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Reliability-Based Residual Service Life Assessment of CFRP-Strengthened Eccentrically Compressed Reinforced Concrete Columns Using Monte Carlo Simulation

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Abstract
The degradation of reinforced concrete (RC) structural members is a pressing global issue. Demolition is expensive, time-consuming, and can compromise adjacent members. Strengthening existing members using additional steel rebar, CFRP strip, RC, or ferrocement jackets offers a practical and modern alternative. At the same time, the durability assessment of such structures remains a critical problem. The article presents the results of improving the model for the reliability-based engineering assessment of the durability (residual resource) indicator of eccentrically compressed RC columns strengthened by CFRP under different load levels, and its calibration and internal validation using data from existing experimental studies. In addition to the set of strengths, geometric, and loading stochastic parameters, the improved model's algorithm incorporates also the so-called "activation factor of the CFRP strip" – the empirical coefficient that represents the strip's percentage of involvement in the strengthened column, with its value depending on the load level during strengthening and the strip's cross-sectional area. The Monte Carlo method was applied to simulate and assess the strengthened column's ULS reserve function, and the model algorithm's implementation was performed using the Mathcad Prime software environment. The analysis of the obtained reliability and durability (residual resource) indices for the strengthened column samples showed convergence with similar values for the CC2 consequence class of designed structures, indicating the potential for further research in this field and the possibility of their use in reconstruction practice.

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1. Introduction

Strengthening building structures is a significant scientific and technical challenge, and its importance has grown in recent years. A notable trend in the construction sector is the development, study, and widespread use of new, advanced materials for strengthening structures, which offer high strength and performance characteristics (Hamoda et al., 2024; Pham et al., 2013).

One such material is carbon fiber-based composite materials (CFRP). A typical example of their use is the external strengthening system with composite materials from various brands, aimed at enhancing the strength and durability of reinforced concrete (RC), concrete, brick, and stone structures (Blikharskyy et al., 2021; Douier et al., 2023).

At the same time, in today's economic climate, optimizing building structures during the design and reconstruction phases is becoming increasingly important, including optimization strategies for column-type load-bearing members aimed at improving stability and critical load capacity (Szmidla et al., 2025; Jurczyńska, 2025), as well as probabilistic methods for assessing the reliability and durability (residual resource) of structural members in the construction field (Ellingwood et al., 2025; Jendele et al., 2024; Li et al., 2016; Li et al., 2023; Tytarenko and Khmil, 2023).

This is especially relevant for RC members due to the composite nature of the material.

Due to the extensive damage caused by military actions, the large-scale reconstruction in Ukraine will require studies on the performance of various RC structures strengthened under different load levels (Blikharskyy et al., 2018; Khmil et al., 2019), and their reliability and durability assessment (Hao et al., 2025; Pichugin, 2014; Pichugin, 2018; Vořechovská et al., 2017; Zignago and Barbato, 2022).

Thus, the relevance of the issue of assessing the durability of strengthened RC structures is very high in the construction field, as it determines the reliability and safety of structures throughout their entire service life, and in the case of our study, the durability (residual resource) of columns after strengthening.

2. Aims

The study aims to improve the model for the reliability-based engineering assessment of the durability (residual resource) indicator of CFRP-strengthened eccentrically compressed RC columns and to calibrate and internally validate it using data from existing experimental studies. The study's additional goal is to comprehensively analyze the obtained reliability and durability (residual resource) indices for the strengthened column samples.

3. Literature review

The design and assessment of RC structures are guided by national and international standards that set foundational principles for structural safety and reliability (DBN V.1.2-14-2018; EN 1990; ISO 2394:2015). ISO 13823 also emphasizes the importance of integrating durability into the design phase to ensure serviceability throughout a structure's life cycle (ISO 13823:2008). Ukrainian concrete design standards provide material-specific guidance, particularly for heavy concrete and structural detailing (DBN V.2.6-98:2009; DSTU B V.2.6-156:2010).

