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PROBLEMS IN PROVIDING EQUAL RELIABILITY OF REINFORCED CONCRETE AND STEEL CONSTRUCTIONS WITHIN THE EXISTING RELIABILITY CONCEPT ACCORDING TO EN 1990

ABSTRACT

In accordance with the basic assumptions of the European design standards (Eurocodes), currently in use in the territory of the Republic of Belarus, it is proposed to carry out the design of building structures, made of different materials, belonging to the same reliability class with the same target value of the reliability level (or with the same degree of reliability), expressed in the permissible values of the reliability index or equivalent to it the probability of failure. However, the practical implementation of this idea involves a very large number of problems. The study is devoted to the analysis of reliability levels and equivalent to them probabilities of failure provided by Eurocodes for models of resistance for bending of steel and reinforced concrete elements under rather abstract conditions: the action of self weight and snow load for the reference period of 1 year, however this analysis allows qualitatively highlight the problems, associated with existing approaches in the theory of reliability, and, in general, the problem of ensuring the equal reliability of structures. Within the framework of the study, state functions for calculating the reliability indices of the elements were compiled with the help of using the first-order reliability methods

(FORM), and a comparative analysis of these indicators was made. The collection and analysis of probabilistic models of basic variables, used for the compilation of state functions for conventional steel and reinforced concrete elements, was carried out. The data obtained during the research can be useful for further improvement and supplementation of National Annexes and harmonization of Eurocodes. The conducted research will help to take a closer look at the problem of regulating reliability indicators for building structures made of various materials within the framework of the existing concept of reliability laid down in Eurocode 1990.

Keywords: reliability, steel element, reinforced concrete element, state function, basic variable, model uncertainty, reliability index, target value, Eurocode.

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ПРОБЛЕМЫ В ОБЕСПЕЧЕНИИ РАВНОНАДЕЖНОСТИ ЖЕЛЕЗОБЕТОННЫХ И СТАЛЬНЫХ КОНСТРУКЦИЙ В РАМКАХ СУЩЕСТВУЮЩЕЙ КОНЦЕПЦИИ НАДЕЖНОСТИ СОГЛАСНО EN 1990

АННОТАЦИЯ

В соответствии с базовыми положениями европейских норм проектирования (Еврокодов), действующих в настоящее время на территории Республики Беларусь, предполагается возможным осуществлять проектирование строительных конструкций, изготовленных из различных материалов, относящихся к одному классу надежности, с одинаковым целевым значением уровня надежности, выраженным в допустимых значениях индекса надежности или же эквивалентной ему вероятности отказа. Однако практическая реализация данной идеи сопряжена с очень большим количеством проблем. Проведенное исследование посвящено анализу уровней надежности и эквивалентных им вероятностей отказа, обеспечиваемых Еврокодами для моделей сопротивления изгибу стальных и железобетонных элементов при довольно абстрактных условиях: действии собственного веса и снеговой нагрузки для базового периода отнесения 1 год, однако данный анализ позволяет качественно осветить проблемы, сопряженные с существующими подходами в теории надежности, и в целом проблемы обеспечения равнонадежности конструкций. В рамках проведенного исследования составлены функции состояния для расчета показателей надежности исследуемых элементов с использованием методов теории надежности первого порядка (FORM), а также проведен сравнительный анализ этих показателей. Выполнен сбор и анализ вероятностных моделей базисных переменных, применяемых для составления функций состояния для условного стального и железобетонного элементов. Данные, полученные в ходе исследования, могут быть полезны для дальнейшего совершенствования и дополнения Национальных Приложений и гармонизации Еврокодов. Проведенное исследование поможет более пристально взглянуть на проблему регламентации показателей надежности для строительных конструкций, выполненных из

различных материалов, в рамках существующей концепции надежности, заложенной в Еврокоде 1990.

Ключевые слова: надежность, стальной элемент, железобетонный элемент, функция состояния, базисная переменная, погрешность модели, индекс надежности, целевое значение, Еврокод.

