buildings

MDPI

Article

Behavioral Analysis of a Mast with a Combined Prestressed Stayed Columns System and Core of a Spun Concrete Circular Cross-Section

Saulius Indriūnas [1,*], Romualdas Kliukas [1] and Algirdas Juozapaitis [2]

[1] Department of Applied Mechanics, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania; romualdas.kliukas@vilniustech.lt

[2] Department of Steel and Composite Structures, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT-10223 Vilnius, Lithuania; algirdas.juozapaitis@vilniustech.lt

* Correspondence: saulius.indriunas@vilniustech.lt; Tel.:+370-65059036

Abstract: Widely used telecommunication structures are usually of the tower or mast type. For medium and tall telecommunications structures, tower-type constructions become less efficient compared to mast-type structures. The goal of our article is to discover a new, efficient telecommunication structure. For relatively low heights, tower systems can be designed with a continuous cross-section, in most cases using reinforced concrete elements. Among them, efficient spun concrete elements, whose load-bearing capacity is higher than that of ordinary solid reinforced concrete elements due to the technological features of their production, should be mentioned. A significantly higher efficiency of masts can be achieved by employing various combined structural systems that utilize a prestressed stayed columns system. It should be noted that there are not many solutions for prestressed stayed columns systems with spun concrete core elements and that research into their design and behavior is not yet sufficiently developed. The behavior of this combined structure is analyzed with regard to the geometric and physical nonlinearity of its elements. The strength and stability of the spun concrete core of such a combined system are evaluated. The impact of the prestressing of this prestressed stayed column structure on the internal forces and displacements of the reinforced concrete core is analyzed. The performance of the new structure compared to conventional tower and mast structures is presented. In the article, it has been determined that by applying the prestressed stayed columns system to telecommunication structures, the innovative structural system becomes 2.5 times more efficient than the classic mast and 5 times more efficient than the typical tower system on the mass criterion.

Keywords: telecommunication structures; conceptual design; prestressed stayed columns system; spun concrete elements; reinforced concrete analysis; non-linear behavior; numerical analysis; structural performance

Citation: Indriūnas, S.; Kliukas, R.; Juozapaitis, A. Behavioral Analysis of a Mast with a Combined Prestressed Stayed Columns System and Core of a Spun Concrete Circular Cross-Section. *Buildings* **2023**, *13*, 2175. https://doi.org/10.3390/buildings13092175

Academic Editors: Ying Tian, Sarah Orton, Trevor Hrynyk, Liping Wang and Francisco López-Almansa

Received: 26 July 2023
Revised: 10 August 2023
Accepted: 24 August 2023
Published: 27 August 2023

1. Introduction

In recent decades, tall telecommunications structures have been widely used and are usually constructed as tower or mast types [1,2]. Each of these construction types has its own advantages and disadvantages. The main advantage of tower structures is their relatively simple calculation, design, and installation [3,4]. Based on the material characteristics, these systems are mainly divided into steel and reinforced concrete structures [5,6]. If steel tower structures are employed, latticed cross-sectional elements are used [7,8]. At relatively lower heights, tower systems can be constructed with solid cross-sections, where reinforced concrete elements are commonly used. For example, they are well-suited not only for telecommunication structures but also for supporting overhead power transmission lines, as they are resistant to atmospheric effects, durable, and have uniform resistance to mechanical loads in any cross-sectional direction [8]. In Europe, reinforced concrete poles are widely used for low, medium, and 110 kV double-circuit voltage systems with heights reaching 30 m and beyond [9]. Among them, it is worth mentioning efficient spun reinforced concrete elements, which have a higher load-bearing capacity than ordinary solid reinforced concrete elements due to the technological features of their production [10]. The advantages of using spun concrete elements have been well recognized in the scientific literature [10–17]. These structures are used as short columns in transport structures such as airport runway extensions, islands, and flyover structures. Also, they are used in the construction of large tanks (bunkers), wind turbine masts, and chimneys. The durability and use of centrifuged structures are further increasing with the introduction of new materials such as non-metallic reinforcements [18–21].

Spun reinforced concrete structures are more durable compared to vibrated structures, as their outer surface is relatively smooth, with a dense protective concrete layer, the strength and density of which is up to 30% higher than that of the inner layers [22]. Spun concrete has minimal water absorption, which means the long-term use of such products in outdoor environments does not significantly reduce their strength [23,24]. Compared to steel structures, reinforced concrete elements do not require periodic maintenance, such as repainting or other corrosion protection. Furthermore, reinforced concrete structures are characterized by good aesthetics, which can be particularly important in urban areas [25].

A major disadvantage of reinforced concrete structural elements is their self-weight, which has a negative effect not only on the stress–strain state but also on their transportation and installation. Improper transporting (of the structure) may cause damage to the structure, which may make the element unusable [25,26].

In the case of tall telecommunications structures or power transmission supports, tower structures have become economically impractical compared to mast structures due to the inherent material costs [27,28]. This is especially noticeable when masts reach tens or hundreds of meters in height [1,29–31]. However, it is important to note that, for structures of a medium height in this category, they fall into the so-called “grey zone”, where tower and mast structures become nearly equivalent in terms of mass criteria.

In order to increase the technical and economic efficiency of typical towers or masts, attempts have been made to select rational cross-sections for their load-bearing elements [32–34]. However, a much greater effect can be achieved by creating/applying new structural forms and corresponding cross-sections for their elements [35,36]. Various combined structural systems are quite common, which use prestressed strut members [37,38]. Among these structural systems, it is worth mentioning prestressed stayed columns systems [37–39]. It is worth mentioning that prestressed stayed columns systems are also successfully used in structures of different purposes as bridges or roof structures [40,41]. There are also known structural solutions for building facade columns or high-rise struts, where various pre-stressed and prestressed stayed columns systems are used [42,43]. Generally, the design, strength, and buckling issues of such steel systems are analyzed [44,45]. The application of a prestressed stayed columns system not only reduces the bending moments of these columns but also their calculated/buckling lengths, thereby increasing the load-bearing capacity of the columns.

The composition of typical steel masts, as well as their behavior and calculations, have been discussed in considerable detail in many scientific publications [46–49]. Recently, there have been relatively fewer research works dedicated to masts with prestressed stayed columns systems. It is important to highlight that the behavior and calculation of spun concrete columns are complex, especially when the investigated structure is slender, and the second-order effects cannot be ignored. In such cases, material (physical) nonlinearity, geometric nonlinearity, geometric imperfections, creep, and cracking effects need to be considered [50]. It should be noted that there is a sufficient number of scientific studies dedicated to the analysis of their stresses and strains [51,52].

Please be aware that the wind effect on the mast or tower structures depends directly on the cross-sectional dimensions of their core member [53–55]. Therefore, various structural solutions that can reduce the dimensions of the core element also reduce the bending moments of it.

Unfortunately, there are not many solutions for reinforced concrete spun columns with prestressed stayed columns systems or this type of arrangement of mast, and research into their design and behavior is not yet sufficiently developed. This article discusses a new combined structural system composed of a spun reinforced concrete core, guy cables, and intermediate prestressed stayed columns elements. The behavior of such a combined structure is analyzed, taking into account the geometric and physical nonlinearity of its constituent elements. The strength and stability of the composite system with a spun reinforced concrete core shall be evaluated. The behavior of prestressed stayed columns under a transverse wind load is examined, and the influence of the pre-stressing of its elements on core internal forces and displacements is presented.

