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A first Attempt to Determine the Partial Factors According to Eurocodes for the Verification of ULS of Steel Elements for Conditions of the Republic of Belarus

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The aim of the study is to develop science-based methodology for estimation the values of the partial factors for design of steel structures for the conditions of the Republic of Belarus, taking into account the specified values of reliability levels. The object of the study is steel structural elements. Methods: mathematical modeling, numerical and analytical methods, parametric and graphic analysis. In January 2010 European standards (EN standards, Eurocodes) for the design, fabrication and erection of building structures were introduced in the Republic of Belarus. The system of European standards (EN 1990) recognise the responsibility of regulatory authorities in each country and guarantee their right to determine values related to regulatory safety matters at national level. According to the reliability concept of building structures adopted in the standard ISO 2394, EN 1990 the target reliability levels for designed structures are set. It caused a necessity to calibrate the partial factors of steel structures for Belarusian National Annex to Eurocode 3 based on the target reliability level using probabilistic methods.

KEYWORDS: basic variable, partial factor, probabilistic models, limit state, target reliability level, structural reliability.

Introduction

The partial factor method (semiprobabilistic method), in which the variability and uncertainty of the design models and basic variables included in the design models are taken into account by means of the partial factor system applicable to the characteristic values of the basic variables has been widely practised. According to 6.1(1)P EN 1990 (2002) the basic requirement of the partial factor method is as follows: *"...it shall be verified that, in all relevant design situations, no relevant limit state is exceeded when design values for actions or effects of actions and resistances are used in the design models"*.

The partial factor system is one of the tools for differentiation and assurance of the target levels of the structural reliability; therefore, the justification of their values with due account to the specific geographic, social and economic conditions is a top-priority objective for every state.

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The present investigation is devoted to the justification of values of the partial factors for the verification of ultimate limit states of steel elements for condition of the Republic of Belarus.

The partial factors values are to be determined by the following methods:

- expert judgement;
- on the basis of the analysis of compliance with the many years' experience and construction traditions;
- statistical methods, which are based on the required probability of design values of the basic variables;
- calibration with application of the probabilistic methods on the basis of the target (required) reliability level.

The approach based on application of the probabilistic methods is the most advanced one making it possible to take into consideration the actual condition of service of the structures and requirements for them as well as to ascertain the scientifically grounded partial factors values. In the today's regulations of the European Union, USA, Canada and other countries, the partial factors values are adopted according to the results of calibrations performed by the probabilistic methods (Allen 1975, Beck 2010, Byfield 1996, Ellingwood 1982).

The main objective when determining the partial factors by the probabilistic method consists in assurance of the required reliability level. The next logic stage in regulation of the partial factors values consists in the calibration of the partial factors system, which is a norm optimisation issue. The calibrated partial factors shall ensure the reliability levels of the most typical structures to be as near to the target reliability levels as possible regardless the materials to be used, prevailing actions and environment conditions; here the number of the partial factors values is restricted.

The general recommendations for calibration have the status of statutory norm in ISO 2394 (2015) and EN 1990(2002) and reflected in the JCSS(2001). The procedure of calibration of the partial factors is described in the works Gulvanessian (2002), Sorensen (2001), Vrouwenvelder (1987).

Given the probabilistic models of the basic variables, the failure probability for the basic period of time can be determined by the reliability theory methods. The calculated values of the failure probability are compared with the target reliability level. Should the result be unsatisfactory, a new set of partial factors values shall be established and the calculation shall be repeated until the moment of achievement of the reliability level.

The initial data for the probabilistic calculation is the information on the basic variables used in the performance functions, therefore the accuracy and adequacy of the probabilistic models of the variables exert predominating influence on the calculation results. This circumstance predetermines the necessity of the systemic investigations of the statistical parameters of the basic variables and formation of the unified principles of their assignment. In the next section the probabilistic models of the basis variables for the conditions of the Republic of Belarus are described.

