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Analysis of the compressive strength distribution in the inclined colonnade columns of a hyperbolic cooling tower

Abstract. Ensuring the reliability of reinforced concrete structural elements in hyperbolic cooling towers during long-term operation under the influence of various environmental and mechanical factors requires an objective assessment of their structural integrity. Accurate evaluation of the concrete compressive strength using non-destructive testing methods is of significant importance when performing in-situ investigations of such existing structures. Variations in concrete strength relative to the design values should be regarded as structural defects. The object of this study was the compressive strength of precast reinforced concrete columns forming the inclined colonnade of a 150 m high hyperbolic cooling tower at the Rivne Nuclear Power Plant (Ukraine). Variability in concrete strength characteristics has a considerable impact on the redistribution of internal forces among the inclined colonnade columns, however, this aspect has not yet received sufficient attention in the available literature. The aim of the study was to process and analyse the obtained non-destructive testing data on the compressive strength of concrete in the colonnade columns and to propose a method for determining the principal component of the tower's inclination direction, taking into account the variability of concrete strength inclined column colonnade. The applied statistical approach made it possible to determine both the characteristic strength of concrete for each individual column and its integral value for the entire group of investigated columns. The obtained results revealed a significant scatter of individual compressive strength values, both across all measurement zones and within each column, although all values exceeded the design strength. A graphical method was proposed to identify the elastic component of the preferential tilt direction of the cooling tower under its self-weight. This approach considers the distribution of strength variability among the inclined colonnade columns, which is associated with their longitudinal stiffness, making it an effective tool for field investigations and structural condition assessment of such facilities. Considering the variation in concrete strength in the inclined colonnade columns due to the cumulative effect of different influencing factors enables the application of the obtained analysis results in the reconstruction and design of reinforced concrete cooling towers

Keywords: inclined column colonnade; in-situ investigation; non-destructive testing; concrete strength variability

INTRODUCTION

Natural-draft cooling towers are widely used at power plants, petrochemical, gas processing, and other industrial facilities to dissipate waste heat into the atmosphere through the evaporation of water. In these structures, an upward airflow is created from the base toward the top, counterflowing the descending cooled water. The main

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structural components of such towers include a thin-walled reinforced concrete (RC) shell, a lower supporting ring, an inclined colonnade, an upper ring beam, and a water collection basin. The geometric dimensions of a cooling tower depend on the required spray area, which is determined based on the parameters of the induced airflow necessary for cooling circulating water (Yang *et al.*, 2019). One of the key factors affecting the evaluation of concrete strength in existing structures is the inherent material variability. N. Pereira & X. Romão (2018) noted that quantifying this variability through non-destructive testing (NDT) significantly improves the planning of subsequent destructive testing programs. Studies by I. Ivanchev (2022) and S.-H. Kwon *et al.* (2025) indicated that NDT methods alone can provide sufficient accuracy, as the obtained compressive strength values closely approximate reference data. D. Breysse *et al.* (2020) emphasised the importance of the combined approach (NDT and core sampling), while Y. Boussahoua *et al.* (2023) examined the influence of the number of cores on the accuracy of combined strength assessment.

The variability of concrete strength in the columns of cooling tower inclined colonnades has not received sufficient attention in the literature. D.H. Hladyshev (2012) experimentally demonstrated the influence of actual vertical stiffness variations in the columns on the redistribution of internal forces between them when the system operates within rigid boundary conditions at the upper and lower supports of the colonnade. Existing design codes do not account for significant deviations in concrete strength classes or modulus of elasticity from their design values, although such variability significantly affects the internal force distribution in the colonnade, producing additional compressive and tensile stresses in the lower ring beam that were not considered in the original design.

The objective of this study was to process and analyse the results of in-situ NDT measurements of the compressive strength of concrete in the inclined colonnade columns of a hyperbolic cooling tower, examining both the individual data points and the behaviour of each column separately. Furthermore, the paper proposed an approach for determining the preferential horizontal component of the tower's tilt direction, taking into account the variability distribution of concrete strength among the columns. The scientific significance of this work lies in the comprehensive investigation of the concrete strength of all inclined colonnade columns in an existing cooling tower with a wetted area of 10,000 m^2. The large dataset obtained for each column allowed for a graphical representation of the distribution characteristics of concrete strength, both along the perimeter of the colonnade and vertically within the structure, to identify an integral direction of minimum strength values, which indicated the preferred direction of tower inclination under self-weight. The accumulation of data on the variability of concrete strength in colonnade columns during long-term operation is also of considerable value for future research in this field.