2. Innovative Structural System

2.1. Structural System and Its Components

According to Petersen [2,3], the most appropriate way to optimize/improve tower and mast structures is by reducing their self-weight and the wind load on the structure. The cross-section can be significantly reduced by using a centrifuged mast in combination with a prestressed stayed columns system. This reduces the self-weight of the system and the wind load on the structure.

The innovative structural system of the telecommunications structure consists of a solid core element, guy cables, and strut elements arranged between the guy cables and the foundation support (see Figure 1). The core of the structure is strengthened at the top with guy cables and pinned supports on the foundations.

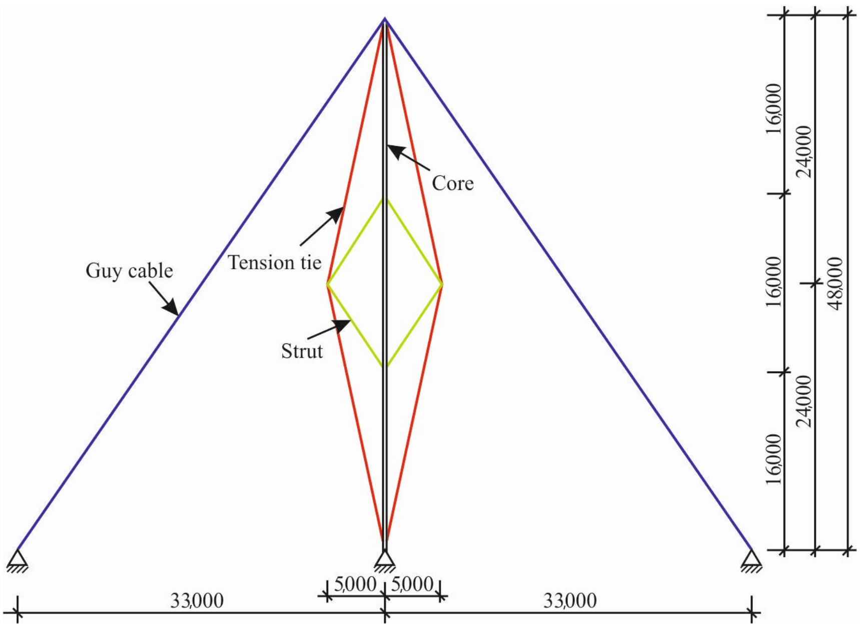


Figure 1. Innovative prestressed stayed columns system.

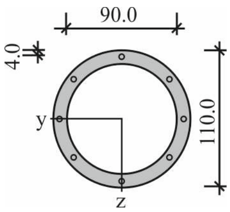
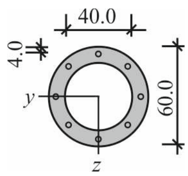
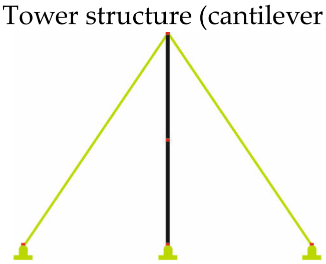
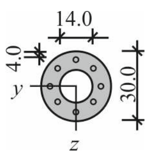
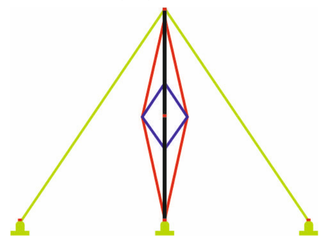
The core is the main component of this combined mast structure, and its cross-section, as well as its mass, are the largest. Therefore, it is the critical part of the structure that determines the magnitude of horizontal wind loads. As mentioned earlier, the larger the cross-section, the greater the wind impact the structure will have to resist, and vice versa. The purpose of the core is to support the telecommunications equipment at a certain height, face all environmental forces, and transmit them through the foundation to the ground.

The prestressed stayed columns system can be seen as fictitious supports with partial stiffness. These elastically flexible supports reduce the effective length, the displacements, and the bending moments of the core of the structure. In the proposed system, it is essential to set the prestressing forces of the tension tie and guy cable correctly. They shall be determined according to the stress–strain behavior of the reinforced concrete core and steel struts. The aim is to balance the bending moments in the core as much as possible, as this gives the most rational core cross-section.

Guy cables are important structural components of the mast, which, acting as partial stiffness supports, restrict the displacement and bending moments of the core element. In such a structural system, the core is subjected to compression and bending, while the guy cables receive/are exposed to only tensile forces. The struts of the prestressed stayed columns system are subjected to axial compression, and tension ties are prestressed and therefore subject only to tensile forces.

In order to compare the performance of the proposed innovative structural system in our study, we have used the other structural systems shown in Table 1.

Table 1. Structural systems and their cross-sections.

Core Diameter	Cross-Sectional Characteristics	Structural System
110 cm		 Tower structure (cantilever)
60 cm		 Mast structure
30 cm		 Innovative structural system

2.2. Dimensions, Cross-Sections, and Possible Parameters of the Spun Reinforced Concrete Core

The longitudinal dimensions of the core element made of spun reinforced concrete are often limited by production and technological constraints. Therefore, products of this type are typically manufactured up to a length of 30 m.

Spun reinforced concrete elements are typically of an annular cross-section. When compared to the full-face sections with the ring-shaped sections, they have a larger moment of inertia and lower mass. Therefore, structural elements made of spun reinforced concrete with an annular cross-section have significantly improved strength and stiffness properties under compression, bending, and torsion.

Numerical experiments were conducted to determine the performance of the new combined structural system. A standard tower and a standard mast were selected for comparison, with cross-sections also designed from spun reinforced concrete elements. The height of the structures was assumed to be the same at 48 m.

Since our investigated combined structural system is a 48 m long mast, it has been decided to produce it in two equal parts of 24 m each. The connection of the elements is intended to be rigid.

Below is Table 1, presenting the cross-sections of our investigated structures, taking into account the internal forces acting on them.

The core, which is dominated by axial compressive forces, is made of spun reinforced concrete, which has a significantly higher compressive strength than concrete of the same composition vibrated by other methods. There are guy cables, struts, and tension ties made of steel.

The materials of the structure are as follows:

* Concrete—C100/115, reinforcement—B500A, steel—S275;
* Exposure classes: XC4, XF1, WF;
* Concrete cover – C_{nom} – 40 mm (C_{min} – 25 mm + C_{Δ} – 15 mm).

3. Stress and Strain State of the Spun Concrete Element

The stress–strain behavior of spun concrete elements is unique. First, this is due to the specific physical and mechanical properties of spun concrete. Second, it is due to the specific shape of the cross-section of the elements and the arrangement of the reinforcement along its perimeter. As the size of the compressed zone in loaded elements changes, the ratio between the tensile and compressive reinforcement cross-sectional areas also varies, and the uniformly distributed longitudinal reinforcement strength along the cross-section perimeter is unevenly utilized [24].