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INTRODUCTION

In accordance with the provisions for ensuring structural reliability set out in normative documents such as TKP EN 1990 [1] and ISO 2394 [2], the design of structural elements must be carried out on the basis of target values of reliability levels expressed in acceptable values of reliability indices or equivalent to them probabilities of failure [3].

At the same time, reliability indices or probability of failure are not indicators of the actual frequency of failure of structures, but they are widely used for comparison of different calculation methods when considering different combinations of loads, structural elements made of different materials, different types of failures, various types of structures. Ultimately, ***the application of the standardized target values of reliability indicators*** is aimed at a relative comparison of the reliability of structural solutions and ***should ensure equal reliability of structures***. However, at present, the practical application of requirements of STB ISO 2394 [2] and TKP EN 1990 [1], is accompanied by a number of inaccuracies, which requires a rethinking of the adopted provisions and backgrounds for the concept of reliability laid down in the Eurocodes.

Thus, the normalized reliability indices are closely related to the accepted backgrounds and, as a consequence, can't be comparable to each other, separately from them, it means that only models with similar backgrounds can be objectively evaluated [4]. As noted in [4], one of the most important similar backgrounds is information about the types of distributions of basic variables, since these data to a large extent are predetermined when obtaining the values of the reliability index of the structural elements. There are discrepancies in the type of distribution of basic variables, in particular, using probabilistic models for snow load, which are shown in [4] According to p.1 C.6 TCP EN 1990 [1]: "*For simplicity, when considering non-fatigue verifications, Normal distributions have been used for variable actions. Extreme value distributions would be more appropriate*". At the same time, an analysis of a number of foreign and domestic works shows that the most common types of distribution used in the approximation of annual snow load maxima are the following: the first limiting distribution of Gumbel, the lognormal distribution and the Weibull distribution, ***nevertheless more preferable from the standpoint of the generally accepted approaches in the theory of reliability is the use of the Gumbel type of distribution*** [5–9].

It should also be noted that even with the same load effects models, for constructions and their structural elements made of different materials, the resistance models, and if more precisely, the basic variables included in these models can differ significantly. So, for example, for the reinforced concrete element, there are "additional" basic variables in comparison with steel element that characterize not only the geometric parameters of the section, but also take into account the thickness of the concrete cover and the reinforcement ratio. In turn, in order to take into account the statistical variability of the strength properties of a reinforced concrete element, the complex account of both the resistance of concrete and the resistance of the reinforcement to the corresponding action on the element is necessary.

Thus, it is of interest to compare the reliability of steel and reinforced concrete elements, using the current system of partial coefficients. Further a brief overview of the main areas of research in the theory of the reliability of structures, in particular, in the problem of ensuring the equal reliability of structures is presented and the problematic places in their implementation in practice are noted.

1. PROBABILISTIC STATE FUNCTIONS OF BENDING STEEL AND REINFORCED CONCRETE ELEMENTS

According to the provisions of the Eurocode 1990, the "viability" of structures and their constituent elements is governed by their not achievement of ultimate limit states (ULS) and serviceability limit states (SLS). Also, in accordance with p. 2.2 (2) of TKP EN 1990 [1], different levels of reliability are adopted for the relevant limit states.

In case of probabilistic approach the construction is investigated using a model which describes the limit state in the form of a function called limit state function g(x) which value depends on all the corresponding calculated parameters x, it means, from all data on probabilistic models of basic variables. In general, the achievement of the limit state can be described by the following formula:

$$g(E, R) = 0, \tag{1}$$

where E and R are a set of load effects and resistance variables, respectively. For the values of the limit state function g (E, R) < 0, it is assumed that the structure is destroyed; in other words, a failure state is reached.

With known data on probabilistic models of random (stochastic) basic variables, the probability of failure during the period under consideration can be calculated by the following formula:

$$P_f = P\,(g(E, R) < 0). \tag{2}$$

In this paper, only the verifications of the ultimate limit states of cross sections (the so-called types of checks "on strength") of conventional steel and reinforced concrete elements subjected to the action of a bending moment are considered.

