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Probabilistic Design Approaches of Centrifugally Cast Concrete Structures in Telecommunications Infrastructure

Ona Lukoševičienė

Civil Engineering Research Centre, Vilnius Gediminas Technical University, Lithuania. E-mail: ona.lukoseviciene@vilniustech.lt

Romualdas Kliukas

Department of Applied Mechanics, Vilnius Gediminas Technical University, Lithuania. E-mail: romualdas.kliukas@vilniustech.lt

Saulius Indriūnas

Civil Engineering Research Centre, Vilnius Gediminas Technical University, Lithuania. E-mail: saulius.indriunas@vilniustech.lt

Arūnas Jaras

Department of Applied Mechanics, Vilnius Gediminas Technical University, Lithuania. E-mail: arunas.jaras@vilniustech.lt

Telecommunication masts and towers, widely used in communication and power transmission systems, are exposed to external environmental actions. Dynamic loads can cause extreme stresses and even structural failures. The research examines several structural systems consisting of a centrifuged concrete core with a circular cross-section, guy wires, tension ties and strut elements. Such a system allows for reduced bending moments, effective buckling length and ensures more efficient use of materials compared to traditional tower and mast systems. The article presents a reliability analysis of a centrifuged concrete core with a circular cross-section, based on probabilistic calculations, including the Monte Carlo simulation, to assess the safety of structures under extreme wind loads. The results of the study show that the proposed structural system with centrifuged concrete and additional tension members are more rational and durable compared to traditional telecommunications structures. By applying probabilistic assessment and structural analysis, it is possible to assess the resistance of structures to extreme loads and optimize their design and operation.

Keywords: Tower, mast, centrifugally cast concrete, probabilistic design.

1. Introduction

In the modern world, telecommunications infrastructure is essential for ensuring the provision of mobile communication, internet and data transmission services worldwide. The increasing need on telecommunications infrastructure has led the demand for tall, durable and sustainable structures such as masts and towers.

Guyed masts and towers, widely used in telecommunications and power transmission, face significant challenges due to wind, ice, and seismic loads. These tall and slender structures are sensitive to dynamic actions, with wind being a predominant factor impacting their stability and structural reliability. Research highlights that dynamic effects, such as vibrations from wind and ice accumulation, can lead to extreme stress levels and even failure in some cases (Madugula et al. 1998, Ballaben et al. 2011). Meanwhile, Madugula et al. (1998) focus on the dynamic response of guyed masts under wind and ice loading, modeling these structures to understand natural frequency changes and prevent catastrophic failure due to excessive vibration or torsion. Expanding on dynamic load management, Cucuzza et al. (2022) introduce optimization techniques to minimize structural mass in guyed masts under wind, ice, and seismic influences, showing how precise parameter adjustments can mitigate oscillations and potential instabilities in telecommunications masts. Kudzys (2006) discusses the specific challenges in power transmission line structures under extreme weather, highlighting the need for reliability assessments incorporating wind and ice loads.

These studies illustrate a comprehensive approach to wind load management and structural optimization, offering insights into enhancing the safety and durability of infrastructure facing dynamic environmental challenges. And highlight the critical need for advanced modelling, risk-based load factors, and improved international standards (EN 1990 2002, EN 1992-1 2004, ISO 2394 1998, ISO 4354) to ensure the safety, durability, and functionality of structures subjected to complex wind conditions.

Centrifugally cast concrete, known for its high strength and density, excellent performance under dynamic loads, is becoming an important material for structures as towers and core of masts. Reinforced concrete structures made from centrifugally cast concrete exhibit properties characteristic of long-term durability. Due to the production technology, centrifugal forces in a spinning mold press the concrete mix against the walls, achieving excellent compaction. The outer surface of such centrifugally cast concrete structures is sufficiently smooth and features a dense protective concrete layer. Concrete compacted through centrifugation is significantly stronger (1.3–1.8 times) than concrete of the same composition produced by other technology. Centrifugally cast concrete structures with circular cross-sections, due to higher concrete strength and flexural rigidity, can be designed with significantly smaller cross-sectional areas, making them lighter (Kliukas et al. 2020). Despite their advantages, reinforced concrete structures have a key drawback—their high self-weight—which negatively affects structural stress and deformation state, as well a transportation and installation processes. Improper transportation can cause damage to the structures, potentially rendering them unsuitable for use. Due to the significant height of telecommunications structures, towers become inefficient in terms of material consumption compared to masts (Indriūnas et al. 2023).