At the same time, reliability theory has evolved to incorporate probabilistic methods, as seen in foundational works on structural safety (Ditlevsen and Madsen, 2007; Ellingwood et al., 2025). Modern design and evaluation of RC structures are increasingly based on advanced digital modeling. For reinforced concrete members, reliable assessment of the stress–strain state is a prerequisite for evaluating reserve capacity, durability and strengthening efficiency. Kopiika et al. (2024) demonstrated that digital image correlation, contactless displacement measurements, code-based calculations and FEM can provide mutually consistent estimates of deflections and concrete/reinforcement strains in RC members. Their findings confirm the value of combining experimental diagnostics with theoretical modelling when assessing the structural performance of reinforced concrete elements. Implementing BIM in designing a three-story RC building improves planning and coordination (Astuti et al., 2023). A probabilistic performance-based approach was developed to mitigate seismic pounding risk between adjacent buildings, which is relevant for seismic standards (Barbato and Tubaldi, 2013). A probabilistic damage model for assessing corroded RC structures was also proposed, enhancing reliability evaluation (Coelho et al., 2022). Reliable prediction of concrete performance requires combining numerical modelling with monitoring-based experimental validation. Apshikur et al. (2025) showed, in the case of winter concreting, that measured thermal and strength responses may differ from simulation results and therefore require correction factors to improve forecasting accuracy. This supports the need to calibrate reliability-based models for RC members using experimental evidence and to explicitly account for uncertainty in material and technological parameters.

Structural reliability theory continues to evolve with the help of advanced computation. The probabilistic reliability of RC structures is increasingly analyzed using Monte Carlo simulations and variance reduction methods (Song and Kawai, 2023). Machine learning and probabilistic modeling are widely used in reliability assessments and durability forecasting (Jitao et al., 2019; Nogueira et al., 2012). The effect of random variability in reinforcement placement on reliability has also been quantitatively explored (Sieńkowska and Buda-Ożóg, 2021). Early contributions to resource estimation and reliability assessments in RC members laid the groundwork for many of today's analytical methods (Lantukh-Liashchenko, 2019; Pichuhin, 2014; Pichuhin, 2018).

Modern reliability assessments leverage simulation and probability theory. The Monte Carlo method has proven effective in assessing reinforcement depassivation risks due to corrosion (Félix et al., 2023). Probabilistic models, such as bridge pier scour effects, are also applied to seismic safety (Hosseini et al., 2023). Structural reliability concepts are further supported by European perspectives on risk-based durability design (Geiker et al., 2023).

Innovative materials and techniques continue to emerge. The application of 3D-printed PLA plastics in civil engineering has been tested for deformability, suggesting possibilities for lightweight formwork or temporary supports (Demchyna et al., 2024). Incorporating galvanized steel mesh and hybrid bonding systems improves beam durability, offering flexibility for different rehabilitation contexts (Douier et al., 2023).

In recent years, there has been a surge in the use of innovative materials like fibre-reinforced concrete (FRC) and CFRP for structural strengthening. The wrapper layer technique with FRC improved RC columns' capacity (Koteš et al., 2020;

Koteš et al., 2022). Similarly, ultra-high-performance FRC jacketing provides a promising method for column reinforcement (Shehab et al., 2023). New jacketing approaches using ferrocement and CFRP have been modeled and predicted effectively through machine learning (Nishant et al., 2024).

The structural behavior of reinforced members under various loading conditions is critical for evaluating retrofit effectiveness. Interfacial bonding was found to play a significant role in the load transfer mechanism in CFRP-strengthened beams (Bao et al., 2025). Improved stiffness and resistance to failure were confirmed for CFRP-confined columns (Blikharskyy et al., 2018; Blikharskyy et al., 2023b). Strengthening applications extended to stone beams with GFRP reinforcement, showing good potential for heritage structures (Blikharskyy et al., 2021). Nonetheless, fire resistance remains vulnerable for CFRP systems without additional protection (Cacho and Sobko, 2020).

Externally bonded reinforcement techniques, including grooves and longitudinal CFRP, enhance column behavior under eccentric loading (Torabian and Mostofinejad, 2017). Reinforcement of beam-column joints using CFRP has also been extensively reviewed, emphasizing their improved seismic performance (Maseer and Abdulridha, 2025). Circularisation of square RC columns followed by FRP confinement showed enhanced strength and ductility (Pham et al., 2013). FRP-based retrofitting systems have gained wide application. The comparative performance of RC columns jacketed with CFRP or fiber-reinforced cementitious composites (FRCC) shows that both methods significantly improve structural capacity (Del Zoppo et al., 2018). Experimental data on full-scale CFRP-strengthened slender columns validate the approach (Gajdosova and Bilcik, 2013). Other alternatives include using stainless-steel plates in different configurations for column strengthening (Hamoda et al., 2024). Parametric studies have also explored internal confinement by CFRP strips (Halim et al., 2024). An earlier study confirmed that FRP-wrapped RC columns under eccentric loads perform well in strength and ductility (Hadi, 2010). Composite materials like CFRP and GFRP have proven effective in strengthening RCmembers. Experimental studies showed that CFRP wrapping enhances column capacity and deformation characteristics (Blikharskyy et al., 2018). A strength model for square RC columns confined by external CFRP sheets was also developed (Benzaid and Mesbah, 2013).