The state function for checking resistance for bending of a cross section of conventional steel element g *(X)* is taken in traditional form:

$$g(\boldsymbol{X}) = \theta_R\, z\, f_y - \theta_E\, [G + C_S\, S(t)], \tag{3}$$

where θ_R, θ_E – random variables that characterize the uncertainties in the calculation models of resistance and load effects respectively;

z – geometric characteristic of the cross section of the element (area, sectional modulus);

f_y – random variable, characterizing the strength of the material (yield strength of steel);

G – random variable, characterizing the permanent load;

S(t) – random variable, characterizing the snow load;

C_S – a variable characterizing the uncertainty of the snow load model (a simplified description of the load distribution on the surface of the coating, etc.).

The design resistance for bending of a conventional reinforced concrete beam singly reinforced at the bottom of the cross section is determined as follows:

$$R_d = A_s \cdot \frac{f_{yk}}{\gamma_s} \cdot \left(h - d - \frac{A_s \cdot \frac{f_{yk}}{\gamma_s}}{2 \cdot b \cdot \alpha_{\tilde{n}\tilde{n}} \frac{f_{ck}}{\gamma_c}}\right) \qquad (4)$$

where A_s – the area of the longitudinal steel reinforcement located in the lower part of the beam;

f_{yk} – the characteristic value of the yield stress of steel reinforcement;

γ_s – the partial factor for reinforcement and prestressed reinforcement;

h – the height of the cross-section of the beam;

d – thickness of concrete cover;

b – the width of the cross-section of the beam;

α_{cc} – is the coefficient that takes into account the long-term load action, the unfavorable way of applying it, etc.;

f_{ck} – the characteristic value of the cylindrical strength of concrete during compression;

γ_c – the partial factor for concrete strength.

In order to express the dependence of the bending resistance on reinforcement ratio, the value of the area of the longitudinal steel reinforcement is expressed through the reinforcement ratio:

$$A_s = \rho \cdot (b \cdot (h - d)), \qquad (5)$$

where ρ – the reinforcement ratio, taken in the conducted research 0.5, 1, 1.5 %, respectively.

Thus, the state function g(X) of a conditional reinforced concrete beam subjected to the bending moment is adopted in the following form:

$$g(\boldsymbol{X}) = \theta_R R - \theta_E [G + C_S S(t)], \quad (6)$$

where R – a random variable characterizing the resistance for bending of a reinforced concrete element in accordance with expression (4).

In order to cover and further analyze as much as possible range of load combinations for different ratios of constant and snow loads, a loading parameter *c* which is the ratio of the snow load at the total load value is used:

$$\chi = S_k / (G_k + S_k), \quad (7)$$

where S_k – the characteristic value of snow load;
G_k – the characteristic value of permanent load.

The values of the loading parameter c can vary from 0, which is typical for underground structures and foundations, up to 1, for example, local effects in bridges and crane beams. It was noted in [10] that for reinforced concrete beams under the action of a snow load the values of the loading parameter c are in the range from 0.4 to 0.7. For structures made of steel, on the basis of design experience, it can be noted that the most objective range for this parameter is c = 0.4 ... 0.8 [11].

2. PROBABILISTIC MODELS OF BASIC VARIABLES

The main data for the realization of probabilistic calculation of building structures is information on the probabilistic models of basic variables entering into the limit state function. In general, it is worth noting that the models of basic variables are divided into two large groups: the resistance model and the load effects model. Resistance models, for example, for a steel element include data on the geometric parameters of the cross section of the element, the yield strength of steel, the resistance model uncertainties. A distinctive feature of the load effects models from the resistance models is their independence from the material of the structural element being studied, however, for the load effects, the basic reference period under consideration is an important factor. For load effects models the following data can be cited as the most common: data on the permanent, imposed, snow, wind and other types of loads, as well as data on the corresponding the load effects models uncertainties. So, for example, for a snow load, the model uncertainty is caused by a simplified description of the load distribution on the roof, etc. The main characteristics of probabilistic models of basic variables are data on the types of distribution of random variables and statistical parameters.