This study examines pre-stressed concrete core with circular cross-sections, produced using centrifuged concrete, as well as combined guyed masts with struts. Research on pre-stressed centrifuged concrete tower and mast structures remains underdeveloped, and their design principles require further in-depth analysis (Guo et al. 2016, Li et al. 2018, Tsai and Alipour 2020, Wang 2019, Zhou 2018). An innovative structural solution is proposed, integrating a centrifuged concrete core with a circular cross-section, guy wires, and prestressed strut elements, tension ties into a single load-bearing system (Indriūnas et al. 2023). The behaviour and calculations of centrifuged core are complex due to their slenderness, requiring consideration of second-order effects, material and geometric nonlinearity, structural imperfections, creep, and cracking.

The reliability, safety, and durability of tall structures depend on various factors, including appropriate design solutions, accurately assessed loads, material quality, manufacturing technology, assembly, transportation, and operational conditions. Therefore, a comprehensive analysis of these elements' properties and the optimization of their design methodologies are essential.

The aim of this study is to assess the reliability of tower and guyed mast structures made of centrifugally cast concrete with a circular cross-section by determining the reliability index. The analysis incorporates additional uncertainties in calculation models and recommendations to enhance the accuracy of structural safety evaluation, improve durability assessment, and optimize design methodologies through probabilistic analysis principles.

2. Reliability Prediction of Structures

Designed structures must meet structural requirements and be suitable for use throughout their entire service life. The required reliability level depends on the purpose of the structures. According to the EN 1990 (2002) recommendations, reliability can be differentiated by identifying three consequence classes (CC) and associating them with three reliability classes: RC1 (Low importance), RC2 (Normal importance), and RC3 (High importance). Considering the reliability classes, the minimum reliability index values for the ultimate limit state are recommended for 1 year and 50 years, as shown in the Table 1.

Table 1. Reliability classes via minimum values of reliability indices (EN 1990, 2002)

Minimum values of reliability index	Reliability class		
	RC1	RC2	RC3
after 1 year	4.2	4.7	5.2
after 50 years	3.3	3.8	4.3

The generalized reliability index may be used to represent the failure probability of structures (JCSS 2000, Vrouwenvelder et al. 2024):

$$P_f = \Phi(-\beta) \quad (1)$$

where $\Phi(\cdot)$ is the cumulative distribution function of the standard normal distribution.

Failure probability may be expressed:

$$P_f = P(Z(t) < 0) \quad (2)$$

Analytical methods, numerical integration, and Monte Carlo simulations may be used to calculate the probability of structural failure.

According to probability-based approaches, the safety margin of structures may be expressed:

$$Z(t) = g[\boldsymbol{X(t)}, \boldsymbol{\theta}] = \theta_R R(t) - \theta_E E(t) \quad (3)$$

where $\boldsymbol{X(t)}$ and $\boldsymbol{\theta}$ are the vectors of basic and additional variables, *R(t)* is the resistance of the structure at time *t*, and *E(t)* represents the effects of loads over time, θ_R and θ_E are supplementary random variables that describe the uncertainties in the design model related to the resistances and action effects of structures (JCSS 2000, Vrouwenvelder et al. 2024).

The mean values and coefficients of variation of additional variables of the safety margin of structures depend on their types and are: $\theta_{Rm} = 0.99 - 1.2$, $\delta\theta_R = 0.10 - 0.15$ and $\theta_{Em} \approx 1.00$, $\delta\theta_R \approx 0.10$ (JCSS 2000; Holicky and Markova 2002, Kaewunruen et al. 2021).

The structural design standard EN 1990 (2000) incorporates the partial factors method, allowing for alternative load combination rules and the direct application of probabilistic techniques. The general principles of structural reliability differentiation are presented, considering the consequences of failure. Actions can be categorized according to their variation over time into permanent actions, variable actions (including those from structural usage and external actions like wind and snow), and exceptional actions. (JCSS 2000). There are two main aspects of the description of an action: it is physical and statistical aspect. Then the physical description gives the types of physical data characterising the action model. The statistical characteristics of variables, including probability distribution functions, are conveyed through statistical descriptions. Modelling these quantities requires specifying appropriate distributions and outlining the correlation patterns between them. (JCSS 2000).

