ISSN 1846-6168 (Print), ISSN 1848-5588 (Online)
https://doi.org/10.31803/tg-20230508125238

Preliminary communication
Received: 2023-05-08, Accepted: 2024-10-25

Reliability Index for Steel Structure's Technical State and Residual Life Assessment

Sergiy Kolesnichenko*, Inna Chernykh, Valentyna Halushko, Polianskyi Kostiantyn

Abstract: The article is dedicated to problem of technical state assessment of real steel truss under operation for residual life prediction after technical investigation. The reliability index is calculated based on design, real and prospective loads. Method of statistical data analysis adopted for stress-strain determination also for all kinds of applied loads. The residual life with the reliability index determined as a transition from satisfactory to emergency technical state. The method provides the possibility for estimation of future safety steel structures operation with technical investigation results only that exclude any subjective opinion.

Keywords: reliability index; residual life; steel truss; technical state

1 INTRODUCTION

During designing of structures, the steel structures include, must be provided the safety operating control during all service life. The safety is guaranteed by the conditions that the limit states will not be reached – the loads on structure and appropriate stresses in elements must have sufficient level of reliability. This main demand contains all designing standards [1, 2].

The safety operation indicators which determined on the results of technical investigations are both: the technical state and residual life - the guaranteed post-investigated operational life. So, the main task of technical investigation is the appointment of these indicators. During the structure's life, the existing degradation processes (corrosion, fatigue and materials conditions) together with loads changing (often increased during operation) may lead to decreasing of reliability. The values of these indicators, determined by the comparison of designing and real technical parameters for structure, could be defined only based on the results of technical investigation.

As a basis for reliability determination, all statistical information that describing structure's life during service, must be considered. But the lack of this information is a reason of restriction for wide application of reliability methods. The way to get statistical information is to carry out the regular technical investigation of existing structures. In this case may be solved a few tasks:

- to establish really structural and cross-sectional dimensions;
- to analyze all possible deterioration processes for elements (corrosion, fatigue);
- to fix changing of loads and for materials;
- to estimate a technical state for each separate structure and building in general;
- to assess a residual life for structures.

If the first three tasks may be solved sufficiently easy, the definition of technical state and residual life mostly assess subjectively and depends on expert experience. Usually during estimation any statistical data do not consider.

In this paper we tried to show the way for the investigators how to prepare the objective assessment of technical state for structure and how to calculate the residual life for it with the strong procedure of reliability calculation if some results of technical investigation exist.

2 LITERATURE REVIEW, RELATED WORKS AND INVESTIGATION CONCEPTS

In modern standards [1, 3, 4] the safety of building structures is proposed to calculate with the common reliability parameter called as "reliability index" β which reflects the possibility of structure's failure depends on actions, cross-section and resistance of materials probabilistic nature [5, 6]. This parameter was proposed by Cornell C. A. [7, 8].

The designing of new structures, also as estimation of safety for operating structures, should be executed depends on consequence class – CC. There are three CC exists [1]: CC1 (low consequence), CC2 (medium consequence) and CC3 (high consequence).

The different values of β proposed for every CC [4, 8, 9, 10], but all these values based on the same approaches and principles: it depends either possibility of human life losses, economic losses, social and environmental consequences and all of these related to the number of structure operated years which corresponds to possibility of structure failure.

In general, the β defined as:

$$\beta = \frac{\overline{S}}{\sigma(S)} = \frac{\overline{R} - \overline{F}}{\sqrt{\sigma^2(R) + \sigma^2(R)}}, \tag{1}$$

$$\overline{S} = \overline{R} - \overline{F}, \tag{2}$$

$$\sigma(S) = \sqrt{\sigma^2(R) + \sigma^2(R)}. \tag{3}$$

In the Eqs. (1)-(3): $\overline{R}$ – mean value of resistance or bearing capacity of the element (structure) – generalized durability of element (structure); $\overline{F}$ - mean value of action effect on element (structure); $\overline{S}$ – reserve of strength for all laws of distribution of R and F; $\sigma^2(R)$ and $\sigma^2(F)$ – resistance capacity and action effect respectively.