For the calculation of the ultimate resistance of reinforced concrete structures using the method of limit states (partial coefficients), it is assumed that the element is in a state of failure and the tensile strength of the concrete is ignored. The curvilinear stress diagram of concrete in the compressive zone of the element is replaced by a conditional rectangle to simplify the calculation (Figure 2). These principles are also accepted in Eurocode 2 [56].

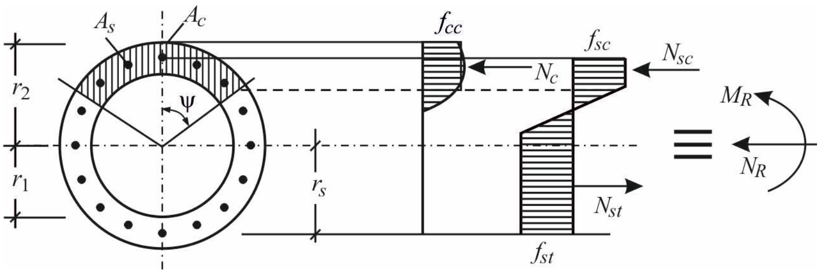


Figure 2. Modeling stresses in concrete and steel bars based on their simplified plastic distributions [52].

Unlike rectangular cross-section elements, where the longitudinal reinforcement in tension and compression zones is compactly concentrated as close as possible to the most loaded layers, in circular cross-section elements, the longitudinal reinforcement is usually evenly distributed throughout the perimeter. In the cracking stage of such elements, the stress–strain diagrams of the tension and compression zone reinforcements are curvilinear, meaning that the reinforcement strength is utilized depending on its location in the cross-section. The load-carrying capacity of the element can be assessed using the universal strength design method, presented in the Lithuanian Construction Technical Regulations (STR 2.05.05:2005 Design of Concrete and Reinforced Concrete Structures), and depends on the previously applicable design standards and rules for such structures (СНиП 2.03.01-84). Calculation by this method is quite complex and is rarely applied.

As can be seen from the illustration in Figure 2 and Equation (1), the ultimate resistance of reinforced concrete elements with an annular cross-section is calculated from the equilibrium condition where the sum of the moments caused by the external and internal forces about an axis passing through the center of the element's cross-section is equal to zero [24,51].

The parameter ψ (Figure 2), which describes the compressive part of the cross-section of the element, is found from the equilibrium condition where the sum of all axial (internal and external) forces is zero:

$$N_R = N_c + N_{sc} - N_{st} - N_E = f_{cc}A_c + f_{sc}A_{sc} - f_{st}A_{st} - N_E = 0, \quad (1)$$

where f_{cc} is the compression strength of the concrete; f_{sc} and f_{st} denote the calculated compressive and tensile strength of the reinforcement, respectively, in kN/m^2; A_c is the compressed zone of the element's cross-section area, in m^2; A_{sc} and A_{st} are the cross-section areas of the longitudinal compression or tension reinforcing bars, respectively; and N_E is the applied total compressive force [52].

The ultimate internal resisting bending moment M_R of the beam-columns of annular cross-sections (Figure 2) may be plastic and expressed as [24]:

$$M_R = 1.2r_s(A_s f_{st} + N_E) \times \left[1 - \frac{A_{st}f_{st} + N_E}{A_c f_{cc} + A_s(f_{st} + f_{sc})}\right], \quad (2)$$

It is interesting that the failure mode of our studied structure is the loss of stability due to a decrease in the element's stiffness. This is not a classical Euler, mathematically defined problem based on the theory of elasticity, which describes the buckling stress of a vertically oriented element made of homogeneous and isotropic material under a centric compressive load. This failure mode is not relevant for reinforced concrete structures because real reinforced concrete structures are subject to defects and transverse loads, and reinforced concrete is not a homogeneous material.

Long and slender reinforced concrete elements subjected to a central compressive force fail before reaching the capacity of the cross-section [57]. This is well illustrated in Figure 3 below, which shows failure modes in a compressed reinforced concrete element shown in the interaction diagram of the axial force and bending moment [50].

Figure 3 shows the failure modes of a reinforced concrete element in a diagram of the interaction between the axial force and bending moment. Curve 0 indicates failure when the bearing capacity of the cross-section is reached, i.e., failure of the concrete in compression or failure of the tension reinforcement. In the case of negligible deflection v (e.g., in the case of rigid columns), the member fails at $N_{u,1}$ (material failure, curve 1).

For a medium element slender and larger deflection v, the load $N_{u,2} < N_{u,1}$ is reached, and the increase in eccentricity from e to $(e + v)$ results in $M_{u,2} > M_{u,1}$ (material failure, curve 2).

In both cases, the failure is still based on the fact that the applied forces are greater than the material's resisting forces.

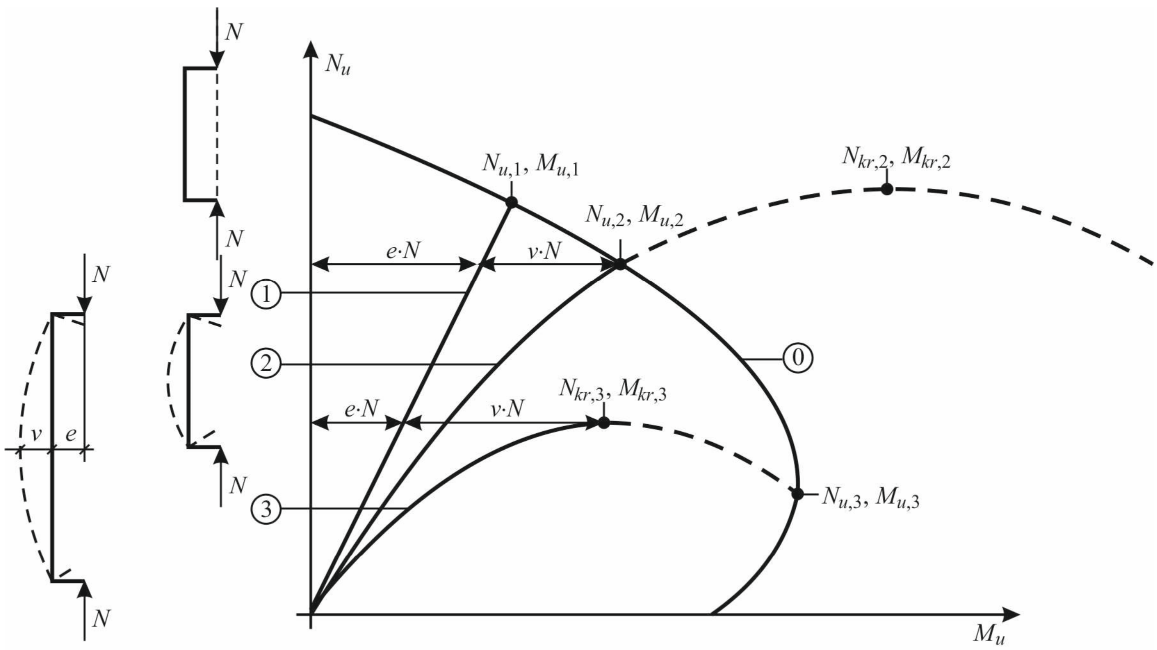
As the member's slenderness continues to increase, the additional deflection v increases too rapidly, and the bar becomes unstable at $N_{kr,3} < N_{u,2}$ without reaching the bearing capacity of the cross-section (stability failure, curve 3) [50].