Wind impacts on buildings and structures are influenced by the overall climate, wind exposure, dynamic characteristics, and the structural shape and dimensions. The distribution of the mean of wind velocities is the Weibull distribution (ISO 4354 2009). The maximum mean wind speeds for longer periods follows a Gumbel distribution for maxima. If the annual data are homogenous as exposure and averaging time, the Gumbel cumulative distribution function is quite appropriate for the probability analysis of structures subjected to annual extreme wind and snow loads (Ellingwood et al. 1999; JCSS 2000).

3. Analysis and Results of Centrifugally Cast Concrete Structures

The telecommunications mast's innovative design incorporates a core, struts, tension ties, and guy wires to form a stable structural system. Struts act as semi-rigid supports, and guy wires function as flexible restraints, reducing displacements and bending moments in the core. The core is primarily subjected to compression and bending, while the guy wires handle tension forces. The addition of two struts significantly decreases the bending effects and buckling length of the mast.

The analysis of centrifugally cast concrete structures followed standards (EN 1990 2000, EN 1992-1 2002). The study involved a linear analysis to optimize the cross-sections and prestressing, followed by a detailed evaluation of core behavior. Second-order effects, material and geometric nonlinearities, and associated factors were assessed using specialized software „FRILO“ for accurate structural modeling (Indriūnas et al. 2023).

Using numerical simulation models, the analysis of a centrifugally cast concrete core with a circular cross-section was conducted by examining four different structural systems. Four structural and design schemes, internal forces diagrams, parameters of the circular cross-section of the core are presented in the Table 1.

Table 1. Different structural system variants

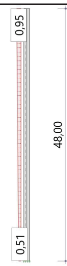
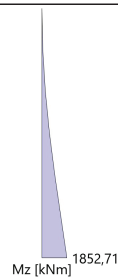
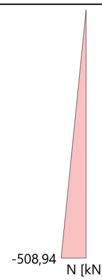
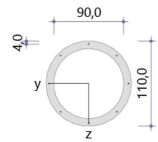
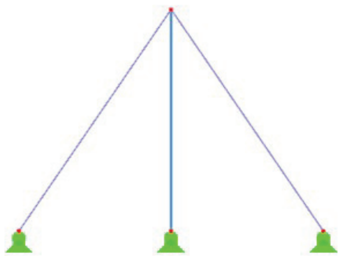
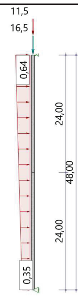
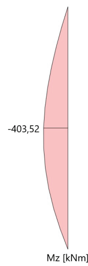
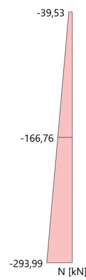
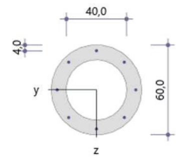
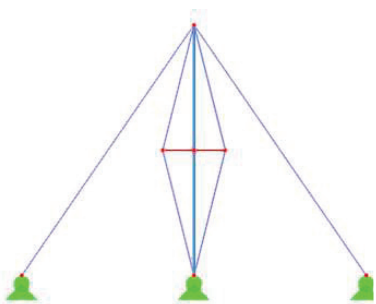
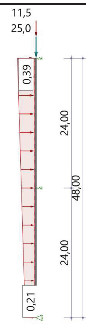
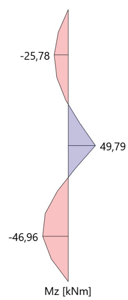
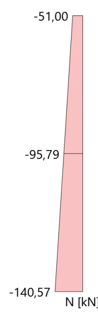
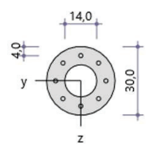
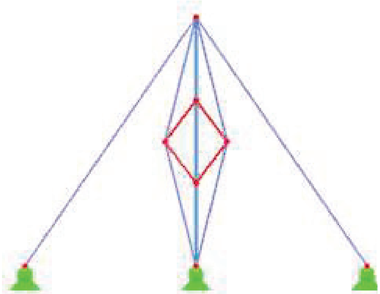
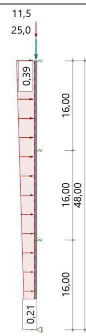
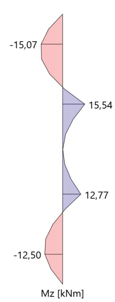
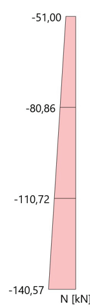
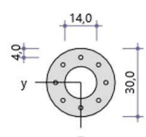
No	Structural system	Design scheme	Design values of bending moments	Design values of axial force	Cross section
I					
II					
III					
IV					