The probabilistic models of the basis variables for the conditions of the Republic of Belarus

A special place is held by the matter of establishment of the probability distribution law for the basic variable. Usually, the distribution law is established on the basis of the statistical analysis of the available experimental data. In the construction industry, the availability of experimental data is limited making it impossible to obtain the statistically valid results. Therefore, theoretical preconditions are often used when choosing the distribution law. It should be noted that there is a general problem of use in the reliability theory of any of reliability random value distribution laws in the range of very low probability values, i.e. outside the range where the applicability of the law was experimentally justified and its parameters were determined. The general recommendations for assignment of the distribution laws to the basic variables have statutory form in the documents ISO 2394 (2015), EN 1990(2002) and JCSS (2001).

The probabilistic models of the basic variables adopted in various investigations differ often from each other. The reliability investigations based on different probabilistic models can lead to different results and, as a consequence, to different values of the partial factors, combination factors and other parameters ensuring the achievement of the target reliability levels. It is important to take into account that the calibrated values of the reliability parameters belong to a specific set of probabilistic models of the basic variables included in the models of resistance and action effects. As noted in ISO 2394(2015) "*The use of calibrated values jointly with other models can cause the unintended high or low reliability levels*".

Probabilistic models for basic variables adopted in accordance with general guidelines JCSS (2001) and for snow load model has been developed taking into account the relevant research for the territory of the Republic of Belarus Tur (2008, 2009), territorial peculiarities supply rolled steel into the country are accounted for the strength characteristics Nadolski (2014, 2015). A special kind of the basic variable represents the combined effect of several actions. In this article, these matters are not considered. **Table 1** presents the probabilistic models of the basic variables included in the design models of resistances and action effects when designing the steel structures, on the basis of which the investigations of the target values of the reliability index were performed and the partial factors values were obtained.

Table 1

Probabilistic models of the basic variables for the conditions of the Republic of Belarus

Basic variables	Distribution	μ/X_k	V
Steel element resistance	Lognormal	1.1 – 1.2	0.05 – 0.08
Uncertainties of the resistance model	Lognormal	1.0 – 1.15	0.05 – 0.10
Self-weight	Normal	1.0	0.03 – 0.06
Permanent load	Normal	1.0 – 1.05	0.07 – 0.10
Imposed load	Gumbel distribution	0.45 – 0.6	0.35 – 0.40
Uncertainties of the imposed load model	Normal	1.0	0.10
Snow load	Gumbel distribution	0.9 – 1.1	0.19 – 0.23
Uncertainties of the snow load model	Normal	1.0	0.15
Wind action	Gumbel distribution	1.0 – 1.1	0.17 – 0.20
Uncertainties of the wind action model	Normal	0.8	0.30
Uncertainties of the action effect model	Lognormal	1.0	0.10

μ is the mean value; V is the coefficient of variation, and X_k is the characteristic value.

Calibration of the Partial Factors in accordance with the Reliability Level Specified by EN 1990 Standard

On the basis of the values of the sensitivity factors obtained using the first-order reliability method (FORM) and with the adopted probabilistic models of the basic variables, the partial factors values ensuring the achievement of the target value of the reliability index b_t = 3.8 for the reliability class RC 2 according to EN 1990 (2002) were obtained.

The values of the partial factors for the resistance (γ_M) as well as permanent (γ_G) and variable (g_Q) actions are presented in the following form:

$$\gamma_M = g_{Rd} \times g_m, \;\; \gamma_G = g_{Sd} \times g_g, \; g_Q = g_{Sd} \times g_\mu \times g_q, \tag{1}$$

where:

g_{Rd} is the partial factor taking into account the uncertainties of the resistance model;

g_m is the partial factor for the material property (yield strength of steel) taking into account the possibility of adverse deviation of the material property from its characteristic value;

g_{Sd} is the partial factor taking into account the uncertainties of the action effect model;

g_g is the partial factor for the permanent load taking into account the possibility of adverse deviation of the permanent load from its representative value;

g_μ is the partial factor taking into account the uncertainties of the action model (for example, for the snow load this factor takes into account the uncertainty of the pattern of distribution of the snow load on the roof);

g_q is the partial factor for the variable action taking into account the possibility of adverse deviation of the variable action from its representative value.