The calculations are carried out using numerical methods. This process, which takes into account geometric and material non-linearity, can be described in the following sequence.

1. Determination of the internal forces by first-order analysis (bending moments and axial forces).
2. Initial selection of the reinforcement area from the results of the first-order analysis (e.g., axial force and bending moment interaction diagram).

3. Determination of the curvature k, which depends on the shape of the cross-section, the amount of reinforcement, the axial force, and the bending moment, based on the length of the element.
4. Determination of the deflection $v(x)$.
5. Determination of the secondary moment due to $N \times v(x)$ and the total moment at any location in the member.
6. If necessary: adjustment of reinforcement to reflect changes in moments.

This process continues iterating until the value of the moment calculated by second-order theory no longer changes. The amount of reinforcement chosen in the last iteration shall not be reduced later, as the reduction in the stiffness of the member will lead to a greater change in the geometry of the member and consequently in the curvature, deflection, and moments [57].



0 − Cross-section capacity curve (N_u and M_u).
1 − N–M − interaction at $v = 0$; $M_{u,1}/N_{u,1} = e$; Material failure (stress problem).
2 − N–M − interaction at $v \neq 0$; $M_{u,2}/N_{u,2} = e + v$; Material failure (stress problem).
$N_{kr,2}$ is not reached due to a previously occurring material failure.
3 − N–M − interaction at $v \neq 0$; $M_{kr,3}/N_{kr,3} = e + v$; Stability failure.
$e = M/N$, v − deflection.

Figure 3. Failure model in a reinforced concrete member in compression, represented by the axial force and bending moment interaction diagram.

4. Behavioral Analysis of a New Structural System

4.1. Numerical Analysis, Selected Object Details, and Loads

The structural analysis was based on the requirements of Eurocodes [56].

First, a linear analysis was conducted on the overall structure in order to properly select the cross-sections of the substructure elements and the prestresses in the tensile elements and guy cables of the mast. With the same initial conditions (load and geometric parameters), it is possible to adjust the internal forces (in particular, the bending moments) not only in the core element and struts but also in the other elements of the system by varying the values of the $E_{f}I_{f} / E_t A_t$ ratio. $E_{f}I_{f}$ is the bending stiffness of the core and $E_t A_t$ is the axial stiffness of the tension tie.

In the second stage, the behavior of the core element was analyzed. Since the structure under study is slender and it is impossible to ignore second-order effects, the general method according to EN 1992-1-1, 5.8.6 was chosen for the structural analysis. The accurate determination of the internal forces according to the second-order theory is meaningful with the use of software [57]. This task takes into account material nonlinearity, geometric nonlinearity, geometric imperfections (imperfections), creep, and cracking effects, which are interrelated and vary with the change in the deformability of the element.

Figure 4 below shows the loading for different types of structures. The self-weight of the elements was taken into account in the calculation of the analyzed structures, and the core was loaded with a uniform distributed wind load. To simplify calculations, the wind load is applied only to the core (Figure 4a–c). The magnitude of the wind load depends directly on the size of the cross-section. Table 2 below shows the wind values according to the size of the cross-section. Pre-stressing was applied to the tensile elements and guy cables (Figure 4d–f).

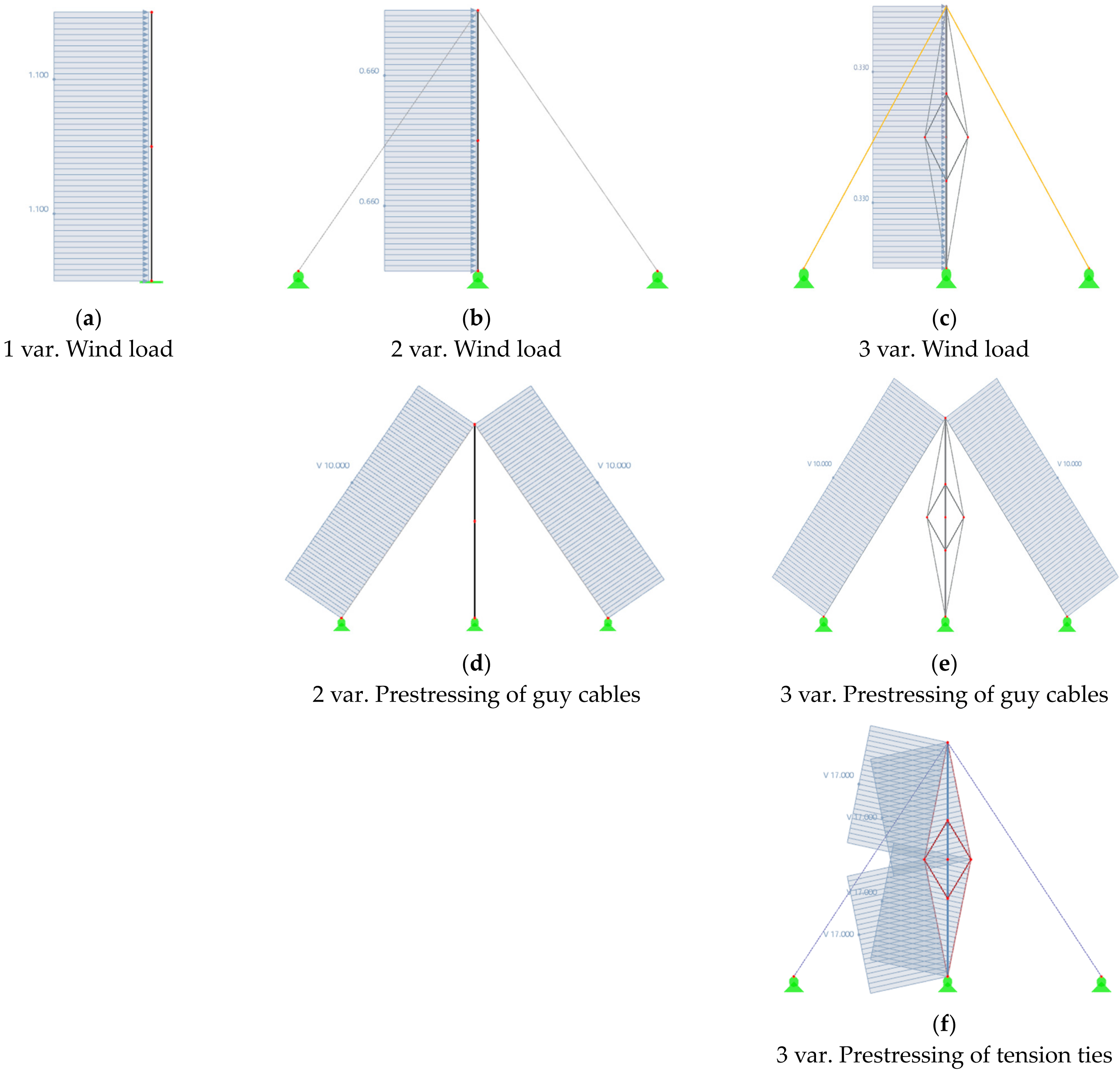


Figure 4. Loads on structural systems. (**a**) Wind load on the cantilever; (**b**) Wind load on the mast system; (**c**) Wind load on the new combined system; (**d**) Prestressing of guy cables on the mast system; (**e**) Prestressing of guy cables on the new combined system; (**f**) Prestressing of the tension ties on the new combined system.