Reliability index also can be determined as:

$$\beta = \frac{1}{V(S)}, \tag{4}$$

where $V(S)$ – variation coefficient of random strength reserve variable.

Also, in some scientific research [10, 12, 13, 14], the values of reliability index β proposed for different technical conditions of building structures. There are three levels of it: new, repair and unfit to use. Also proposed so-called "reliability classes – RC" or consequences of failure: insignificant, normal and large. In fact, these conditions, classes or consequences of failure may be accepted as technical states when exists necessity of technical conditions definition for operated structures during investigation procedure.

After the technical state determination, the task of residual life calculation for the structure also is very significant. We suggest that the residual life is an estimation of the remaining useful service of an element or structure (building) considering of its present condition and future functioning (the element or structure will next require reconstruction, rehabilitation, restoration, renewal or replacement) [15, 16]. With accordance of this suggestion, it is possible to connect the technical states and residual life, when the residual life is a time that defines as a transition from one technical state to another, for example from state that need of repair to the emergency state.

After calculation of β for more stressed structure's elements, the general β for all structure should be determined where the types of elements connection (series, parallel or mutual) examined. Now do not exist of correct rules for it, some examination formulae proposed in [6, 17]. For normal statically determined structures recommended [5, 18] to calculate it as for serial elements connection.

3 DETERMINATION OF STRUCTURE'S TECHNICAL STATE BASED ON TECHNICAL INVESTIGATION

Two main tasks must be solved for the building structures under operation when the reliability index β is applied:

- the β must be accepted with such its values, that building structure could not be possible for future operation if these values are lower than determine for every consequence class CC;
- the β levels must be determined for possible fulfillment of repairing works – reconstruction or repairing works.

The Tab. 1 contains the maximum values of reliability index β for different technical states - new structures, structures which need to be repaired and for structures in emergency state. The values, given in the Tab. 1 taken as more appropriate for industrial steel structure from the [9] based on recommendations [3, 19].

Table 1 Maximum values of β depends of CC and types of structure's technical states

Consequence class - CC	β (new structures)	β (needs to repair state)	β (emergency state)
CC1	3,3	2,8	1,8
CC2	3,8	3,3	2,3
CC3	4,3	3,8	2,8

There was a task to determine the technical state for steel roof trusses which are situated in industrial machine making building. The state must be determined based on technical complex investigation with theoretical value of β.

The framework of the industrial building consists with steel columns and trusses with the span of 18 meters and 6 meters of columns bay spacing. Consequence class of the building – CC2.

General view of industrial building and trusses with defects and damages are shown on the Fig. 1.

There was analysis of actions with normative values of loads on 1966 year of construction have done. The structures were investigated in 1988, 2011 and 2021 years. On the moment of last investigation, the building was under operation 55 years with the designing life of $T_0 = 60$ years.

1) Based on the results of technical investigation fulfilled in 2021 year, there were the measuring drawings have prepared with all necessary cross-sectional values with real parameters (influence of corrosion, differences with standard values). The design drawings were absent.
2) Non-destructive method was used for determination of real steel resistance R_y (MPa) with future calculation of variation coefficient VR_y.
3) The calculation of structure on following actions (loadings) have done - see Tab. 2 (column - number of loadings):

- Project (q_1), ideal parameters: dead loads + roof load + snow – parameters taken on building standards on the year of designing.
- Investigation 1 (q_2): dead loads + roof load + snow – parameters taken on building standards on the year of investigation in 22 years. Corrosion deterioration is absent.
- Investigation 2 (q_3): dead loads + roof load + snow – parameters taken on building standards on the year of investigation in 45 years. Corrosion deterioration of upper chord elements close to 15%.
- Investigation 3 (q_4) – the real actions 4 after 55 years of operation, with defects and damages – corrosion damages: dead load + roof load + snow load (values in the current building standards). Corrosion damages for upper chord elements – 30%, bearing elements – 15%, other elements – up to 5%.
- Predictive (q_5), the corrosion process continuation in time up to 45%: dead loads + roof load + snow load (values in the current building standards), operating period – 60 years.

