.8	122.9		129.6
	40		431.2	125.5		123.4
	60		423.7	123.6		120.9
Dmitrov	20		420.4	125.3		116.7
	40		414.7	124.3		114.3
	60		408.6	123.9		110.9

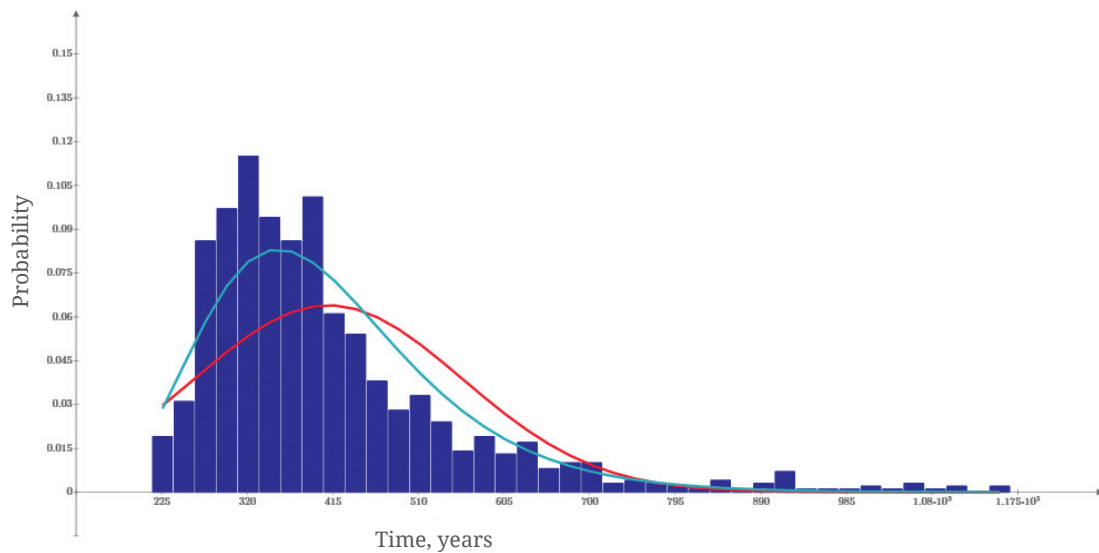


Fig. 11. Bar chart for distribution of service life of 24.6-metre long superstructure

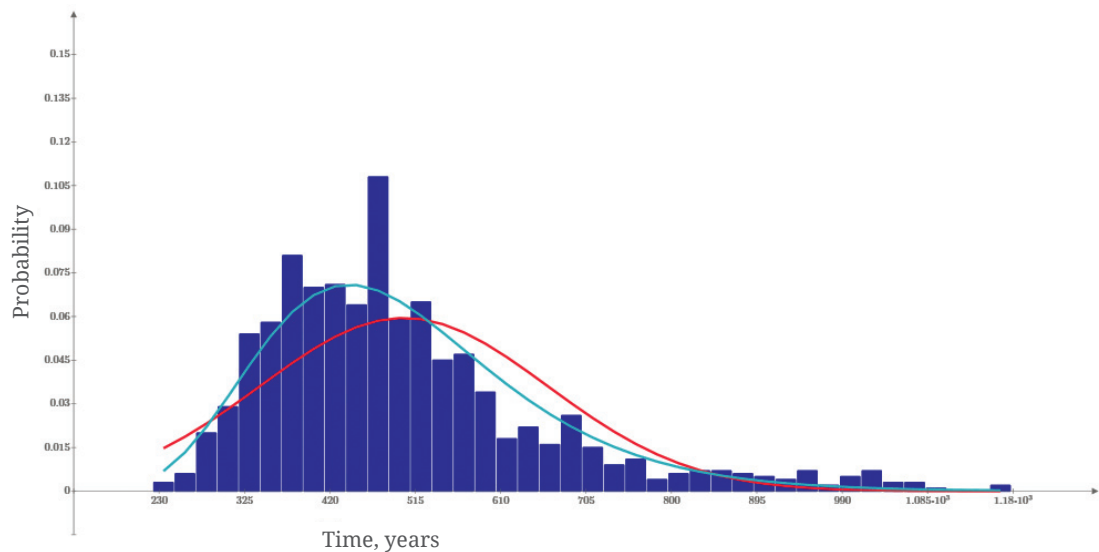


Fig. 12. Bar chart for distribution of service life of 32.6-metre long superstructure