Table 2. Core cross-sections and applied wind load.

Cross-Section of the Core	Wind Load
30 cm	0.33 kN/m
60 cm	0.66 kN/m
110 cm	1.10 kN/m

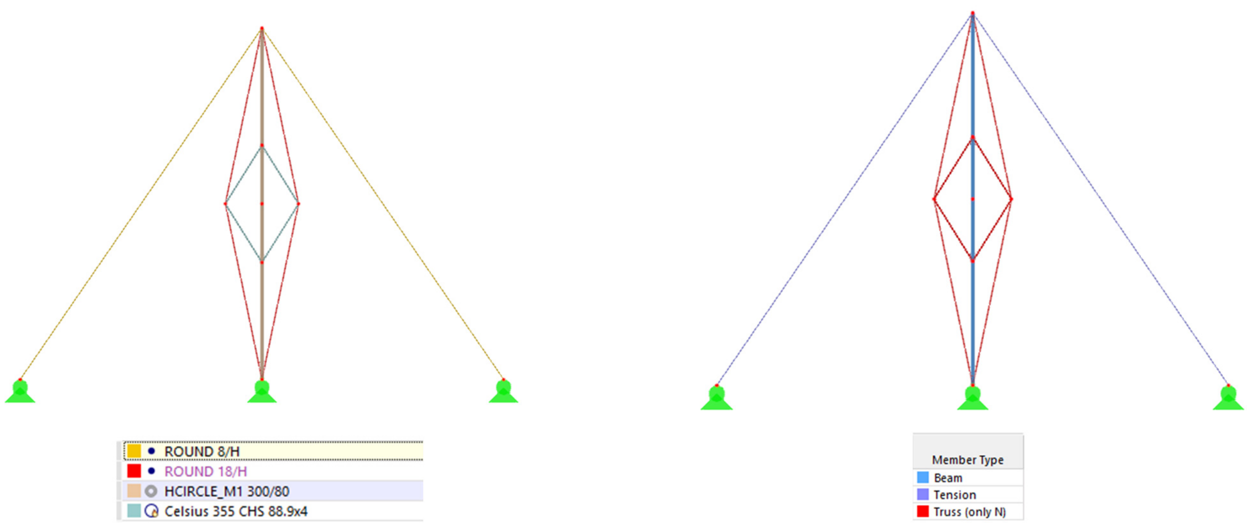
The temperature, ice loads, installation, and other special loads were not assessed.

The main issue in the behavior of the analyzed prestressed stayed columns system is the occurrence of compressive forces in the tension ties, which require larger cross-sections and, consequently, a higher mass due to the resulting buckling. Various structural systems are known to employ the pre-tensioning of certain compressive elements in order to reduce or eliminate compressive stresses within them [37]. Therefore, a pre-tension force of 17 kN was applied to the tension members. The initial tension forces in all guy cables were set to the same value of 10 kN, and the coordinates of the brackets were also set to the same. It should be noted that additional axial compressive force in the core is induced by the pre-tensioning of the tension members and guy cables.

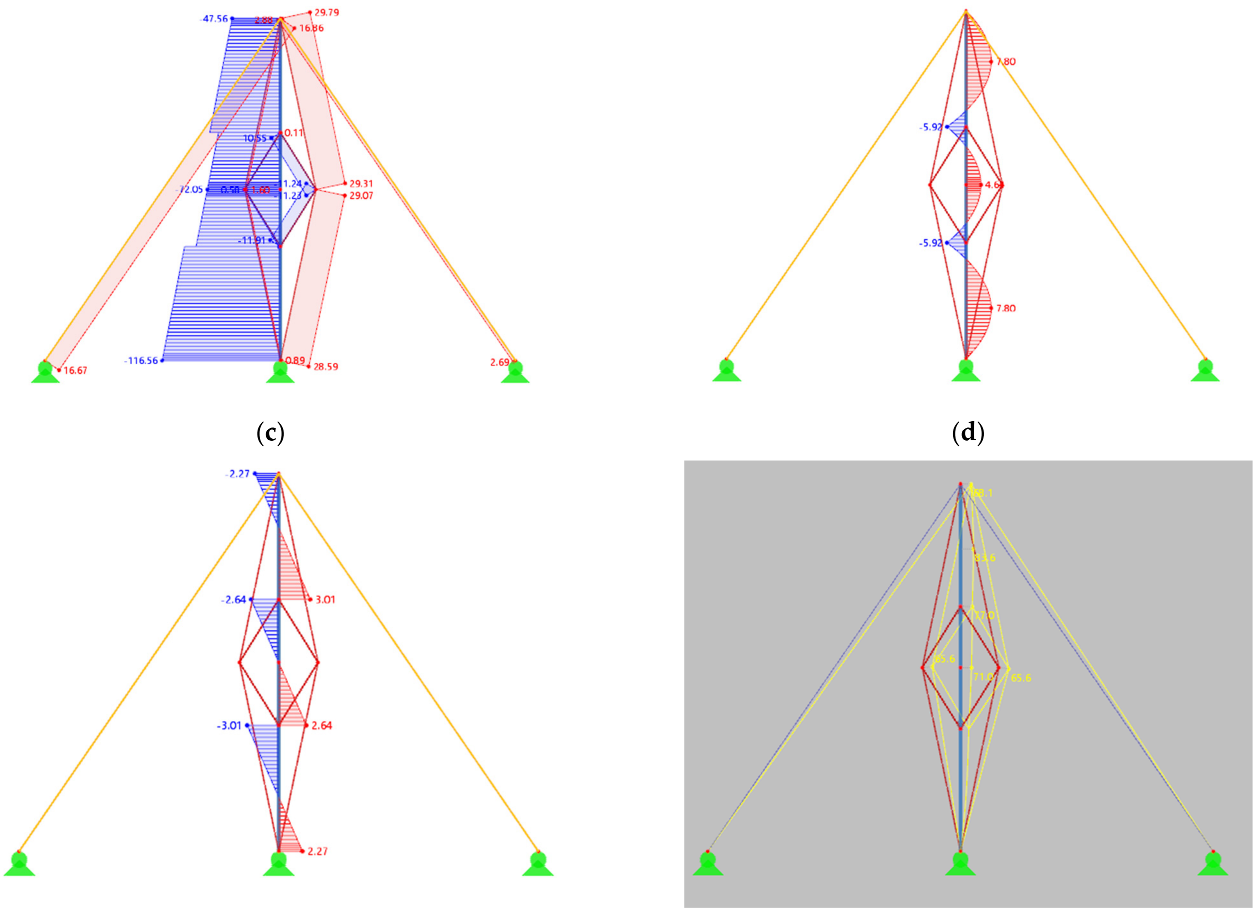
4.2. Results of Linear and Nonlinear Structural System Analysis

The internal forces (bending moments, axial forces, transverse forces) and the displacements of the structure were calculated for the loads shown in Figure 4. The calculations are carried out iteratively by varying the cross-sections of the members until the bending moments are equalized.