Durability remains a core concern, particularly in long-lifespan infrastructure. Integrating durability assessment with life cycle analysis offers a holistic view for sustainable materials selection (Li et al., 2023). Long-term durability under marine exposure was successfully demonstrated in bridge projects like the HZM link, where performance was forecasted for 120 years (Li et al., 2016). Digital tools and IoT-based monitoring systems are also beginning to transform how RC durability is assessed (Taffese et al., 2019). The remaining service life of RC buildings can be evaluated by analyzing the failure probability of individual structural members (Cho et al., 2025).

Prestressed CFRP bands have been investigated as a strengthening method for RC columns, showing significant performance improvements (Waghmare et al., 2019). Further advancements in evaluating durability during operation have been achieved by utilizing Monte Carlo methods to assess the reliability of RC structures (Tytarenko and Khmil, 2023). In this regard, modelling reliability for RC beams subjected to 50% ULS load using Monte Carlo simulations has provided more profound insights into structural behavior under stress (Tytarenko et al., 2024a).

The analysis of common defects and damages in RC structures has been a central focus in understanding these materials' durability and residual service life (Tytarenko et al., 2024c). These models also extend to the influence of combined mechanical and environmental actions, which significantly affect the durability and reliability of concrete structures (Vořechovská et al., 2017).

Durability is a critical issue, especially in aggressive environments. The behavior of FRP-strengthened RC beams exposed to marine conditions and long-term environmental loading shows that FRP can maintain performance over time, though bonding systems play a significant role (Hao et al., 2025; Douier et al., 2023). Studies on sulfate attack revealed that CFRP confinement can help maintain column integrity under axial loads even in deteriorating conditions (Huynh-Xuan et al., 2021). Reinforcement against marine deterioration with FRP systems was also reviewed comprehensively (Hadi et al., 2024). The effect of environmental degradation and fire on RC structures was studied extensively. Corrosion's impact on structural performance and using probabilistic models to predict degradation were highlighted (Coelho et al., 2022). Long-term performance and failure probability were considered in service life evaluations (Cho et al., 2025). The behavior of CFRP-strengthened elements in fire conditions revealed the need for thermal protection to ensure durability (Cacho and Sobko, 2020).

Advancements in simulation have improved understanding of damage behavior and repair strategies. Numerical modelling of damaged columns helps estimate residual load-bearing capacity under compressive stress (Klymenko et al., 2024). The influence of loading levels during strengthening on reliability has been addressed in experimental studies (Khmil et al., 2019). The crack resistance of RC columns enhanced with jacketing and CFRP layers has also been experimentally validated (Krainskyi et al., 2020; Selejdak et al., 2020).

Cellular automata have recently been used for modeling corrosion in CFRP-strengthened bridge columns, providing valuable data for assessing long-term performance (Wang and Kim, 2024). The application of numerical methods in strengthening analysis continues to evolve, such as comparing concrete columns strengthened with fiber concrete layers and reinforced concrete (Vavruš and Koteš, 2019). Moreover, probabilistic methods and finite element analysis (FEM) have been integrated into crack width analysis, offer-ing a more reliable way to assess structural integrity (Zięba et al., 2020).

4. Theoretical study

4.1. The proposed model's algorithm

In accordance to the well-known Limit State in the analysis of member's eccentric compression, and considering the so-called "activation factor of the CFRP strip" (γ_{fa}) as proposed by us, the design ULS bending moment for the strengthened column (which in this case corresponds to its load-bearing capacity), after applying all simplifications, can be expressed by the following formula:

$$M_{ult}=(f_{yd}A_s+f_{fd}A_f\gamma_{fa})(d-0.5x_m)+f_{ydc}A_{sc}(0.5x_m-z_{s1}), \quad (1)$$

where: f_{yd}, f_{ydc}, f_{fd} – the calculated yield strengths for steel reinforcement under tension and compression, and the design strip's tensile strength, respectively; γ_{fa} – activation factor of the CFRP strip (the empirical coefficient) that represents the strip's percentage of involvement in the strengthened column, with its value depending on the load level during strengthening and the strip's cross-sectional area; A_s, A_{sc}, A_f – the cross-sectional areas of steel reinforcement in tension and compression, and the tension strip, respectively; d, x_m, z_{s1} – the effective depth and the average height of the compressed zone for the member's cross-section after strengthening, and the distance between the compression steel reinforcement and the most compressed edge of the cross-section, respectively.