LITERATURE REVIEW

Any deviation in the compressive strength of concrete in precast RC columns of the inclined colonnade, whether an increase or decrease relative to the design values at random sectors along the perimeter of the tower shell, should be regarded as a defect. A decrease in strength reduces the structural reliability and service life, whereas an increase results in unnecessary construction costs. The variability of these parameters also indicates insufficient quality control during production at the precast concrete plants where the columns were manufactured (Chen *et al.*, 2014). The simultaneous occurrence of both types of deviations leads to uncontrolled redistribution of vertical and horizontal load components from the colonnade columns to the lower supporting ring of the shell, the walls of the water collection basin, or RC foundations of various types. Considering the variation in concrete strength due to the cumulative action of multiple factors enables the results of such analysis to be applied in the reconstruction, strengthening, and design of similar structural systems.

Ensuring the reliability and durability of RC structural components that form part of cooling towers requires an objective assessment of their technical condition during long-term service. The issues of durability of cooling tower structures during extended operation have been highlighted by M. Kaminski & M. Maszczak (2012), who analysed the main causes leading to damage in inclined colonnade columns and shells. Evaluating the actual compressive strength of concrete is of crucial importance in diagnosing the technical condition of existing structures after prolonged service, during which they are subjected to multiple environmental and mechanical effects.

According to DSTU B V.2.7-224:2009 (2010), the mean compressive strength of concrete f_{cm} generally differs from its characteristic strength f_{ck}, which depends on the variability expressed by the coefficient of variation, representing the actual manufacturing and curing conditions of the concrete. The concrete class is determined based on the characteristic strength f_{ck}, which corresponds to the closest value in the parametric series specified in DBN V.2.6-98:2009 (2010). With a low coefficient of variation, a plant can achieve the required concrete class at a lower average controlled strength f_{cm}. Conversely, in cases of reduced cement content, inadequate compaction, or a high water-to-cement ratio, an elevated coefficient of variation necessitates an increase in cement consumption to meet the design class based on the target level.

According to DSTU B EN 13791:2013 (2014), the compressive strength of concrete in existing structures may be determined by various methods: core sampling from the structure, non-destructive testing, or a combined method that integrates both. NDT methods have proven effective for assessing in-situ concrete strength, as indicated by O.M. Pshinko *et al.* (2011), R. Pucinotti (2015), and T. Demir *et al.* (2023). Core extraction is relatively expensive, technically demanding, and in some cases infeasible. In operating cooling towers, coring from the precast columns of the inclined colonnade is practically difficult due to both operational and structural constraints. N.T. Nguyen *et al*. (2013) analysed concrete strength variability in slab structures and determined the minimum number of NDT measurements required for reliable estimation. The number and arrangement of testing zones for assessing concrete strength in individual structural elements are specified in DSTU B V.2.7-224:2009 (2010). However, a question remains regarding how many identical elements should be selected for NDT. Clause 5.11 of the same standard recommends testing 10% of the elements from a production batch to determine the release strength of concrete by NDT methods.

Assessing the compressive strength of existing inclined colonnade columns is necessary not only for determining their technical condition but also for further numerical modelling of the entire structure. In practice, design calculations typically assume uniform concrete strength across all elements or use statistically derived average values for groups of similar elements, as discussed by M. Nandini & T.N. Guruprasad (2017) and M.H. Sagar *et al*. (2022). Therefore, evaluating the concrete strength distribution among the inclined colonnade columns of cooling towers remains a relevant problem that requires further investigation.

MATERIALS AND METHODS

The object of this study was the inclined colonnade columns of a natural-draft cooling tower with a total height of H = 150 m located at the Rivne Nuclear Power Plant (Fig. 1). The tower remained unused for 15 years before the commencement of the in-situ investigation, and therefore was not affected by operational thermal or mechanical processes during that period.