The new structural system is well-balanced, with appropriately sized cross-sections (see Figure 5a) and pre-tensioning forces (see Figure 4d–f). This can be observed in the moment diagram of the core (see Figure 5d). The magnitudes of positive and negative moments are nearly equal in absolute value. The elements of the tension ties and guy cables are only subjected to tensile forces due to pre-tensioning. The displacement diagram (see Figure 5f) shows a uniform distribution of displacement values along the element. Furthermore, based on the values of displacements obtained from linear analysis, the partial stiffness values of supports were determined and later used in the nonlinear analysis. Since the tower (cantilever system) and mast system are a standard structural solution, their analysis is presented only in the results of the second stage.



(**a**) (**b**)



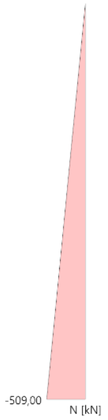
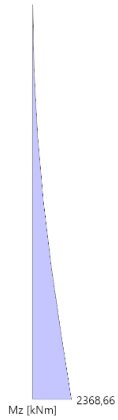
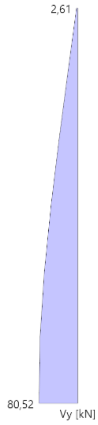
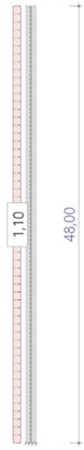
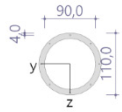
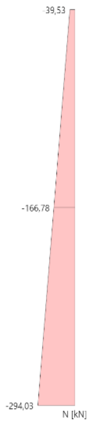
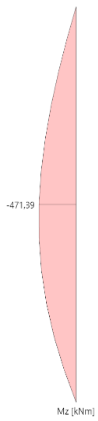
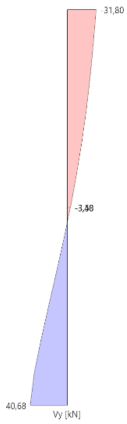
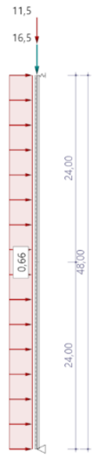
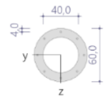
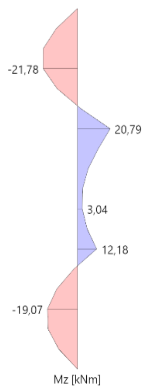
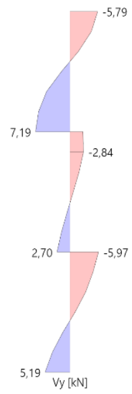
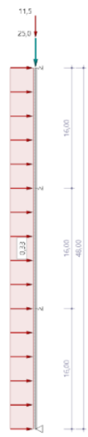
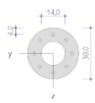
(**c**) (**d**)

(**e**) (**f**)

Figure 5. Results of the analysis of the new structural system: (**a**) Cross-sections of the structural system; (**b**) Element types; (**c**) Axial forces; (**d**) Bending moments; (**e**) Transverse forces; (**f**) Displacements.

The effectiveness of the new structural system becomes even more visible when performing the nonlinear analysis on the reinforced concrete core element. As the effective length of the element increases, the deflections in the structure grow rapidly, leading to the occurrence of cracking and a reduction in the stiffness of the element. Consequently, the secondary moments increase accordingly. If the maximum moment in the new structure reaches approximately 22 kNm (see Table 3), in the classical mast system, it amounts to 472 kNm. This can partly be explained by the double wind load due to the increased cross-section. The moment being more than 20 times smaller in the new structural scheme is a significant measure of the structural efficiency. It is also noteworthy that the new system, having the highest pre-tensioning value, is capable of achieving the lowest axial force in the element compared to other analyzed systems.

Table 3. Structural systems and internal force diagrams of the analyzed structural variants.

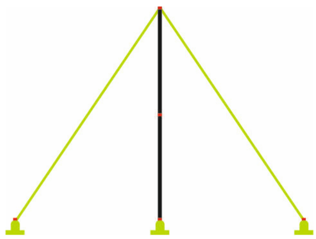
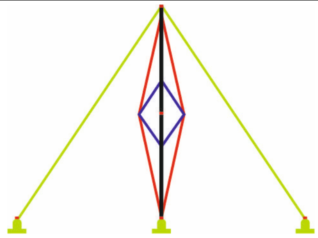
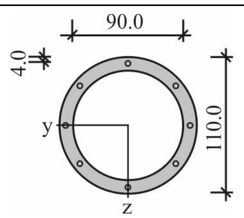
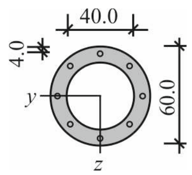
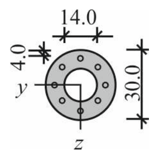
Variants	Axial forces	Bending moment	Shear forces	Structural system	Cross section
1 var.					 A_s = 133 cm²
2 var.					 A_s = 115 cm²
3 var.					 A_s = 10 cm²

The internal force analysis of the core element clearly shows that the moments are significantly lower when an innovative structural system is used. This allows for taking smaller core cross-sections and a reduced amount of required tensile reinforcement.

4.3. Technical and Economic Efficiency of the Innovative Structural System

An analysis of the variations in the studied structures clearly shows that the innovative structural system is 2.5 times more efficient in terms of mass than the standard mast structure (see Table 4, Var. 2) and 5 times more efficient than the tower structure (see Table 4, Var. 1). Additionally, the cross-sectional size of the core element decreases significantly when the prestressed stayed columns system is applied. Also, the compressive forces are considerably reduced, as the majority of the axial load is due to the self-weight of the core element.

Table 4. Technical and economic comparison of designs.

	1 var.	2 var.	3 var.
Structural system	 Tower structure (cantilever)	 Mast structure	 Innovative structural system
Cross-section			
Weight of elements	Reinforded concrete—37.700 t Reinforcment part—7.80 t	Reinforced concrete—18.85 t Reinforcment part—6.05 t Steel: guy cables—0.092 t	Reinforced concrete—6.624 t Reinforcment part—1.21 t Steel: strut—0.632 t tension ties—0.048 t guy cables—0.092 t
Total weight	37.700 t	18.942 t	7.396 t

A potential disadvantage of the new structural system is the resulting increased complexity of assembly due to the different material properties and the additional elements of the prestressed stayed columns system.

The comparison of structural variants clearly demonstrates that by combining different materials and integrating a prestressed stayed columns system into the classical mast structure, significant results can be achieved. The core, composed of a solid spun reinforced concrete element with an annular cross-section, can be reduced by more than 2.5 times according to the mass criterion.

5. Conclusions

1. A new structural solution for a telecommunication reinforced concrete mast system was presented, consisting of a solid core element, guy cables, and strut elements arranged between the guy cables and the foundation support. This structural arrangement allows for the creation of partial stiffness supports and thus reduces the effective length, displacements, and bending moments of the core of the structure. This, in turn, allows the core of the mast cross-sections to be designed in a more rational and lower-mass way.

2. A technical and economic comparison between the new structural system, the cantilever system (tower), and the classical mast variant showed the clear efficiency of the new structural system. It has been determined that by applying the prestressed stayed

columns system to telecommunication structures, the innovative structural system becomes 2.5 times more efficient than the classic mast and 5 times more efficient than the typical tower system on the mass criterion.