After step-by-step simplification, the formula for finding the average height of the compressed zone for the strengthened column's cross-section will be as follows:

$$x_m=0.5d(2\varepsilon_{cu}-\varepsilon_c)(\varepsilon_{cu}+\varepsilon_c+\varepsilon_{fu})^{-1}, \quad (2)$$

where: ε_c, ε_{cu}, ε_{fu} – the concrete's relative compressive strain and relative ultimate compressive strain, and the strip's calculated ultimate strain under tension, respectively (Bambura and Hurkivskyi, 2014; DBN V.2.6-98:2009).

The $f(x)$ ULS reserve function, where x indicates the system's random variables, is represented in the equation below (Tytarenko et al., 2024a), and, in this case, it models the probability of failure of the strengthened column:

$$f(x)=M_{ult}-M_E, \quad (3)$$

where: M_E – the external bending moment caused by the effect of the axially applied eccentrically compressive force.

The value of M_E can be found using the following formula:

$$M_E=N_{ult}e_{cal}, \quad (4)$$

where: N_{ult}, e_{cal} – the longitudinal ULS compressive force and its calculated eccentricity, relative to the axis passing through the centroid of the compressed zone of the column's cross-section, respectively.

According to Eq. (3), failure happens when $f(x) < 0$, and no failure happens when $f(x) \geq 0$ (Tytarenko et al., 2024a).

The final phase of the algorithm involves estimating the durability (residual resource) of the strengthened column by analyzing its structural reliability (Lantukh-Liashchenko, 2019):

$$T=[(\beta_d-\beta_{lim})T_d^2(\beta_c-\beta_{lim})^{-1}]^{0.5}, \quad (5)$$

where: β_d, β_c, β_{lim} – the values of design, initial, and limit in operation reliability index (safety characteristic), respectively; T_d – the design service life (EN 1990; DBN V.1.2-14-2018).

The design cross-section of the strengthened eccentrically compressed member with a rectangular cross-section is shown in Fig. 1.

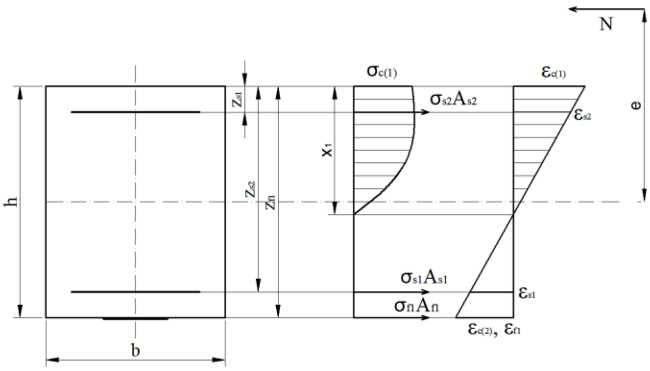

Fig. 1. The design cross-section of the strengthened eccentrically compressed member with a rectangular cross-section: cross-section, stress diagram, strain diagram (from left to right)

4.2. Design characteristics of laboratory column samples

The calculated properties of the members from the experimental study series (Blikharskyy et al., 2018; Blikharskyy et al., 2023a; Blikharskyy et al., 2023b) were used to further test the theoretical model:

- samples of columns were fabricated with dimensions of 2200×180×140 mm;
- cantilevers were provided at the ends of the members to transfer the vertical load with an eccentricity of 150 mm;
- during manufacturing, special connectors were attached to the reinforcing bars and linked to mechanical fastening devices, enabling the measurement of steel reinforcement deformations;
- the reinforcing bars were tested separately (Zhang et al., 2015).

The formwork dimensions of the unstrengthened samples and their reinforcement scheme are shown in Fig. 2.

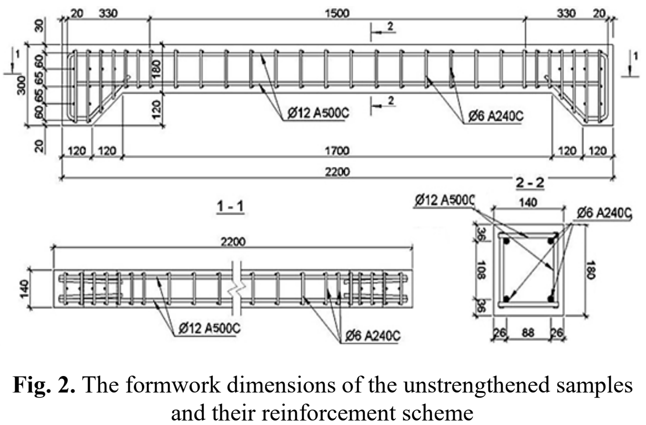

Fig. 2. The formwork dimensions of the unstrengthened samples and their reinforcement scheme