Figure 1. Natural-draft RC cooling tower, height H = 150 m, wetted area 10,000 m^2
Source: photo by the author

The RC shell of the cooling tower, shaped as a hyperboloid of revolution, is supported by 44 pairs of precast V-shaped RC columns, each having a diameter of 900 mm (Fig. 2). These paired columns form the inclined support colonnade (a total of 88 columns). The colonnade transmits loads from the tower shell through the lower supporting ring of stiffness to the monolithic circular reinforced concrete foundation. According to the design documentation (1984), the concrete grade of the columns is M400, which corresponds to the modern concrete class C25/30 (f_{ck} = 30 MPa) in compliance with DBN V.2.6-98:2009 (2010).

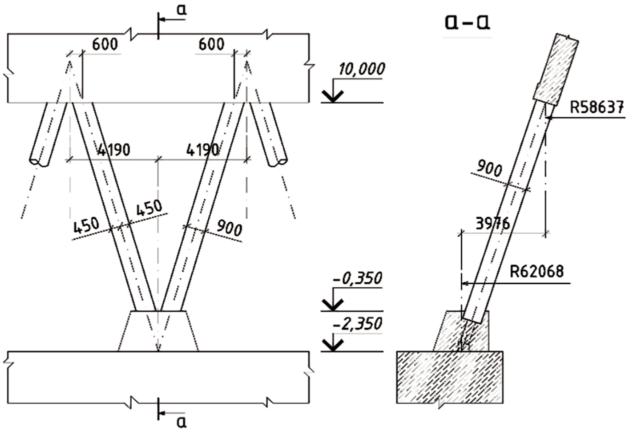

Figure 2. Geometric configuration of the paired V-shaped precast RC columns of the inclined colonnade
Source: compiled by the author

An instrumental in-situ investigation was conducted on 42 paired V-shaped precast RC columns of the inclined colonnade using NDT methods. The testing was performed in accordance with DSTU B V.2.7-220:2009 (2010), applying the mechanical rebound (plastic deformation) method using a spring-type rebound hammer model A2. Due to the high structural responsibility of the cooling tower and the potential risks associated with coring after long-term service, core sampling was not performed.

For the investigation, testing zones were prepared on the surface of each column within the inclined colonnade. Within each zone, the compressive strength of concrete was measured at 9-11 individual points. Based on these measurements, the following parameters were calculated for each column: the mean compressive strength of concrete, the standard deviation, according to equation (1), and the coefficient of variation, according to equation (2):

$$\sigma_i^{col} = \sqrt{\frac{\left(f_{c,i}^{test} - f_{cm,i}^{test}\right)^2}{n-1}}, \tag{1}$$

where σ_i^{col} – standard deviation of strength values; $f_{c,i}^{test}$ – individual concrete strength value within the testing zone; $f_{cm,i}^{test}$ – mean concrete strength within the testing zone; n – number of measurements in the zone.

$$V_{c,i}^{col} = \frac{\sigma_i^{col}}{f_{cm,i}^{test}}, \tag{2}$$

where $V_{c,i}^{col}$ – coefficient of variation for the column.

The characteristic compressive strength of concrete for each column $f_{ck,i}^{col}$ was then determined using equation (3), based on the column's mean compressive strength and the corresponding coefficient of variation:

$$f_{ck,i}^{col} = f_{cm,i}^{test} \cdot (1 - 1{,}64 \cdot V_{c,i}^{col}), \qquad (3)$$

where $f_{ck,i}^{col}$ – characteristic compressive strength of the column.

Similarly, the overall characteristic compressive strength of concrete for all investigated columns f_{ck}^{tow} was determined using equation (4), taking into account the mean compressive strength and coefficient of variation for all testing zones across all columns:

$$f_{ck}^{tow} = f_{cm}^{test} \cdot (1 - 1{,}64 \cdot V_c^{tow}), \qquad (4)$$

where c – characteristic compressive strength of all investigated zones across all columns; f_{cm}^{test} – mean compressive strength across all columns; V_c^{tow} – coefficient of variation for all zones.

The statistical and graphical approach applied in this study enables the determination of both the individual characteristic compressive strength of concrete for each column, and the integrated characteristic strength for the entire set of investigated columns within the inclined colonnade, which provides a basis for comparative analysis and further structural assessment.

RESULTS AND DISCUSSION

During the instrumental investigation, a total of 826 individual data points of concrete compressive strength $f_{c,i}^{test}$ were obtained and statistically processed. The data analysis was carried out both for the entire dataset and separately for each column of the inclined colonnade of the cooling tower. The summarised results are presented in Table 1.