4) For probabilistic calculation additionally have defined (Tab. 3):

- the geometrical dimensions of areas, including corrosion damages for mean, minimum and maximum values: $\overline{A}$, $A_{\min}$, $A_{\max}$;
- designing loads of all standards demands on the day of design - N_d;
- designing loads of modern standards on the day of technical investigation - $\overline{N}$;
- loads of modern standards on the day of technical investigation but only with characteristic (normative)

values, where all reliability coefficients with designing values are equal of $1 - N_n$;

- there were nine values of stresses have been calculated for each loading with combination of N and A: $s_1 = f(N_d; A_{\min})$; $s_2 = f(N_d; \overline{A})$; $s_3 = f(N_d; A_{\max})$; $s_4 = f(\overline{N}; A_{\min})$; $s_5 = f(\overline{N}; \overline{A})$; $s_6 = f(\overline{N}; A_{\max})$; $s_7 = f(N_n; A_{\min})$; $s_8 = f(N_n; \overline{A})$; $s_9 = f(N_n; A_{\max})$. During calculation the real geometrical characteristics for area A were taken, were calculated the mean values of actions $s_{mv} = \overline{F}$ and variation coefficients $V \cdot \overline{F}$.

5) The mean value for steel resistance have accepted as: $R_y = \overline{R}$ (MPa) and variation coefficient $V \cdot R_y = V \cdot \overline{R}$.
6) For each truss elements were calculated the values of $\xi = \overline{R}/\overline{F}$ and β. For each β value was defined values of P_f and P_s.


General view of industrial building General view of the trusses Curvature of the truss's elements

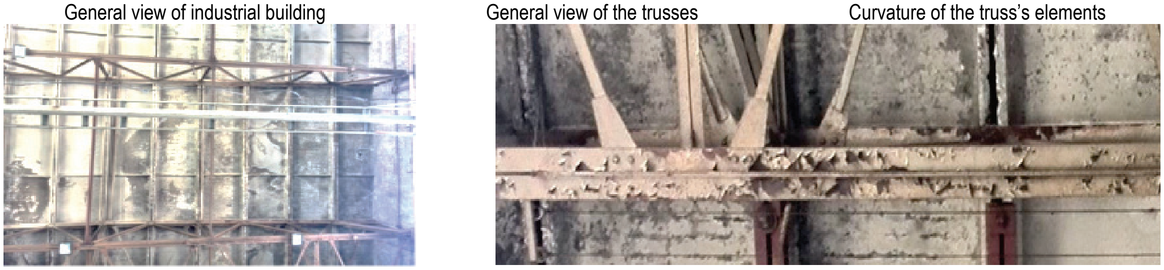
Roof flowing with intensive corrosion damages of trusses elements 25-30% corrosion of trusses elements cross-section

Figure 1 General view of industrial building and trusses with defects and damages