According to the above experimental studies, the CFRP strip (Sika Carbodur S512 type, split lengthwise in half) was attached to the tension face of the column while applying initial load levels of 30 %, 50 %, and 70 % of the ultimate load of the unstrengthened samples at the moment of strengthening, or without initial load level. Prior to bonding, the surfaces of the wrap and strip were pre-treated using the specialized solution “Colma Reinger” to ensure their “activation”, with a treatment duration of 30 minutes. To fix the strip within the cantilever zones, two layers of SikaWrap 230 fabric were applied (see Fig. 3).

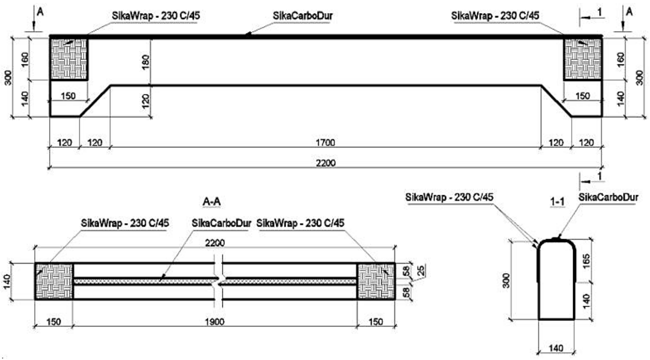

Fig. 3. The test sample construction, which is strengthened using the CFRP system

The key specifications of the strip included (Bambura and Hurkivskyi, 2014):

- strength and deformability characteristics – $f_{fk} = 3.00\times10^3$ MPa, $f_{fd} = 2.08\times10^3$ MPa, $\varepsilon_{fuk} = 1.70$ %, $\varepsilon_{fu} = 1.30$ %, $E_f = 1.60\times10^5$ MPa;
- geometric characteristics – $b = 25$ mm (width), $t = 1.2$ mm (thickness), $A_s = 30$ mm^2 (cross-sectional area).

In total, ten columns were tested – two unstrengthened, two strengthened without initial load level, and two each strengthened under loading at 0.3, 0.5, and 0.7 of the ultimate load of the unstrengthened samples at the moment of strengthening.

The strengthened columns were tested until failure. The load was applied using a hydraulic jack in increments of 10 kN. All members were tested in a horizontal position (see Fig. 4).

Fig. 4. Test stand with strengthened sample

The following failure criteria were adopted in the studies under analysis:

- attainment of yielding strain in the tensioned steel reinforcement or failure of compressed concrete upon reaching its ultimate strain values (DSTU B V.2.6-156:2010);
- debonding of the strip (Bambura and Hurkivskyi, 2014).

5. Results and discussion

5.1. Statistical characteristics of the system’s random variables

The proposed model in the part of assessing the reliability of strengthened columns operates with a set of random variables (see Table 1 below for more details), namely:

- concrete compressive strength (f_c);
- steel reinforcement yield strength (f_y, f_{yc});
- tensile strength of the strip (f_f);
- activation factor of the strip (γ_{fa});
- longitudinal load corresponding to the ULS (N);
- eccentricity of longitudinal load (e);
- dimensions of sample ($b\times h\times l$).

Among the above variables, the strip’s activation factor (γ_{fa}) holds a special place due to its novelty. This is the empirical coefficient proposed by us, and which represents the strip’s percentage of involvement in the strengthened sample of column, with its value depending on the actual load level during strengthening (without initial load level, under 30 %, 50 % or 70 % of the ultimate load of the unstrengthened samples at the moment of strengthening) and the strip’s cross-sectional area ($A_s = 30$ mm^2). Therefore, this coefficient is presented as an innovative approach to consider the effect of the load level during the strengthening process, while simultaneously being treated as a random variable in the function $f(x)$. This approach has also been used in the authors’ studies on the reliability of strengthened beams (Khmil et al., 2019; Tytarenko et al., 2024a).

The other variables used in the proposed algorithm are deterministic.