Table 3. Parameters of the centrifugally cast concrete core with a circular cross-section for probabilistic assessment

Stuctural system	Characteristic values		Mean values		Reliability index
	Resistance R_k [kNm]	Action effect E_k [kNm]	Resistance R_m [kNm]	Action effect E_m [kNm]	
I	3800	1083	4548	541,5	3,923
II	1180	199,0	1412	99,50	4,250
III	125,0	23,74	149,6	4,565	4,471
IV	125,0	9,130	149,6	11,87	4,192

The behaviour of the centrifugally cast concrete core with a circular cross-section is analysed under different structural scenarios. The column, 48 meters in height, is designed from C50/60 centrifugally cast concrete with a circular cross-section, and B500A is used for reinforcement. The nominal concrete cover is 40 mm, with a minimum of 25 mm plus an additional allowance of 15 mm. The designed structure meets the requirements of environmental exposure classes (WF, XF1, XC4). In the structural systems—guy wires, struts, and tension ties—the S275 steel strength class was selected.

The design values of resistance and bending moments of action effects of centrifugally cast concrete cores of structural systems, calculated using the general method by software, “FRILO”, are presented in Table 2.

Table 2. Design values of resistances and action effects of core of structural systems

Structural systems	Design values	
	Resistance R_d [kNm]	Action effect E_d [kNm]
I	2740	1854
II	960	404
III	95	49,79
IV	95	15,54

The probabilistic assessment of the structural systems cores was conducted following the recommendations of standards (EN 1990 2002, ISO 2394 1998, JCSS 2000). The calculation parameters for the probabilistic assessment, mean values of basic variables, and reliability indices are presented in Table 3.

Resistance is characterized by a normal distribution with a coefficient of variation of 0.1, while the wind-induced bending moment is described by a Gumbel distribution with a coefficient of variation of 0.4. The probabilistic model accounts for uncertainties in the calculation model for both resistance and bending moment of action effects, $\theta_{Rm} = 1.2$ and $\theta_{Em} = 1.00.$ The coefficients of variation are $\delta\theta_R = 0.15$ for resistance and $\delta\theta_E = 0.10$ for the bending moment of action effects. The values of failure probability are calculated using Monte Carlo simulation.

4. Discussion and Conclusions

Furthermore, probabilistic assessment methods, including Monte Carlo simulation, provide a more comprehensive and precise evaluation of structural safety, considering extreme load conditions and material uncertainties. The implementation of these approaches in design and construction will contribute to safer, more efficient, and sustainable telecommunications infrastructure for the future. The application of probabilistic methods in practice requires significant computational resources and specialized software, which is not yet widely integrated into standard design processes. Effectively apply probabilistic methods in the industry, it is essential not only to enhance engineers' competence in probabilistic analysis but also to develop software tools that facilitate the integration of these methods into daily design processes. This study highlights the importance of probabilistic approaches in enhancing structural reliability and durability. By incorporating uncertainty in material properties, environmental actions and their variations, these methods provide a more precise and robust framework for ensuring long-term structural safety. Applying probabilistic methods, it is crucial to have reliable initial statistical input data (e.g., mean values, coefficients of variation of random variables), which is why expanding existing databases and developing reliable models for real engineering cases is essential.

The structural systems of variants III and IV consist of a centrifugally cast concrete core with a circular cross-section, guy wires, tension ties and strut elements. These systems create elastically flexible supports within the core, reducing the effective buckling length, bending moments and deflections. Such structural solutions are more efficient, sustainable, and rational, as the circular cross-section core can have a smaller cross-section and mass compared to tower (variant I) and mast systems (variant II). Probabilistic analysis revealed that the reliability index of the centrifugally cast concrete core, as an individual structural element, depends on the structural scheme and cross-sectional parameters. The innovative structural system should be considered as a composite system consisting of separate structural elements—the core, guy wires, and strut components—each contributing to the overall performance and reliability of the structure.

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