Table 1. Statistical results of concrete compressive strength analysis

Statistical data for the total of 826 individual values			Statistical data for 84 columns	
Range of individual concrete strength values across test zones $f_{c,i}^{test}$, MPa	Coefficient of variation across all test zones V_c^{tow}, %	Characteristic value of concrete compressive strength for all tested zones f_{ck}^{tow}, MPa	Range of coefficient of variation values for individual columns, $V_{c,i}^{col}$, %	Range of characteristic concrete strength values for individual columns $f_{ck,i}^{col}$, MPa
35.7-67.2	8.44	44.34	3.25-14.48	32.5-57.5

Source: compiled by the author

As shown in Table 1, a wide dispersion of individual concrete strength values $f_{c,i}^{test}$ is observed across all testing zones. Nevertheless, the characteristic compressive strength of concrete for all testing zones $f_{c,i}^{test}$ exceeds the design strength f_{ck} = 30 MPa, while the coefficient of variation V_c^{tow} is below the normative limit $V_{\tilde{n}}$ = 13.5% as specified in DBN V.2.6-98:2009 (2010).

Variations are also observed in the characteristic strength values per column $f_{ck,i}^{col}$. However, all of these values remain higher than the design strength, indicating satisfactory concrete quality overall. The significant scatter of values suggests inconsistent technological control during the production of the precast column batches. Despite this, 96.3% of the individual coefficients of variation $V_{c,i}^{col}$ remain below the normative threshold, indicating generally adequate quality control during the manufacturing process.

A separate analytical approach was applied to independently determine the characteristic compressive strength of concrete $f_{ck,i}^{col}$ for each column and to identify groups of columns with comparable strength characteristics. The relationship between the measured concrete strength values and the number of columns corresponding to these values is illustrated in Figure 3. The distribution of the 826 measured strength values was approximated by a normal distribution curve (Gaussian function).

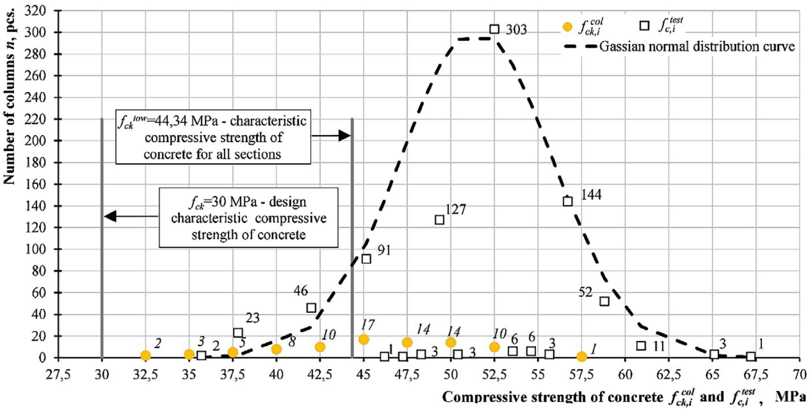

Figure 3. Comparison between the distribution of 826 individual concrete strength values $f_{c,i}^{test}$ following the normal distribution and the characteristic strength values $f_{ck,i}^{col}$ with the corresponding number of columns exhibiting identical or similar strengths

Source: compiled by the author

Given that the 84 precast columns of the inclined colonnade exhibit a significant range of characteristic compressive strength values $f_{ck,i}^{col}$, the direction of the resultant vector of these strength values f_{ck}^{R} can be determined using a sector angle α_R. This sector angle is measured from the direction of the first tower axis to the radius along which lies the vertical plane corresponding to one of the directions of the resultant f_{ck}^{R}. The direction represents the integral gradient of strength reduction across all columns. The sector angle α_R was calculated using equation (5):

$$\alpha_R = \frac{\sum_{i=1}^{n}(\alpha_i \cdot r_i \cdot f_{ck,i}^{col})}{\sum_{i=1}^{n}(r_i \cdot f_{ck,i}^{col})}, \qquad (5)$$

where α_R – sector angle of the resultant direction; α_3 – angular position of the i-th column measured from the reference axis; r_3 – radius of the i-th column from the central axis of the cooling tower; $f_{ck,i}^{col}$ – characteristic compressive strength of the i-th column.