Table 1. Statistical data of the system’s random variables

Variable		Unit	Coefficient of variaton		Mean	Standard	
Log-normal distribution of (x)							
f_c		[MPa]	0.1350		25.04	3.38	
f_y			0.0594		553.97	32.91	
f_{yc}			0.0350		254.61	8.91	
f_f			0.0800		2394.11	191.53	
γ_{fa}	×0.0	[–]	1.2	$\times10^{-2}$	0.417	5.0	$\times10^{-3}$
	×0.3		2.2		0.368	8.1	
	×0.5*		2.9		0.311	9.0	
	×0.7		3.4		0.264	9.0	
Normal distribution of (x)							
N	×0.0	[kN]	1.9	$\times10^{-3}$	168.73	0.32	
	×0.3		5.6		162.30	0.91	
	×0.5*		5.2		154.30	0.80	
	×0.7		6.8		147.20	1.00	
e		[mm]	6.6		152.0	1.00	
b			7.9		138.9	1.10	
h			8.3		181.5	1.51	
l			9.1×10^{-4}		2198.0	2.00	

Note: strengthening was carried out under the initial load level of 0.5 (for example) of the ultimate load of the unstrengthened samples.

The statistical characteristics for the factor (γ_{fa}) and several other random variables (N, e, b, h, and l) – namely, the means, coefficients of variation, and standard deviations – were obtained based on the results' analysis from the experimental studies above. In particular, the geometric parameters were processed for all ten laboratory samples. In contrast, the longitudinal load and the activation factor were processed for each pair of samples tested under the same load level. Finally, the corresponding statistical characteristics for the random strength variables (f_c, f_y, f_{yc}, and f_f) were taken from recommendations and standards currently used per Ukrainian building practice, and from some studies on the effectiveness of composite materials for strengthening RC members (Bambura and Hurkivskyi, 2014; DBN V.2.6-98:2009; Pichuhin, 2014).

5.2. Calibration and internal validation of the model

Considering its high versatility, the Monte Carlo method (Nogueira et al., 2012; Tytarenko and Khmil, 2023) was used to simulate and assess the strengthened column's ULS reserve function $f(x)$. In turn, random variables in our model were generated based on the specified statistical data, utilizing the built-in random number generation features of the Mathcad Prime software environment (Tytarenko et al., 2024a). A total of 10^5 simulations (realizations of the ULS reserve function) were conducted to estimate the probability of failure (P_f). This probability was determined by calculating the ratio of the number of failure cases to the overall number of simulation trials. The reliability indices (P_f, β_d) for the various load levels under samples' strengthening, fixed at 0.3, 0.5, and 0.7 of the ultimate load of the unstrengthened samples at the moment of strengthening, or without initial load level, are collected in Table 2.

Table 2. Reliability indices (P_f, β_d) for columns strengthened with Sika Carbodur S 25×1.2 mm CFRP strip

Reliability indicator	Load level at the moment of strengthening (×LL)			
	×0.0	×0.3	×0.5	×0.7
P_f, $\times 10^{-5}$	3.75	5.01	6.95	8.84
β_d	3.96	3.89	3.81	3.75

Among others, the estimated probability of failure is $P_f = 3.75\times10^{-5}$ (×0.0) with a 95 % confidence interval of (0–7.55)$\times10^{-5}$. For $P_f = 8.84\times10^{-5}$ (×0.7), the corresponding 95 % confidence interval is 3.02×10^{-5}–1.47×10^{-4}. These values represent example extreme cases, while intermediate failure probability values also exist within the analyzed range. Thus, the obtained results indicate the statistical uncertainty associated with the Monte Carlo simulation, which is considered acceptable for engineering reliability assessment.

Based on the data analysis in the table above, it becomes evident that the reliability of strengthened columns decreases with an increase in the load level during strengthening. The obtained values are somewhat lower than those proposed in the standards (EN 1990; DBN V.1.2-14-2018). For example, Eurocode recommends a minimum value of $\beta = 4.30$ for the CC3 consequence class and a service life reference period of 50 years, while DBN suggests accepting this value of 4.76 for the same consequence class and "A" responsibility category. This may be explained by the fact that these standards recommend values for designed structures, but not existing ones. Nevertheless, the derived reliability indices, particularly P_f, can be referred to the lowest responsibility category of the CC2 class according to DBN above ($P_f \approx 5\times10^{-5}$). Fig. 5 below shows the graph of the dependency "Load level at the moment of strengthening – Reliability index" for the obtained results.