3. This article only focuses on the conceptual analysis of the innovative structural system. This new structure could be added to the rather narrow range of telecommunication structures in line with structures such as towers or masts. The results show that the new structure is very efficient compared to classical structures, and therefore, it is appropriate to develop the research of this work in more depth and detail. In our further research, we are planning the following:

- Establishing a methodology for analyzing the behavior of an innovative structural system, considering geometrical and physical non-linearity.
- Determining the rational parameters for this system.
- Providing an optimization algorithm for the new structure.
- Evaluating the technical and economic efficiency of the new structural system (based on the cost criterion) and the possibilities for practical applications.

Author Contributions: Conceptualization, R.K. and A.J.; methodology, R.K. and S.I.; software, S.I.; validation, R.K. and S.I.; formal analysis, R.K., A.J., and S.I.; investigation, R.K., A.J., and S.I.; resources, A.J. and S.I.; data curation, R.K. and S.I.; writing—original draft preparation, R.K., A.J., and S.I.; writing—review and editing, R.K., A.J., and S.I.; visualization, S.I.; supervision, R.K. and A.J.; project administration, R.K.; funding acquisition, R.K. and A.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data used to support the findings of this study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Smith, B.W. *Communication Structures*; Thomas Telford: London, UK, 2007; ISBN 9780727734006.
2. Halasz, R.; Petersen, C. *Abgespannte Maste und Schornsteine. Statik und Dynamik;* Ernst und Sohn: Berlin, Germany, 1970; ISBN 9783433000397.
3. Petersen, C. *Grundlagen der Berechnung und Baulichen Ausbildung von Stahlbauten*; 4., vollständig überarbeitete und aktualisierte Auflage; Springer Vieweg: München, Deutschland, 2013. https://doi.org/10.1007/978-3-8348-8610-1.
4. *TIA/EIA-222-G.5*; Structural Standard for Antenna Supporting Structures and Antennas. Telecommunications Industry Association: Arlington, VA, USA, 2006.
5. Støttrup-Andersen, U. *Masts and Towers for the UMTS Network in Sweden, EuroSteel 2005*; Druck und Verlagshaus Mainz, Aachen, Maastricht, Nederland. 9p.
6. *CSA-S37-01C 2001*; Antennas, Towers and Antenna-Supporting Structures. Canadian Standard Association (CSA): Mississauga, ON, Canada, 2001.
7. Støttrup-Andersen, U. Masts and Towers. In Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium. Valencia, Spain. 28 September–2 October 2009; Universidad Politecnica de Valencia: Valencia, Spain, 2009; pp. 127–138. https://doi.org/10.1201/b10428-69.
8. Koner, B.; Surpur, P.; Venuraju, M.T. Design Optimization of Free Standing Communication Tower Using Genetic Algorithm. *Int. Res. J. Eng. Technol.* **2018**, *5*, 981–985.
9. Remitz, J.; Wichert, M.; Empelmann, M. Ultra-Hiht Performance Spun Conrete Poles—Part I: Load-Bearing Behavior. In Proceedings of the 11th High Performance concrete (HPC) and the 2nd Concrete Innovation Conference (CIC), Tromso, Norway, *March* 2017.
10. Fouad, F.H.; Steele, J.T. A Hybrid Monopole Structure for Electrical Transmission lines. In *Electrical Transmission in a New Age, Proceedings of the ASCE Conf, Omaha, NE, USA, 9–12 September 2002*; Jackman, D.E., Ed.; ASCI: Reston, VA, USA, 2002; pp. 331–338.
11. Crissey, D.R.; Sharpless, K.L. Hybrid Pole Solutions. In *Electrical Transmission in a New Age, Proceedings of the ASCE Conf, Omaha, NE, USA, 9–12 September 2002*; Jackman, D.E., Ed.; ASCI: Reston, VA, USA, 2002; pp. 249–258.
12. Volgyi, I.; Farkas, G.; Nehme, S.G. Concrette strength tendency in the wall of cylindrical spun-concrete elements. *Period. Polytech. Civ. Eng.* **2010**, *54*, 23–30.
13. Kuebler, M.; Polak, M.A. Torsion test on spun-cast prestressed concrete poles. *PCI J.* **2012**, *57*, 120–141.
14. Dilger, W.H.; Ghali, A. Response of Spun Cast Concrete Poles to Vehicle Impact. *PCI J.* **1986**, *31*, 62–82.