In the present work, the actual data of the statistical parameters of the snow load are presented on the basis of the studies carried out for the territory of the Republic of Belarus [12] for the period under consideration, equal to 1 year. It should be noted that the values of the statistical parameters of such climatic loads, as snow, have a significant dependence on the territorial features of a particular region of the country. Thus, according to researches data [12, 13] for northern regions, the coefficient of variation of snow load is almost half that for the southern regions (for Vitebsk – 0.44, for Pinsk – 0.72). Taking into account this situation, the averaged values of the statistical parameters for describing the distribution of annual maxima of the snow load are adopted. It should also be noted that the statistical data used can't be objectively comparable with similar data obtained in the course of meteorological observations in European countries with a similar climate, since even small deviations of these parameters can make quite significant changes in the results of calculating reliability parameters. In general, an analysis of the sensitivity of the value of the reliability index to the statistical parameters is of interest. Attempts to take this factor into account were performed in [14], where the statistical parameters are taken in the range values.

Probabilistic models of the strength characteristics of steel and the uncertainties in the computational model are adopted averaged in accordance with the recommendations [5]. It should be noted that in most works on reliability research the parameters of the above-mentioned basic ones have a similar character.

Probabilistic models of compression resistance of concrete, yield strength of steel reinforcement, as well as probabilistic models of geometric parameters of the cross section and the uncertainty of the calculational model (the resistance model uncertainty for reinforced concrete element under bending) were adopted in accordance with the data of [10] and general recommendations of JCSS [15].

All probability models used for calculations are given in table 1.

Table 1

Accepted probabilistic models of basic variables for the analysis of reliability of steel and reinforced concrete elements subject to bending moment

Basic variables	Symbol	Distribution	μ/X_k	V	σ
Basic variables of the resistance model for steel element					
Resistance of steel element	R_k	LN	1.15	0.065	0.075
The resistance model uncertainty of steel element	$K_{R,s}$	LN	1.08	0.075	0.081
Basic variables of the resistance model for reinforced concrete element					
Characteristic value of cylindrical strength of concrete on compression for C30/37	f_{ck}	LN	42/30	0,138	5.8
The characteristic value of the yield strength of steel reinforcement	f_{yk}	LN	560/490	0,053	30
The height of the cross-section of the reinforced concrete element	h	Norm	0.6	0.013	0.008
The thickness of protective layer of concrete	d	Norm	0.03	0.2	0.006
The width of the cross-section of the reinforced concrete element	b	Det	0.3	–	–
The resistance model uncertainty of the reinforced concrete element	$K_{R,RC}$	LN	1.0	0.1	0.1
Basic variables of the load effects model					
The load effects model uncertainty	$K_{E,RC(s)}$	LN	1.0	0.1	0.1
Permanent action	G	Norm	1.0	0.085	0.085
Snow load (annual maximum)	S_1	Gumb	0.41	0.55	0.23
The snow load model uncertainty	$C_{0,s}$	LN	1.0	0.15	0.15

The values of the partial factors for the reinforcement and the prestressed reinforcement γ_s=1.15, for concrete γ_c=1.5, as well as the value of the coefficient α_{cc}=1.0, which takes into account the long-term load action, and the unfavorable method of its application, are taken from the data of TKP EN 1992-1-1 [16].

The values of the partial factors for the permanent and variable actions γ_g=1.35 and γ_q=1.5, respectively, the reduction factor ξ = 0.85, and also the value of the factor for combination value of the snow load ψ_0=0.6 are presented on the basis of the data of TKP EN 1990 [1].

3. THE ANALYSIS OF THE RESULTS

Within the framework of the study, the first-order reliability method (FORM) was used to obtain the reliability parameters of the conditional steel and reinforced concrete elements under bending. The considered period of time (reference period) is assumed to be 1 year. The rules for combining the actions are used in accordance with expressions 6.10a / b [1].

The results are presented in the form of graphs, where the values of the loading parameter χ are plotted along the abscissa axis, and the values of the reliability index β are plotted along the ordinate. Figure 1 depicts the dependence of the value of the reliability index β on the load parameter χ at reinforcement ratio 0.5, 1.0 and 1.5 %, respectively.

Thus, the dependence of the reliability index of a bending reinforced concrete element on the reinforcement ratio is investigated.