Table 2 Calculation of stresses in the truss elements

Element	Number of loadings	Internal forces, N, (kN)	Length, l, (mm)	Cross-section profile	Area, A (см^2)	Stresses, σ (MPa)	Yield strength f_y, (MPa)
Upper chord element	q_1 (project)	–288.7	1510	2L90×8	27,92	123,1	205
	q_2 (22 years)	–322		2L90×8	27,92	137,3	215
	q_3 (45 years)	–340		2L90×8 (–15%)	23,7	165,0	
	q_4 (55 years)	–345.4		2L90×8 (–30%)	19,54	200,8	
	q_5 (60 years)	–349.9		2L90×8 (–45%)	13,4	**274,8**	
Lower chord element	q_1	294.5	3000	2L75x6	17,56	167,7	205
	q_2	328.4			17,56	187,0	223
	q_3	346.8			17,56	197,5	
	q_4	352.3		2L75×6 (–5%)	16,68	211,2	
	q_5	356.9		2L75×6 (–10%)	15,8	**225,8**	
Bearing element	q_1	–212.6	2690	2L90×8	27,92	124,9	205
	q_2	–237.5			27,92	139,4	215
	q_3	–250.7			27,92	147,2	
	q_4	–254.7		2L90×8 (–15%)	23,7	161,6	
	q_5	–258		2L90×8 (–25%)	20,94	178,56	
Inclined element (+)	q_1	148.8	2690	2L60×6	13,82	107,7	205
	q_2	165.4			13,82	119,7	209
	q_3	175.2			13,82	126,8	
	q_4	177.9		2L60×6 (–5%)	13,1	135,8	
	q_5	180.2		2L60×6 (–10%)	12,44	144,9	
Inclined element (–)	q_1	–105.7	2950	2L75×6	17,56	146,8	205
	q_2	–117.9			17,56	163,8	223
	q_3	–124.5			17,56	172,9	
	q_4	–126.5		2L75×6 (–5%)	16,68	177,2	
	q_5	–128.1		2L75×6 (–10%)	15,8	176,3	
vertical element (–)	q_1	–31.7	2700	2L60×6	13,82	69,5	205
	q_2	–36.4			13,82	79,8	209
	q_3	–37.4			13,82	82	
	q_4	–38		2L60×6 (–5%)	13,13	83,9	
	q_5	–38.6		2L60×6 (–10%)	12,44	79,36	

Table 3 Results for reliability index calculations for truss elements

Element	Number of loadings	Mean $s_{mv} = \overline{F}$ (MPa)	Dispersion	Deviation	$V\overline{F}$	$\overline{R}$	$V\overline{R}$	$\xi = \overline{R}/\overline{F}$	β	P_f	Ps
Upper chord (–)	q_1 (project)	118,20	43,60	6,60	0,06	205	0,024	1,73	10,54	≈0	≈1
	q_2 (22 years)	127,12	52,50	7,25	0,057	215	0,024	1,69	9,88	≈0	≈1
	q_3 (45 years)	137,54	236,39	15,37	0,11	215	0,024	1,56	4,78	≈0	≈1
	q_4 (55 years)	151,59	964,31	31,05	0,20	215	0,024	1,42	2,01	0,0222	0,9778
	q_5 (60 years)	172,19	3169,37	56,30	0,327	215	0,024	1,25	0,76	0,2265	0,7735
Lower chord (+)	q_1	162,91	67,26	8,20	0,050	205	0,025	1,26	4,35	≈0	≈1
	q_2	175,22	92,24	9,60	0,0548	223	0,025	1,27	4,30	≈0	≈1
	q_3	182,15	176,63	13,29	0,073	223	0,025	1,22	2,83	0,0023	0,9977
	q_4	186,52	241,04	15,53	0,083	223	0,025	1,20	2,21	0,0135	0,9865
	q_5	193,02	381,57	19,53	0,101	223	0,025	1,16	1,48	0,0706	0,9294
Bearing element (–)	q_1	119,96	63,98	8,00	0,066	205	0,024	1,71	9,06	≈0	≈1
	q_2	129,12	69,49	8,34	0,064	215	0,024	1,67	8,76	≈0	≈1
	q_3	133,98	111,26	10,55	0,078	215	0,024	1,60	6,90	≈0	≈1
	q_4	132,83	241,32	15,53	0,116	215	0,024	1,62	5,02	≈0	≈1
	q_5	137,41	563,86	23,75	0,172	215	0,024	1,56	3,19	≈0	≈1
Inclined element (+)	q_1	105,23	19,43	4,41	0,042	205	0,025	1,95	14,76	≈0	≈1
	q_2	112,96	32,52	5,70	0,050	209	0,021	1,85	13,35	≈0	≈1
	q_3	117,52	71,94	8,48	0,072	209	0,021	1,78	9,58	≈0	≈1
	q_4	120,57	100,82	10,04	0,083	209	0,021	1,73	8,07	≈0	≈1
	q_5	124,63	160,57	12,67	0,102	209	0,021	1,68	6,29	≈0	≈1
Inclined element (–)	q_1	143,02	43,58	6,60	0,046	205	0,025	1,43	7,42	≈0	≈1
	q_2	153,86	66,90	8,18	0,053	223	0,025	1,45	6,98	≈0	≈1
	q_3	159,73	135,02	11,62	0,072	223	0,025	1,40	4,91	≈0	≈1
	q_4	156,93	170,80	13,07	0,083	223	0,025	1,42	4,65	≈0	≈1
	q_5	151,07	235,67	15,35	0,102	223	0,025	1,48	4,40	≈0	≈1
vertical element (–)	q_1	68,13	6,61	2,57	0,037	205	0,025	3,01	23,87	≈0	≈1
	q_2	74,79	21,31	4,62	0,062	209	0,021	2,79	21,07	≈0	≈1
	q_3	76,21	30,89	5,56	0,073	209	0,021	2,74	18,75	≈0	≈1
	q_4	74,75	39,71	6,30	0,084	209	0,021	2,80	17,48	≈0	≈1
	q_5	68,38	51,16	7,15	0,104	209	0,021	3,06	16,76	≈0	≈1