Fig. 1 and 2 presents the partial factors values g_i depending on the load ratio $x = Q_k / (G_k + Q_k)$ ensuring the achievement of the target value of the reliability index b_t = 3.8. The results are presented for the imposed and snow loads only. The dependences g_i – x have similar nature when considering the wind load. For the purpose of the probabilistic description the mean values of the statistical parameters of basic variables were adopted from the range which is presented in Table 1. Such a presentation makes it possible to reflect the qualitative aspect of dependence under investigation. The obtained partial factors values are consistent with the results obtained by other investigators Holicky (2009), Sadovský (2006), Sýkora(2011) .

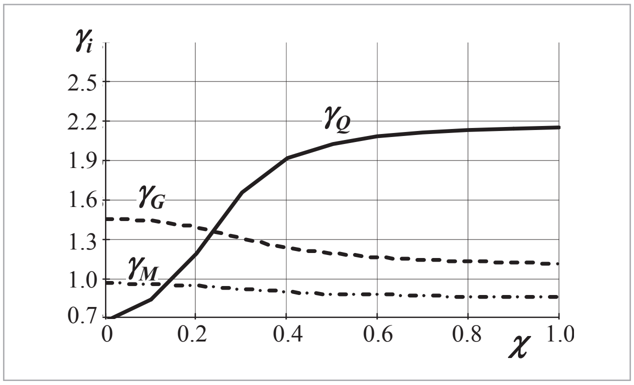

Fig. 1

Partial factors values ensuring the achievement of the target reliability index b_t = 3.8 for the imposed load

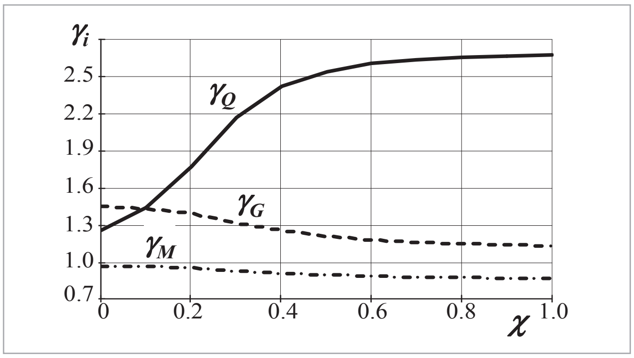

Fig. 2

Partial factors values ensuring the achievement of the target reliability index b_t = 3.8 for the snow load

Analysis of the Partial Factors Values Established based on the Reliability Level Specified by EN 1990 Standard

The analysis of the partial factors values required for ensuring the reliability level specified in EN 1990 (2002) standard has revealed inconsistencies in the reliability concept adopted in the Eurocodes, namely:

- the obtained partial factors values exceed considerably those applied at present in the national and worldwide practice of normalising the variable actions;
- the numerical analysis of the prosperity of the design values of the basic variables has shown that the probability of exceeding the design values of the variable actions is at the level of 10^{-4}...10^{-5}. Using the appropriate distribution law makes it possible to determine the prosperity of the design value. For example, adoption of the Gumbel distribution for the snow load at the ground / gives the probability of exceeding the obtained design load value:

$$P = \exp\left[-\exp\left[-a\,(s_d - b) \right] \right] \tag{2}$$

where:

s_d is the design value of the snow load at the ground:

$$s_d = S_k \times g_q \tag{3}$$

a and b are the distribution parameters to be determined through the mean value μ and standard deviation σ of the whole samples:

$$a = \pi / (\sigma \sqrt{6}) \quad (4)$$

$$b = \mu - 0.5772 / a \quad (5)$$

When describing the snow load at the ground by the Gumbel distribution and with the values of the partial factor taking into account the load variability at the ground only γ_q (see formula 2), the probability of exceeding the design values was 10^{-5} per year.

Here it is necessary to keep in mind that the values of the variable actions are normalised from the distribution of the annual maxima. Therefore such a probability is only applicable when normalising the rare natural and climatic phenomena or accidental value of the action and unacceptable for the design values of the variable actions when considering the permanent design situations. In addition, the fractile of this level requires the considerable extrapolation far beyond the observable values that causes uncertainties and reduce the trustworthiness of evaluation of the final result.
In the revealed situation, the analysis of the structural reliability levels on the basis previous experience of standardization with the adopted probabilistic models of the basic variables.