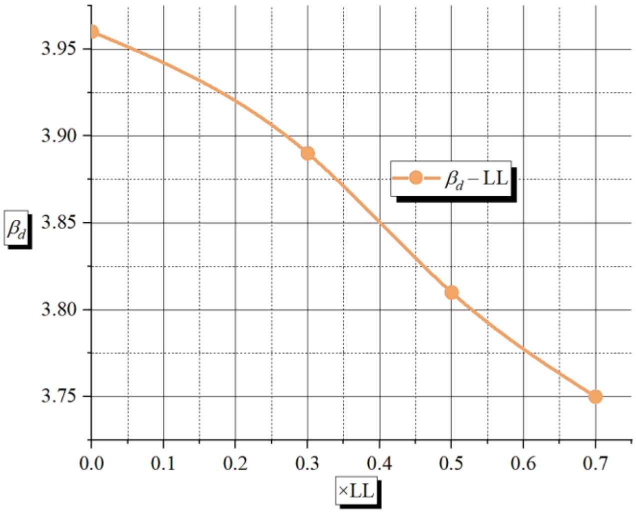

Fig. 5. Graph of the dependency "Load level at the moment of strengthening (×LL) – Reliability index (β_d)"

As shown in Fig. 5, the design reliability index (β_d) decreases (from 3.96 to 3.75) with increasing load level (LL) at which strengthening was applied, namely 0.0, 0.3, 0.5, and 0.7 of the ultimate load of the unstrengthened samples.

Based on Eq. (5), and the data in Table 2, the relationship between the engineering values of predicted durability (residual resource) of the column after strengthening (T), its design service life (T_d), and design reliability index (β_d) can be traced as follows (Lantukh-Liashchenko, 2019):

$$\beta(t)=\beta_d-(\beta_c-\beta_{lim})t^2(T_d^2)^{-1}, \quad (6)$$

where: $\beta(t)$ – the obtained reliability function (also known as the strengthened member's "life cycle model"), which represents the relationship between the engineering values of design reliability index (β_d), and the column's residual resource (t) after strengthening (in the assumption that $\beta(t) = \beta_{lim}$, and $t = T$ we can get the predicted value of this resource).

Finally, the β_{lim} indicator can be determined using the following formula:

$$\Phi(\beta_{lim})=[\Phi(\beta_c)]^n, \quad (7)$$

where: $n = T_d$; $\Phi(\beta_x)$ – the commonly used standard normal distribution function (Tytarenko et al., 2024b).

To create the dependency graphs based on Eqs. (6), (7), the input parameter values listed in Table 3 below were adopted (EN 1990; Lantukh-Liashchenko, 2019).

Table 3. Adopted indices (β_c, T_d, β_{lim}) to assess the residual resource of columns (t) after strengthening

Consequence class	β_c	β_{lim} for T_d [yrs]		
		100	80	60
CC3	4.3	3.14	3.20	3.29
CC2	3.8	2.45	2.53	2.63
CC1	3.3	1.67	1.78	1.90

The ranges of the values for initial reliability index ($\beta_c = 3.3\ldots4.3$), depending on the consequence class and a 50 years reference period, and for design service life ($T_d = 60\ldots100$ yrs) for main types of structures, are taken from standards' recommendations (EN 1990; DBN V.1.2-14-2018). The dependency graphs of the values of design reliability index ($\beta_d = \beta$) on residual resource ($T = t$) for the column samples after strengthening are presented below, regarding the most common CC2 consequence class (see Fig. 6–8).

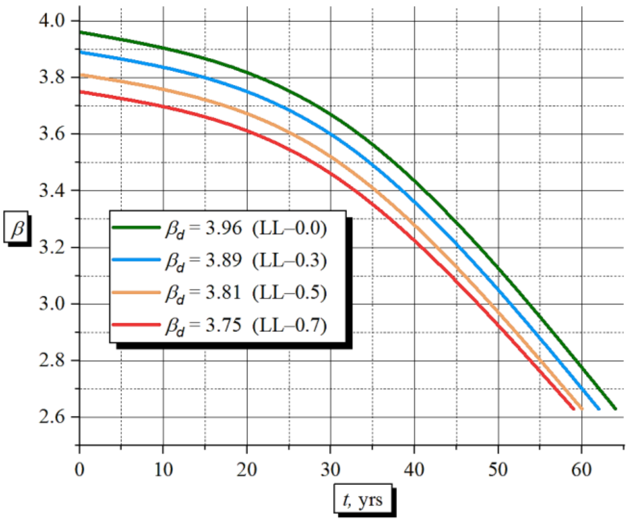

Fig. 6. The dependencies "$\beta - t$" for T_d = 60 yrs (CC2)