7) Because of truss designed as statically determined structure, the serial type of its members connections have accepted. The calculation of general β for every loading defined with formulae [5, 18] for $P_s(q)$ as:

$$P_s(q) = \prod_{i=1}^{n} \left[1 - P_{fi}(q) \right]. \tag{5}$$

where $P_{fi}(q)$ – failure probability for i element (Tab. 4).

The β for probabilistic calculation provides the results that are not the same as for discrete ones, determined for structure as static determine system - see Table 2 and Table 3. As an example, based on discrete structure calculation, the result of fourth loading with maximum stress values σ = 211,2 MPa, do not exceed the real steel yield strength f_y = 223 MPa, but reliability index here is β = 1,805, what is lower, than proposed level for emergency technical state 3, which is 2.8 (Tab. 1 and Tab. 4). Also, already for loading 3, the reliability index β = 2,83, that responds of "needs to repair state" $\beta \in [2,3 - 3,8]$ and coincide with the results of investigation - the corrosion damages are bigger than 15%, but comparing with static discrete results calculation, this technical state may be defined almost as for a new structure, which needs not the repairing works.

These results came to illusion for the building's proprietor who ordered the technical investigation that renovation works for the building are not necessary for this time and residual life should not be determined for this case.

Table 4 Results of calculation for truss as a system

Year, loadings	Operation time	P_s	β
1966 – q_1	0	≈1	4,3
1988 – q_2	22	≈1	4,3
2011 – q_3	45	0,9977	2,83
2021 – q_4	55	0,9646	1,805
2026 – q_5	60	0,72	0,585

4 DETERMINATION OF RESIDUAL LIFE

Based on reliability index determination, the definition of residual life for analyzed structure (CC2) may be proposed with the following recommendations.

1) The analysis of function β calculated on the results of technical investigations (Fig. 2) shows that residual life could not exceed 4 years maximum and must be appointed even after third investigation (45 years of operation) for prevention of transition to the emergency state (3 state). It had not done because of results of static calculations answered for demands of safe operation. So, any repairing works were not fulfilled.
2) After 55 years of operation some repairing works were completed and a new value of β = 3.8 have done. Here, we consider that steel structures may be partially renewed [20] and a new value of β may be defined. This value is equal as for a new structure for CC2. To set a

value β = 4.3 is not correct, because of only the most damaged elements of the truss were reinforced and some old elements have insignificant degradation corrosion process.