Using this approach, the sector angle for the characteristic concrete strength distribution was determined to be $\alpha_R = 174.53°$. The graphical representation of the resultant direction of the integral decrease in concrete characteristics is shown in Figure 4, which also illustrates the strength variation around the tower perimeter.

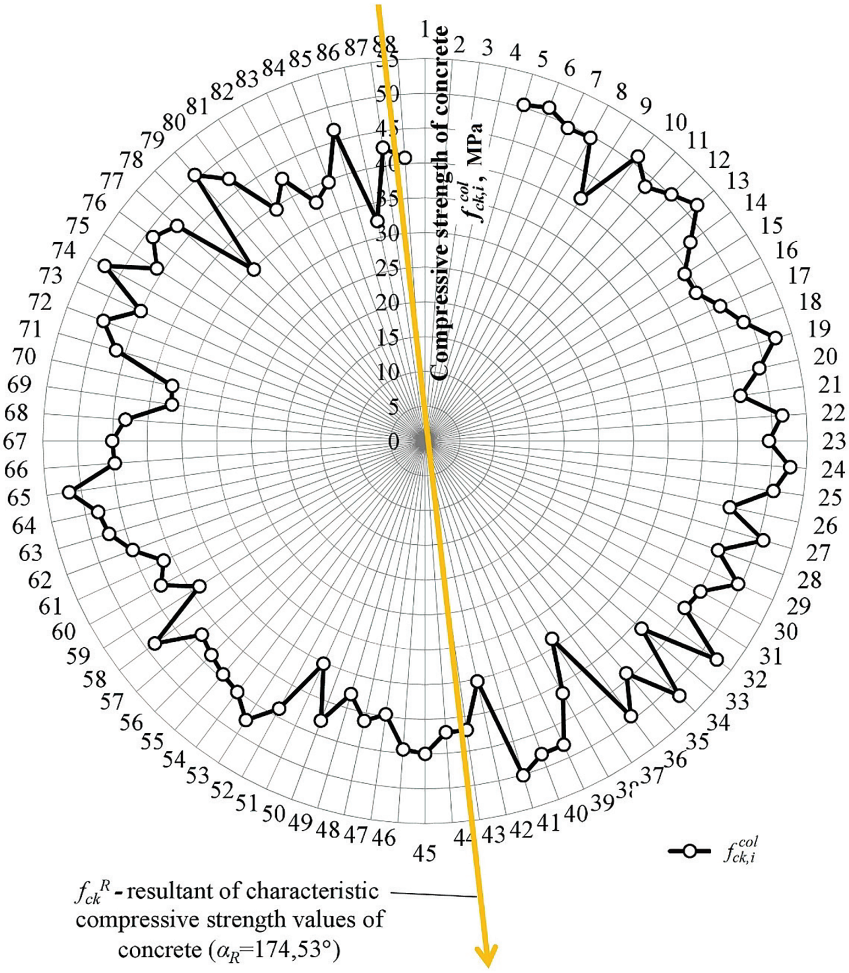

Figure 4. Direction of the resultant vector f_{ck}^{R} for $f_{ck,i}^{col}$, indicating the integral reduction of concrete strength across the inclined colonnade columns of the cooling tower

Source: compiled by the author

This approach provides a practical and reliable method for determining the elastic preferential direction of the tower's potential inclination under its self-weight, taking into account the variability of concrete strength in the inclined colonnade columns. By projecting the characteristic concrete strength values $f_{ck,i}^{col}$ onto the diameter of the cooling tower lying within the vertical plane corresponding to the angle α_3 and performing a linear approximation of these values, the practical direction of the integral reduction trend was determined. Figure 5 presents a graph illustrating the characteristic compressive strength values of the columns $f_{ck,i}^{col}$ projected onto the resultant f_{ck}^{R} direction. The graph it can be seen that the approximate limit values of the concrete strength of the columns are equal to $f_{ck,max}^{col} = 46.8$ MPa, $f_{ck,min}^{col} = 44.2$ MPa.