Table 5

Calculation results for service life of 32.6-metre long superstructure slab (reliability index $\beta = 4.3$)

Region	Number of trains per day	Distribution parameters			Reliability index, β	Estimated service life, years
		type	μ	σ		
Moscow	20	Lognormal	493	162.2	4.3	119.8
	40		492.7	162.1		119.7
	60		492.4	162		119.6
Klin	20		527.8	171.3		130.7
	40		527.4	171.2		130.6
	60		527	171.1		130.5
Dmitrov	20		503	160.1		128
	40		502.6	159.9		128
	60		502.2	159.9		127.7

CONCLUSIONS

The findings enable us to make the following conclusions:

1. All superstructures meet the requirement set out in section 6.1.11 of SP 453.1325800.2019. In all cases, the estimated service life of unified reinforced concrete 24.6 and 32.6-metre long superstructures exceeds 100 years.

2. The minimum service life was determined under the climatic conditions of Moscow with the ITsZhT trains running on superstructures 60 times per day and the maximum reliability level being $\beta = 4.3$. The minimum service lives are as follows: 103 years for

the 24.6-metre superstructure; and 119 years for the 32.6-metre superstructure. When the frequency of load cycling increases, the service life is shorter.

3. All of the resulting service lives are distributed in accordance with the lognormal law.

4. When the live-load intensity is low and stresses in reinforcement steel are small, the service life is to a greater extent determined by the duration of protective layer concrete carbonation and corrosion of primary reinforcement bars. This can be seen from the calculation results for a 32.6-metre beam where the frequency of live load has almost no effect on the service life.

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Bionotes

Dmitry A. Shestovitskiy – Cand. Sci. (Eng.), Associate Professor at the Department of Bridges; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky ave., Saint-Petersburg, 190031, Russian Federation; RSCI ID: 720812, Scopus 57204927842, ORCID: 0000-0002-2828-4290; shestovitskiy@mail.ru;

Gleb A. Efremov – lecturer at the Department of Bridges; **Emperor Alexander I St. Petersburg State Transport University (PGUPS)**; 9 Moskovsky ave., Saint-Petersburg, 190031, Russian Federation; RSCI ID: 1250259, ORCID: 0000-0001-9311-3765; frost0077@mail.ru;

Nikolay V. Kozak – Cand. Sci. (Eng.), Associate Professor of the Department of Highways, Bridges and Tunnels; **St. Petersburg State University of Architecture and Civil Engineering**; 4 2-ya Krasnoarmeyskaya St., St. Petersburg, 190005, Russian Federation; RSCI ID: 5997-7504, Scopus: 57207108767, Researcher ID: AAZ-4166-2021, ORCID: 0000-0002-7707-4388, www.researchgate.net/profile/Nikolai-Kozak-2; https://scholar.google.com/citations?user=_XXHUX0AAAAJ&hl=ru; kozak.spbgasu@gmail.com

Об авторах

Дмитрий Александрович Шестовицкий – кандидат технических наук, доцент кафедры «Мосты»; **Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС)**; 190031, Санкт-Петербург, Московский пр., 9; РИНЦ ID: 720812, Scopus 57204927842, ORCID: 0000-0002-2828-4290; shestovitskiy@mail.ru;

Глеб Александрович Ефремов – старший преподаватель кафедры «Мосты»; **Петербургский государственный университет путей сообщения Императора Александра I (ПГУПС)**; 190031, Санкт-Петербург, Московский пр., 9; РИНЦ ID: 1250259, ORCID: 0000-0001-9311-3765; frost0077@mail.ru;

Николай Викторович Козак – кандидат технических наук, доцент кафедры автомобильных дорог, мостов и тоннелей, **Санкт-Петербургский архитектурно-строительный университет**; 190005, г. Санкт-Петербург, 2-я Красноармейская ул., д. 4; РИНЦ ID: 5997-7504, Scopus: 57207108767, Researcher ID: AAZ-4166-2021, ORCID: 0000-0002-7707-4388, www.researchgate.net/profile/Nikolai-Kozak-2; https://scholar.google.com/citations?user=_XXHUX0AAAAJ&hl=ru; kozak.spbgasu@gmail.com.

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Corresponding author: Дмитрий Александрович Шестовицкий, shestovitsky@mail.ru.

Автор, ответственный за переписку: Dmitry A. Shestovitskiy, shestovitsky@mail.ru.

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