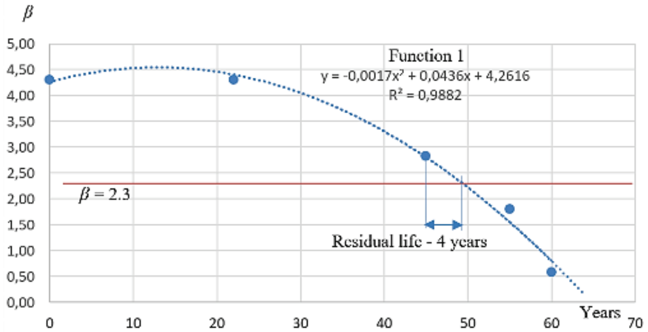

Figure 2 The values of β calculated on the results of technical investigations

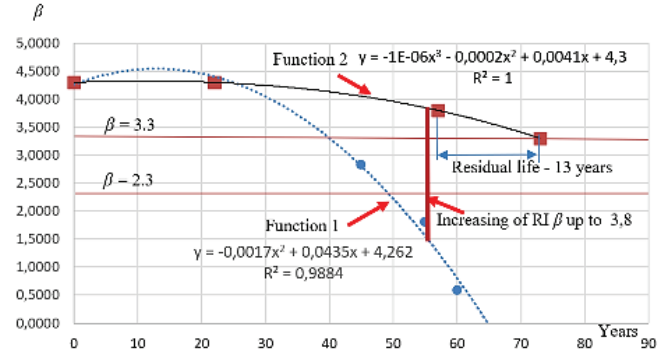

Figure 3 The calculation results for RI β and residual life for roof trusses of the industrial building

3) A new function for β has defined – the function 2, see Fig. 3. As the points of definition for the function were: point 1 – as for a new structure (0 years of operation) and point 2 – the results of β calculation after first investigation (22 years of operation). There were the values that are bigger than current β value after repairing works. The last point for function is the point with the current values of β = 3.8 (55 years of operation).
4) Then, the residual life may be defined in 13 years – the time for future compulsory technical investigation, when the technical state will come from the state as for a new structure to the state which needs the repair with β = 3.3. After that the technical investigation should be completed, the corresponding value of β will determine as new point for the function 2. This function will be corrected for the future calculation of residual life.

5 CONCLUSIONS

Based on demands of modern standards and scientific research, with the example of calculation of real steel structure, proposed the following:

1) Algorithm of reliability index β assessment taking in consideration of technical investigation results during a long term of structure's operation.
2) The assessment provided the possibility for technical state of structure determination in probabilistic kind.
3) The determination of residual life as transition from one to another technical state with fixed values of reliability index β could be possible for analyzed structure.

Also, this method may be applicated for other types of steel structures, especially for those, which are under potential corrosion influences and dynamic loadings – bridges, crane beams, bunkers, reservoirs, pipelines. All these structures potentially dangerous on corrosion and fatigue, needs to be regular technical investigated with prediction of real residual life and terms of repairing works.

6 REFERENCES

[1] Eurocode 0: ENV 1990:2002+A1. *Basic of structural design*. CEN, Brussels, 2002. 116.
[2] Eurocode 3: ENV 1993-1-1, Part 1.1. *Design of steel structures*. CEN, Brussels, 2005.
[3] ISO 13822:2010. *Bases for design of structures – Assessment of existing structures*. ISO 2010. 44.
[4] ISO 2394:2015. *International standard. General principles on reliability for structures*. ISO 2015. 112.
[5] Rosowsky, D. V. (1999). Structural Reliability. *Structural engineering handbook*. Ed. Chen Wai-Fah. Boca Raton: CRC Press LLC.
[6] Yumei, K. & Xue, D. (2019,). Failure mode and reliability analysis of frame structure. *13th International conference on applications of statistics and probability in civil engineering, ICASP13*. May 26-30, Seoul, South Korea, 1-8.
[7] Cornell C. A. (1969). A Probability based structural code. *ACI-Journal, 66*(12), 974-985.
[8] Cornell C. A. (1969). Stochastic process models in structural engineering. Dept. of Civil Engineering. Stanford University. *Technical Report No. 34*, 14-18.
[9] Steenbergen, R. D. J. M., Rózsás, Á. & Vrouwenvelder, A. C. W. M. (2018). Target reliability of new and existing structures - A general framework for code making. *HERON, 63*(3), 219-242.
[10] Diamantidis, D. & Sykora, M. (2019, October 17). Reliability differentiation and uniform risk in standards: a critical review and a practical appraisal. *Scientific symposium future trends in civil engineering*. Zagreb, Croatia, 241-260. https://doi.org/10.5592/CO/FTCE.2019.11
[11] Rackwitz, R. (2000). Optimization – the basis of code-making and reliability verification. *Structural Safety, 22*, 27-60.
[12] Steenbergen, R. D. J. M. & Vrouwenvelder, A. C. W. M. (2010). Safety philosophy for existing structures and partial factors for traffic loads on bridges. *HERON, 55*(2), 123-140.
[13] Van Coilea, R., Hopkinc, D., Bisbyb, L. & Caspeelea, R. (2017). The meaning of eta: background and applicability of the target reliability index for normal conditions to structural fire engineering. *Procedia Engineering, 210*, 528-536.
[14] Diamantidis, D., Holicky, M. & Sykora, M. (2016). Risk and reliability acceptance criteria for civil engineering structures. *Conference Structural Reliability and Modelling in Mechanics*. Ostrava, Czech Republic.
[15] Hovde, P. J. & Moser, K. (2004). Performance Based Methods for Service Life Prediction. CIBPublication, 294, Rotterdam: International Council for Building Research, *Studies and Documentation*, pp. 107, (ISBN 90-6363-040-9).