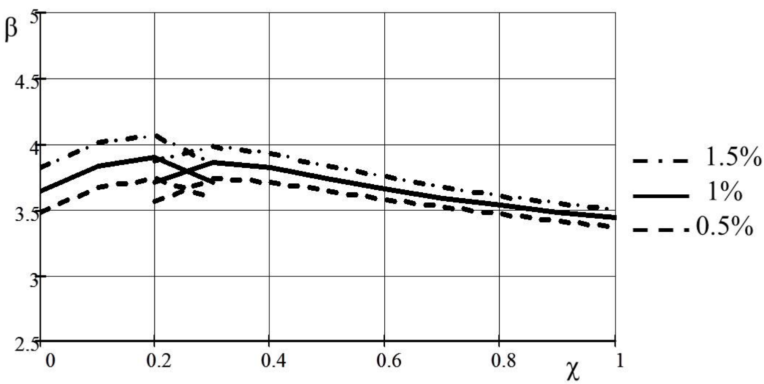

Figure 1. The values of the reliability index for a reinforced concrete element under bending

On the basis of the data obtained, it can be concluded that with increasing reinforcement ratio, the reliability of the reinforced concrete element under bending increases, these results are accordant with the results of the research [19]. Most objectively, this is reflected when the reinforcement ratio is from 1 to 2 %, which, taking into account the design experience, is the most common range of reinforcement ratio in the design of reinforced concrete structures.

Numerous studies in the field of reliability of structures indicate that for steel elements, reliability is basically predetermined by a variable load. One of the reasons for this situation is that other basic variables have small variability. The consequence of the foregoing is the considerable sensitivity of the index of reliability of steel elements with a large share of variable load (snow) to the statistical parameters of this load. Figure 2 illustrates the changes in the value of the reliability index β for a steel element with a slight change in the statistical parameters for describing the annual snow load maxima (μ_1 =0.41 and V_1=0.55; μ_2=0.46, V_2=0.60).

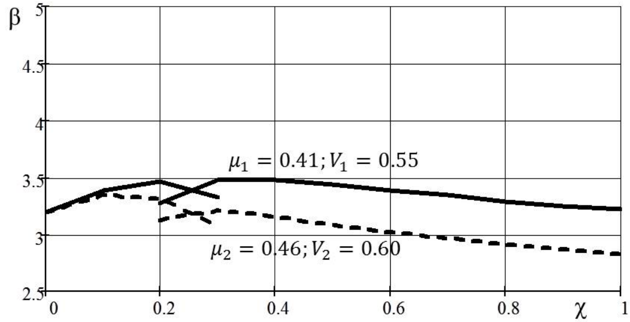

Figure 2. Values of the reliability index for a steel element under bending using various statistical parameters for the probabilistic description of the snow load

Figure 3 shows the graph when the statistical data of the resistance model uncertainties for a steel element under bending with μ_1 = 1.08 and V_1 = 0.075 to μ_2 = 1.2, V_2 = 0.15, respectively, are changed. On the basis of the obtained graph, it can be concluded that even with a significant change in the probabilistic models of the basic variables, not related to the variable actions, the change in the reliability index for the steel element is not significant. This, in turn, makes think about much greater expediency of further refining the load effects models.

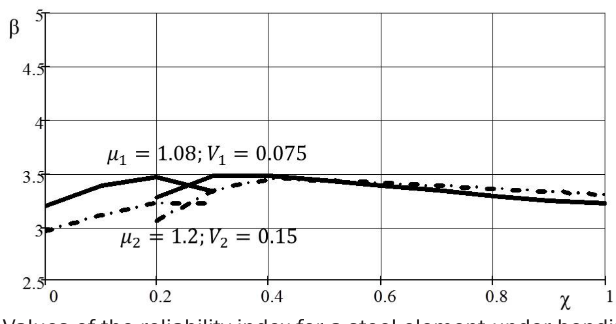

Figure 3. Values of the reliability index for a steel element under bending for various statistical parameters for a probabilistic description of the uncertainties in the bending resistance model

In turn, for a reinforced concrete element, the change in the statistical parameters of the resistance model uncertainty has a sufficiently large effect on the value of the reliability index. In this regard, it should be noted that there are some inconsistencies in the adoption of statistical parameters for describing uncertainty of the resistance model for bending for reinforced concrete elements, so according to the data of studies [7, 10, 17], the mean value is taken for this basic variable μ = 1.0–1.2 with the corresponding coefficient of variation V = 0.10–0.15.