Assessment of the Reliability Levels on the Basis of the Previous Belarusian Experience of Standardization

As an alternative, the assessment of the reliability levels based on the previous experience of standardization for the Belarus has been performed. The results are presented as diagrams where the reliability index values β are laid off as ordinates and the load ratio χ – as abscissas. **Fig.3** presents the upper and lower limits of variation of β under the simultaneous action of the permanent and imposed loads, and **Fig.4** – the same limits under action of the permanent and snow loads. The abrupt jump of the values β in **Fig.4** is conditioned by the change of the partial factor for the snow load according to the SNiP (1985). According to Clause 5.7 SNiP (1985) the partial factor γ_S^* for snow load for roof members is $\gamma_S^* = 1.5$ for $G_k^* / S_k^* \geq 0.8$ and $g_S^* = 1.6$ for $G_k^* / S_k^* < 0.8$. The partial factor γ_s^* changes at $\chi \approx 0.58$ that corresponds to $G_k^* / S_k^* = 0.8$. Where the parameters defined in SNiP (1985) are denoted by the symbol «*». Symbols G_k^* and S_k^* represent characteristic values of permanent and snow load, respectively. The similar results of the analysis of the reliability indices for the Russian Federation (Sykora 2014) should also be noted.

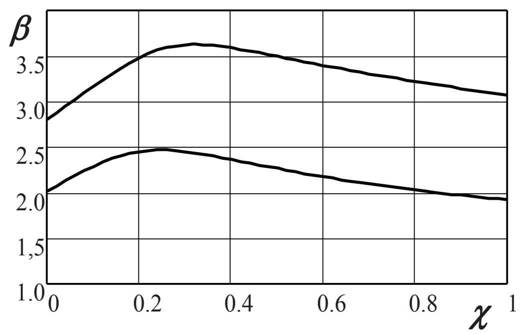

Fig. 3

Dependences of $\beta - x$ for the imposed load

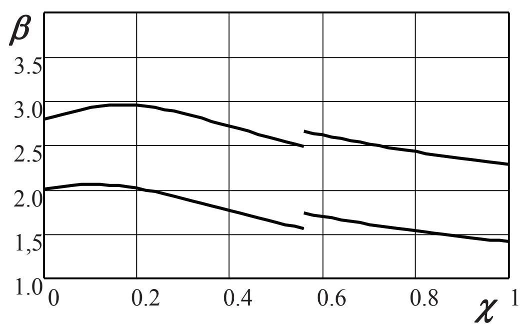

Fig. 4

Dependences of $\beta - x$ for the snow load

On the basis of the analysis of the results of investigations of the reliability levels ensured by the previous practice of standardization and designing of steel structures, the least value of the failure probability $p_f = 10^{-2}$ for the assignment period of 50 years was adopted for the further calibration of the partial factors.

Conclusions

For purposes calibration the partial factors the probabilistic models of basic variables included in the model of resistance of steel elements are developed for the Republic of Belarus. Reasonable probabilistic models of resistance and action effects are allowed to calibrate values of the partial factors for design models of steel structures for a target reliability level of building structures according to Eurocodes. The further analysis showed that the use of the obtained value of the partial factors leads to probability of exceeding (the fractile of annual extremes) the design values more than for accident load.

The way out of this situation is the revision of the numerical values of the parameters of reliability or a slightly different approach to the design reliability. This made it necessary to carry out an assessment of reliability parameters on the basis of previous experience of standardization. The numerical values of the reliability levels of steel structures have been obtained based on the previous normalising experience as applied to the conditions of the Republic of Belarus. When performing the verification of the ultimate limit states of the steel elements of the mean reliability class (residential or office buildings, etc.), the minimum value of the failure probability for the assignment period of 50 years is recommended to be $p_f = 10^{-2}$ for the adopted probabilistic models of the basic variables.

The results can be applied in the development of the provisions of the norms relating to the project to ensure the reliability of structures, as well as allow you to perform probabilistic calculations of steel structures. It is expected that the results obtained from this study will provide background materials for development of National annexes and also for a future improvement of Eurocodes.

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