[16] Omoare, A., Arum, C. & Olanitori, L. (2022). Models for the Prediction of Service Life of Buildings - A Review. *LAUTECH Journal of Civil and Environmental Studies, 9*(1), 48. https://doi.org/10.36108/laujoces/2202.90.0160

[17] Beck, A. T. (2020). Optimal design of redundant structural systems: fundamentals. *Engineering Structures, 219*, 110542. https://doi.org/10.1016/j.engstruct.2020.110542

[18] Hawraa Qasim Jebur & Salah Rohaima Al-Zaidee. (2019). Non-deterministic approach for reliability evaluation of steel portal frame. *Civil Engineering Journal, 5*(8), 1684-1697. https://doi.org/10.28991/cej-2019-03091363

[19] Holicky, M., Diamantidis, D. & Sykora, M. (2015). Determination of target safety for structures. *12th International conference on application of statistics and probability in civil engineering, ICASP12*. Vancouver, Canada. 1-9.

[20] Kolesnichenko, S., Selyutin, Y., Chernykh, I. & Mnatsakanian, K. (2017). General principles of steel structures risk operation estimation and assessment of their residual life (in Ukrainian). *ScienceRise, 11*(40), 37-42. https://doi.org/10.15587/2313-8416.2017.116444

Authors' contacts:

Sergiy Kolesnichenko, DSc, PhD, Assoc. Prof
(Corresponding author)
Donbas National Academy of Civil Engineering and Architecture,
Faculty of Civil Engineering,
Heroiv Nebesnoi Sotni str., 14, Kramatorsk, Donetsk reg., Ukraine 84333
ksv@donnaba.edu.ua

Inna Chernykh, PhD, Assoc. Prof
Donbas National Academy of Civil Engineering and Architecture,
Faculty of Civil Engineering,
Heroiv Nebesnoi Sotni str., 14, Kramatorsk, Donetsk reg., Ukraine 84333
I.Y.Chernykh@donnaba.edu.ua

Valentyna Halushko, DSc, PhD, Assoc. Prof
Donbas National Academy of Civil Engineering and Architecture,
Faculty of Civil Engineering,
Heroiv Nebesnoi Sotni str., 14, Kramatorsk, Donetsk reg., Ukraine 84333
v.o.halushko@donnaba.edu.ua

Polianskyi Kostiantyn, PhD, Assoc. Prof
Donbas National Academy of Civil Engineering and Architecture,
Faculty of Civil Engineering,
Heroiv Nebesnoi Sotni str., 14, Kramatorsk, Donetsk reg., Ukraine 84333
k.v.polyansky@donnaba.edu.ua