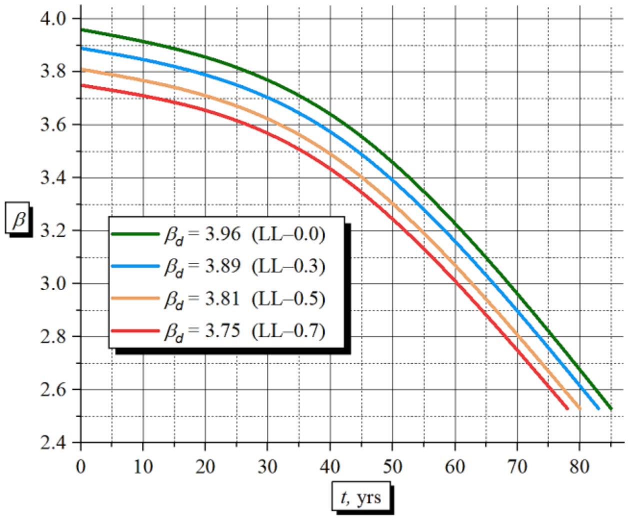

Fig. 7. The dependencies "$\beta - t$" for T_d = 80 yrs (CC2)

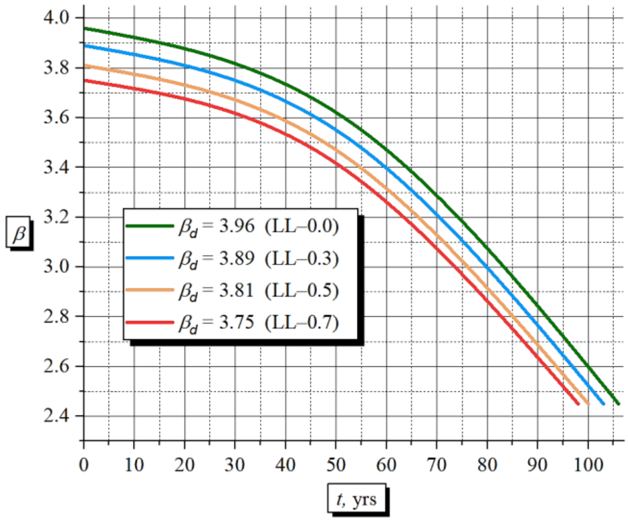

Fig. 8. The dependencies "$\beta - t$" for T_d = 100 yrs (CC2)

As shown in Figs. 6–8, the design reliability index (β) decreases as the residual life (t) of the column samples after strengthening increases, as well as with the load level (LL) at which strengthening was applied (the corresponding values of the design reliability index β_d are included in the Figs.) across all design service life values (T_d = 60, 80, and 100 yrs) for the main types of structures.

Furthermore, the preliminary assessment of the influence of random variables on the predicted reliability index and durability engineering indicator shows that the model response is moderately sensitive to variations in γ_{fa}; at higher load levels (see Table 1), its influence increases. However, the maximum effect is associated with the strength parameters of steel reinforcement and CFRP strips, as well as load parameters, while geometric parameters have the least influence. A more detailed ranking of the influence of random variables (taking into account the reliability of the estimates of the variation coefficient and standard deviation) requires a broader experimental database.

The analysis of the obtained results suggests that they are recommendatory, as the durability (residual resource) engineering reliability-based indicator of the strengthened column samples is generally comparable to the design service life of designed structures of the CC2 consequence class ($\beta_d \approx \beta_c$), as defined by current standards (EN 1990; DBN V.1.2-14-2018). However, this correlation does not apply to structures of the CC3 consequence class, where the required initial reliability index ($\beta_c = 4.3$) is considerably higher than the β_d values achieved. Therefore, the durability (residual resource) indices obtained here can be a basis for further research on RC structures strengthened under load and can be implemented in reconstruction projects.

6. Summary and conclusion

Based on reliability, an improvement of the model for predicting the durability (residual resource) engineering indicator of eccentrically compressed RC columns strengthened with CFRP-strip under different load levels has been made. This can be an excellent tool for finding the optimal design option for such structures, considering their durability after strengthening, specifically at the reconstruction stage. In addition to the set of strengths, geometric, and loading stochastic parameters, the improved model's algorithm incorporates also the so-called "activation factor of the CFRP strip" – the empirical coefficient that represents the strip's percentage of involvement in the strengthened column, with its value depending on the load level during strengthening and the strip's cross-sectional area.

Analyzing the obtained reliability and durability (residual resource) indices for the strengthened column samples showed convergence with similar values for the CC1 and CC2 consequence classes of designed structures. However, they decrease accordingly when compared to the CC3 class. For future research, we suggest using larger sample sizes and greater volumes of experimental data to enhance the accuracy of reliability assessments in Monte Carlo simulations. Finally, the quality of the CFRP-strip installation as external reinforcement, and its involvement in the operation under different loading levels, also requires further studies, especially from the point of view of assessing the RC structures' durability.

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