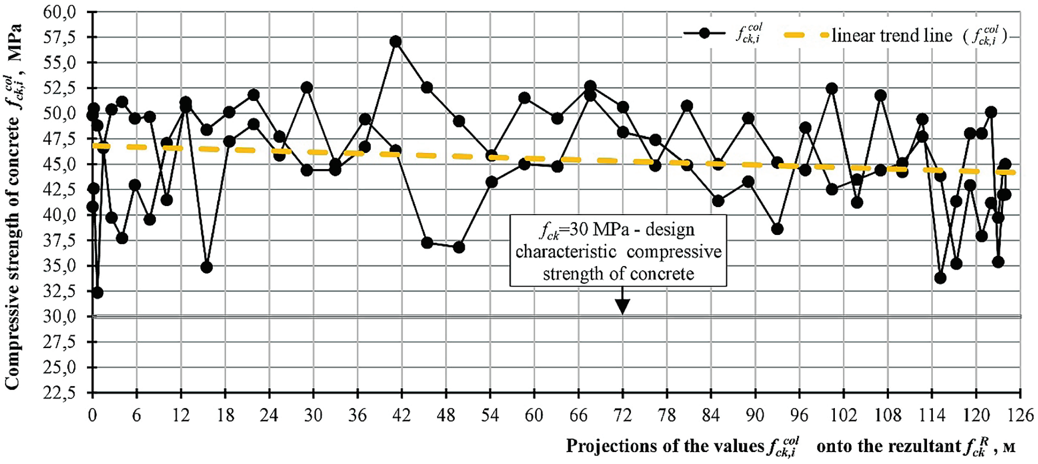

Figure 5. Characteristic compressive strength values of the columns $f_{ck,i}^{col}$ projected onto the resultant direction f_{ck}^{R} in the plan view of the tower axes

Source: compiled by the author

The analysis of data obtained from the in-situ investigation of the concrete strength of the inclined colonnade columns in the cooling tower supports the conclusions made by P.V. Yasnyi *et al.* (2016), S.-H. Kwon *et al.* (2025) regarding the appropriateness of using NDT methods for assessing buildings and structures during long-term operation. The findings of the investigation highlight the significance of accurately identifying and accounting for the concrete compressive strength of each individual column within the inclined colonnade of the cooling tower during structural evaluation. A comparison of the range of characteristic concrete compressive strength values $f_{ck,i}^{col}$ = 32.5 - 57.5 MPa across the 84 columns of the inclined colonnade (as shown in Figure 3) with the overall characteristic concrete strength f_{ck}^{tow} = 44.34 MPa, determined from the 826 individual strength measurements at various test zones, confirmed that the strength parameters of each column in the inclined colonnade must be evaluated individually. The results demonstrate that it is inappropriate to rely solely on fixed sample sets of test points, as recommended in DSTU B V.2.7-224:2009 (2010), when assessing a large population of structural elements. The dispersion of strength values $f_{ck,i}^{col}$ directly affects the redistribution of internal forces between the inclined colonnade columns and the lower support ring of the cooling tower shell.

Existing design standards do not account for significant deviations in the concrete strength class and thus in its characteristic compressive strength from the design value. However, these deviations substantially influence the redistribution of internal forces among the inclined columns, introducing additional compressive and tensile stresses in the sector regions between column supports on the lower stiffening ring. These additional stresses are not theoretically accounted for in the original tower design methodology. The conducted investigation has demonstrated the importance of considering the integral variability of concrete strength characteristics across all inclined colonnade columns. The obtained findings are consistent with the conclusions presented by N.T. Nguyen *et al.* (2013) and N. Pereira & X. Romão (2018), who emphasised the significance of incorporating spatial heterogeneity of material properties into structural analysis of large-scale RC systems. For research and diagnostic purposes, the proposed approach to determining the resultant direction of concrete strength variation may serve as an additional analytical tool in the comprehensive assessment of the tower's structural performance.

In their numerical studies, M. Nandini & T.N. Guruprasad (2017) analysed the influence of the geometry of inclined columns in existing cooling towers using finite element modelling, and M.H. Sagar *et al.* (2022) performed structural simulations of towers with V-shaped inclined columns, assuming a uniform concrete strength for all columns. However, as demonstrated in the present research, the concrete strength and consequently the initial elastic modulus of the colonnade columns can vary significantly along the tower perimeter. Therefore, it is proposed that numerical analyses of the load-bearing capacity of existing cooling towers should incorporate the experimentally determined concrete strength characteristics for each individual column, rather than adopting a uniform material property across the entire colonnade.