According to the recommendations of JCSS [15], μ = 1.2, V = 0.15. However, the lack of a clear regulation even in this matter leads to a rather tangible "displacement" of the reliability index: for μ = 1.0, V = 0.10, the reliability index for a reinforced concrete element under bending at 0.5 % till 2 % of reinforcement, respectively, is on average 0.5 less than at μ = 1.2, V = 0.15 with other identical models of basic variables. Figure 4 shows the graph for various statistical data of the uncertainties in the bending resistance model of a reinforced concrete element with a reinforcement ratio 1 % (μ_1 = 1.0 и V_1 = 0.10; μ_2 = 1.2, V_2 = 0.15 respectively).

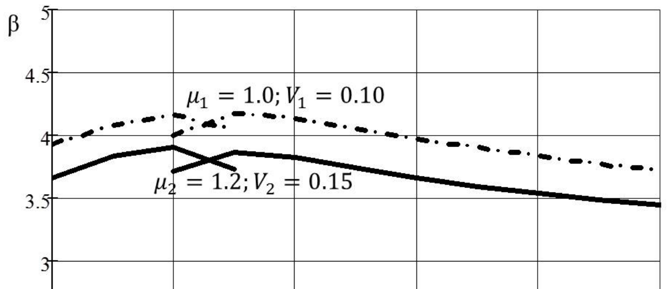

Figure 4. Values of the reliability index for a reinforced concrete element under bending with the reinforcement ratio 1 % for various statistical parameters for a probabilistic description of the uncertainties in the bending resistance model

It should be noted that with the increase in the reinforcement ratio, the difference in the values of the reliability index when various statistical parameters are used for the probabilistic description of the uncertainties in the bending resistance model increases.

4. PROBLEMS IN DETERMING THE RELIABILITY INDEX FOR DIFFERENT TIME PERIODS

Often to the calculation of the reliability index for the 50 year reference period the adoption of statistical data (to account time dependence) for variable actions by means of transformations characteristic to the Gumbel type of distribution [7, 18] is used, while the statistical parameters for the permanent load don't change, which leads to the independence of the reliability index from time in situations when the effect from permanent load is dominant (this situation is quite typical for reinforced concrete structures), which, in turn, leads to a "fixed" level of reliability, independently on time, under the influence of only permanent load, this can't be an objective result, but this approach is widely used for load combination according to Ferry-Borges Castanheta model, when for distribution of dominant load need to use maximum load during reference period

Below in figure 5, the dependence of the value of the reliability index β on the loading parameter χ for a reinforced concrete element under bending at a reinforcement ratio 1 % for the reference periods: 1 year and 50 years, respectively, is shown. The graph for 50 years is obtained by the recalculation of the statistical parameters for the snow load from 1 year to the 50-year reference period with the preservation of the probabilistic models of other basic variables corresponding to a 1 year reference period.

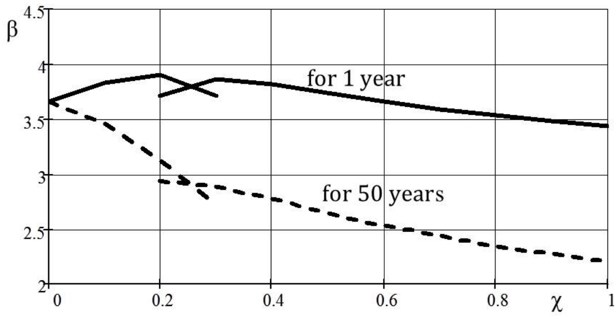

Figure 5. The values of the reliability index for a reinforced concrete element under bending for a reference periods 1 year and 50 years respectively

There are also the following alternative approaches to the calculation of the reliability index for different time periods, based on the application of formula C.3 of TKP EN 1990 [1]:

a. the statistical parameters for all basic variables are taken as for 1 year, the calculation of the reliability index for any other period under consideration is carried out by applying formula C.3 of the TKP EN 1990 [1]. This approach is shown in Figure 6 for a reinforced concrete element under bending with a reinforcement ratio1 %.
b. the statistical parameters for the variable action are applied by the recalculation for the relevant period under consideration according to the selected type of distribution (usually for a snow load according to the Gumbel type of distribution [17]), then the recalculation of the reliability index for the entire state function is carried out by applying formula C.3 TKP EN 1990 [1]. This approach is shown in Figure 7 for a reinforced concrete element under bending with a reinforcement ratio 1 %.

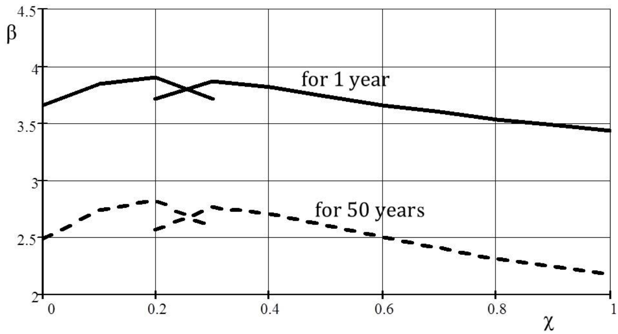

Figure 6. The values of the reliability index for a reinforced concrete element under bending for reference periods 1 year and 50 years respectively according to method a

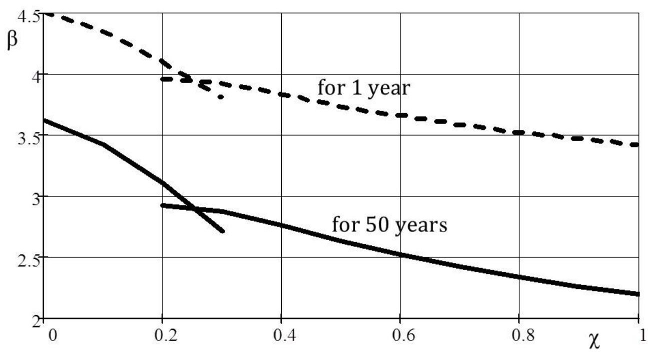

Figure 7. The values of the reliability index for a reinforced concrete element under bending for reference periods 1 year and 50 years respectively according to method b

Thus, the differences in the currently used approaches to the calculation of the reliability index of structures for various periods of time are clearly illustrated. Therefore, due to the fact that different approaches are currently in use in various studies, difficulties arise in the objective comparison of the results obtained.

CONCLUSION

Within the framework of the study, the probabilistic models of basic variables were collected and analyzed, and the state functions for steel and reinforced concrete elements under bending were composed. According to the data obtained, a number of features should be highlighted in ensuring the equal reliability of steel and reinforced concrete structures in accordance with the provisions of the theory of reliability and backgrounds laid down in TKP EN 1990 [1]:

1. For a reinforced concrete element, there is a large dependence of the value of the reliability index on the reinforcement ratio. Also for a reinforced concrete element there is a significant sensitivity of the index of reliability to the statistical parameters of the resistance model uncertainty.
2. For steel elements the variable action predetermines reliability. So for situations when there is a large share of variable action (for example snow load) there is a significant sensitivity of the index of reliability of steel elements to the statistical parameters of this action.
3. The discrepancy in the reliability concept adopted in the TKP EN 1990 [1] is also worth noting when calculating the reliability index for the reference periods of 1 year and 50 years respectively which leads to the necessity of the adoption of a more objective methodology for calculating the reliability index for different periods of time.

In general, it should be noted that there is a need to calculate and normatively fix the parameters of the structural reliability of structures at the national level (by bringing them into the National Annex), using valid data on probabilistic models of basic variables, especially for variables influenced by climatic features of the Republic of Belarus. Also there is a need for research on the refinement of probabilistic models for various resistance models for various structural elements made of different materials.

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