CONCLUSIONS

The material presented in this study enables a comprehensive analysis of the adopted approach for assessing the variability of concrete compressive strength within the prefabricated columns of the inclined colonnade of a RC cooling tower, providing a foundation for further evaluation of force redistribution among the columns within the ring-frame structural system. A total of 826 experimental data points obtained from in-situ testing of the concrete strength of 84 RC columns were analysed. The observed significant variation in the characteristic compressive strength of concrete among the inclined colonnade columns does not correspond to the design assumption of uniform load distribution between columns. The statistical approach developed and applied in this study allows for the independent determination of characteristic concrete strength for each individual column within the inclined colonnade, followed by logical comparison with the integral characteristic strength derived from the complete set of individual test data across all surveyed columns.

A novel methodological approach was proposed for determining the elastic resultant direction of preferential inclination of the cooling tower due to its self-weight, taking into account the spatial distribution of concrete strength variability and the corresponding variation of the initial elastic modulus of the concrete in the inclined colonnade columns. The determination of the resultant vector of characteristic strength reduction across the tower plan makes it possible to identify the elastic inclination resultant of the thin-walled reinforced concrete shell within each frame system of the colonnade. This renders the proposed approach highly applicable and practical for in-situ investigations of large RC cooling towers and similar shell-supported structures.

It is evident that, after long-term service life, other defects and damage mechanisms may also develop within such structures, which can only be identified through comprehensive diagnostic inspections. All these defects and deteriorations directly affect the operational reliability and structural integrity of the tower. Moreover, a non-uniform distribution of concrete strength may occur not only in the inclined colonnade columns but also in other critical structural components, such as the lower stiffening ring and the monolithic thin-walled shell, which significantly influence the overall spatial stiffness of the structure. These aspects require further targeted experimental and numerical studies to refine assessment methodologies for the long-term safety and performance of cooling towers.

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CONFLICT OF INTEREST

None.

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Аналіз розподілу міцності бетону на стиск у колонах похилої колонади гіперболічної градирні

Анотація. Забезпечення надійності залізобетонних конструктивних елементів гіперболічних градирень під час тривалої експлуатації за впливу різних факторів навколишнього середовища та механічних факторів потребує об'єктивної оцінки їх конструктивної цілісності. Точне визначення міцності бетону на стиск із застосуванням неруйнівних методів контролю має суттєве значення під час проведення натурних обстежень таких існуючих споруд. Відхилення міцності бетону від проєктних значень слід розглядати як конструктивні дефекти. Об'єктом цього дослідження була міцність на стиск збірних залізобетонних колон, що утворюють похилу колонаду гіперболічної градирні заввишки 150 м на Рівненській атомній електростанції (Україна). Варіативність характеристик міцності бетону має значний вплив на перерозподіл внутрішніх зусиль між колонами похилої колонади, проте цей аспект ще не отримав достатньої уваги в доступній літературі. Метою дослідження було опрацювання та аналіз отриманих даних неруйнівного контролю міцності бетону на стиск у колонах колонади та запропонування методу визначення головної складової напрямку нахилу градирні з урахуванням варіативності міцності бетону колон похилої колонади. Застосований статистичний підхід дав змогу визначити як характеристичну міцність бетону для кожної окремої колони, так і її інтегральне значення для всієї групи досліджуваних колон. Отримані результати виявили значний розкид окремих значень міцності на стиск як у всіх зонах вимірювання, так і в межах кожної колони, хоча всі значення перевищували проєктну міцність. Запропоновано графічний метод ідентифікації пружної складової переважного напрямку нахилу градирні під дією власної ваги. Цей підхід враховує розподіл варіативності міцності між колонами похилої колонади, що пов'язано з їх поздовжньою жорсткістю, що робить його ефективним інструментом для натурних обстежень та оцінки технічного стану таких споруд. Врахування варіації міцності бетону в колонах похилої колонади внаслідок кумулятивного впливу різних чинників дає змогу застосувати отримані результати аналізу під час реконструкції та проєктування залізобетонних градирень

Ключові слова: похила колонна колонада; натурне обстеження; неруйнівний контроль; варіативність міцності бетону