15. Harling, A. Maste und Türme aus hochfestem Beton. In *Wirklichkeitsnahe Erfassung der Rissbildung zylindrischer Baukörper*; Hitzegrad Print Medien & Service: Dortmund, Germany, 2015; p. 283.
16. Wen, Q.-J.; Jing, H.-W.; Sanda, S.; Shuang, S.-S. Experimental Investigation of Mechanical Properties of Centrifugal Concrete in Circular Pipes. *J. Mater. Civ. Eng.* **2017**, *29*, 04016251**.**
17. Dilger, W.H.; Ghali, A.; Krishna Mohan Rao, S.V. Improving the Durability and Performance of Spun-Cast Concrete Poles. *PCI J.* **1996**, *41*, 68–90.
18. Fam, A. Development of a novel pole using spun-cast concrete inside glass-fiber-reinforced polymer tubes. *PCI J.* **2008**, *53*, 100–112.
19. Shalaby, A.M.; Fouad, F.H.; Albanese, R. Strength and deflection behavior of spun concrete poles with CFRP reinforcement. *PCI J.* **2011**, *56*, 55–77.
20. Raju, R.A.; Akiyama, M.; Lim, S.; Kakegawa, T.; Hosono, Y. A novel casting procedure for SFRC piles without shear reinforcement using the centrifugal forming technique to manipulate the fiber orientation and distribution. *Constr. Build. Mater.* **2021**, *303*, 124232.
21. Mina, A.L.; Petrou, M.F.; Trezos, K.G. Resistance of an Optimized Ultra-High Performance Fiber Reinforced Concrete to Projectile Impact. *Buildings* **2021**, *11*, 63.
22. Kießling, F.; Nefzger, P.; Kaintzyk, U. *Freileitungen: Planung, Berechnung, Ausführung*; 5 Auflage; Springerr-Verlag: Berlin/Heidelberg, Germany, 2001; https://doi.org/10.1007/978-3-642-56738-4.
23. Kliukas, R.; Jaras, A.; Lukoševičienė, O. Reinforced spun concrete poles—Case study of using chemical admixtures. *Materials* **2020**, *13*, 302. https://doi.org/10.3390/ma13020302.
24. Vadlūga, R.; Kliukas, R. Žiedinio ir skritulinio skerspjūvio konstrukcijų panaudojimas transporto ir energetikos statyboje. *Balt. J. Road Bridge Eng.* **2011**, *7*, 77–83. https://doi.org/10.3846/bjrbe.2012.11.
25. Kliukas, R.; Daniūnas, A.; Gribniak, V.; Lukoševičienė, O.; Vanagas, E.; Patapavičius, A. Half a Century of Reinforced Concrete Electric Poles Maintenance: Inspection, Field-Testing, and Performance Assessment. *Struct. Infrastruct. Eng.* **2018**, *14*, 1221–1232. https://doi.org/10.1080/15732479.2017.1402068.
26. Kliukas, R.; Vadlūga, R. Elektros tinklo laikančiųjų gelžbetoninių konstrukcijų patikimumo ir ilgalaikiškumo problemos. *Statyba* **2000**, *VI*, 162–168. https://doi.org/10.3846/13921525.2000.10531582.
27. Oliveira, M.I.R.D.; Silva, J.G.S.D; Vellasco, P.C.G.D; Andrade, S.A.L.D; Lima, L.R.O.D. Structural Analysis of Guyed Steel Telecommunication Towers for Radio Antennas. *J. Braz. Soc. Mech. Sci. Eng.* **2007**, *XXIX*, 185–195. https://doi.org/10.1590/S1678-58782007000200008.
28. Shea, K.; Smith, I.F.C. Improving Full-Scale Transmission Tower Design through Topology and Shape Optimization. *J. Struct. Eng*. **2006**, *132*, 781–790. https://doi.org/10.1061/(ASCE)0733-9445(2006)132:5(781).
29. Ghafari Oskoei, S.A. Earthquake-Resistant Design Procedures for Tall Guyed Telecommunication Masts. Thesis Ph.D., Department of Civil Engineering and Applied Mechanics, McGill University, Québec, Canada, 2010.
30. Gantes, C.; Khoury, R.; Connor, J.J.; Pouangare, C. Modeling, Loading, and Preliminary Design Consideration for Tall Guyed Towers. *Comput. Struct.* **1993**, *49*, 797–805. https://doi.org/10.1016/0045-7949(93)90027-B.
31. Marjanović, M.; Petronijević. M. Design of 120m Guyed Steel Mast in Alibunar According to Eurocode. In *18th International Symposium of MASE*; MASE-Macedonian Association of Structural Engineers: Skopje, Macedonia, 2019; pp. 1090–1099.
32. Guo, H.; Li, Z. Adaptive Genetic Algorithm and Its Application to the Structural Optimization of Steel Tower. In *Proceedings of the 2009 Fifth International Conference on Natural Computation, 14–16 August 2009*; IEEE: Tianjian, China, 2009; pp. 113–117. https://doi.org/10.1109/ICNC.2009.241.
33. *Recommendations for the Design and Analysis of Guyed Masts*; International Association of Shell and Spatial Structures: Madrid, España, 1981.
34. Farkas, J.; Jármai, K. *Economic Design of Metal Structures*; Millpress: Rotterdam, Holland, 2003.
35. De Souza, R.R.; Miguel, L.F.F.; Lopez, R.H.; Miguel, L.F.F.; Torii, A.J. A Procedure for the Size, Shape and Topology Optimization of Transmission Line Tower Structures. *Eng. Struct.* **2016**, *111*, 162–184. https://doi.org/10.1016/j.engstruct.2015.12.005.
36. Hosseini, N.; Ghasemi, M.R.; Dizangian, B. ANFIS-based Optimum Design of Real Power Transmission Towers with Size, Shape and Panel Design Variables using BBO Algorithm. *IEEE Trans. Power Deliv.* **2021**, *37*, 29–39. https://doi.org/10.1109/TPWRD.2021.3052595.
37. Belenya, E. *Prestressed Load-Bearing Metal Structures*; Mir Publishers: Moscow, Russia, 1977.
38. Krishnan, S. Cable-Stayed Columns and Their Applications in Building Structures. *J. Build. Eng*. **2020**, *27*, 100984. https://doi.org/10.1016/j.jobe.2019.100984.
39. Saito, D.; Wadee, M.A. Numerical Studies of Interactive Buckling in Prestressed Steel Stayed Columns. *Eng. Struct.* **2009**, *31*, 432–443. https://doi.org/10.1016/j.engstruct.2008.09.008.
40. Xue, W.; Liu, S. Design Optimization and Experimental Study on Beam String Structures. *J. Constr. Steel Res.* **2009**, *65*, 70–80. https://doi.org/10.1016/j.jcsr.2008.08.009.
41. Sun, G.; Xiao, S.; Qu, X.; Zhuang, P. Experimental and Numerical Study on Truss String Structure Considering Hysteretic Performance Asymmetry. *J. Build. Eng.* **2023**, *70*, 106311. https://doi.org/10.1016/j.jobe.2023.106311.
42. Wadee, M.A.; Gardner, L.; Osofero, A.I. Design of Prestressed Stayed Columns. *J. Constr. Steel Res*. **2013**, *80*, 287–298. https://doi.org/10.1016/j.jcsr.2012.09.021.

43. Shen, J.; Lapira, L.; Ahmer Wadee, M.; Gardner, L. Probing In-Situ Capacities of Prestressed Stayed Columns: Towards a Novel Structural Health Monitoring Technique. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **2022**, *381*, 2244. https://doi.org/10.1098/rsta.2022.0033.
44. Machacek, J.; Pichal, R. Buckling and Collapse Capacity of Prestressed Steel Tube Stayed Columns with One and Two Crossarms. *Thin-Walled Struct.* **2018**, *132*, 58–68. https://doi.org/10.1016/j.tws.2018.07.045.
45. Wu, K.; Wadee, M.A.; Gardner, L. Stability and Ultimate Behaviour of Prestressed Stayed Beam-Columns. *Eng. Struct.* **2019**, *201*, 109723. https://doi.org/10.1016/j.engstruct.2019.109723.
46. Wahba, Y.M.F.; Madugula, M.K.S.; Monforton, G.R. Evaluation of Non-Linear Analysis of Guyed Antenna Towers. *Comput. Struct.* **1998**, *68*, 207–212. https://doi.org/10.1016/S0045-7949(98)00025-X.
47. Meshmesha, H.; Sennah, K.; Kennedy, J.B. Simple Method for Static and Dynamic Analyses of Guyed Towers. *Struct. Eng. Mech.* **2006**, *23*, 635–649. https://doi.org/10.12989/sem.2006.23.6.635.
48. Shi, H.; Salim, H. Geometric Nonlinear Static and Dynamic Analysis of Guyed Towers Using Fully Nonlinear Element Formulations. *Eng. Struct.* **2015**, *99*, 492–501. https://doi.org/10.1016/j.engstruct.2015.05.023.
49. Meshmesha, Hussam M.;Kennedy, John B.;Sennah, Khaled;Moradi, Saber. Static and dynamic analysis of guyed steel lattice towers. *Structural Engineering and Mechanics, Volume 69, Number 5, March 10* **2019**, *567-577*. https://doi.org/10.12989/sem.2019.69.5.567
50. Leonhardt, F. *Vorlesungen über Massivbau, Teil 1 Grundlagen zur Bemessung im Stahlbetonbau*; 3 Auflage; Springer: Berlin/Heidelberg, Germany, 1984; ISBN 978-3-540-12786-4. https://doi.org/10.1007/978-3-642-61739-3.
51. Kudzys, A.; Kliukas, R. The Resistance of Compressed Spun Concrete Members Reinforced by High-Strength Steel Bars. *Mater. Struct.* **2008**, *41*, 419–430. https://doi.org/10.1617/s11527-007-9255-8.
52. Kudzys, A.; Kliukas, R. Precast Spun Concrete Piers of Road Bridges and Their Probability-Based Design. In *IABSE Symposium: Large Structures and Infrastructures for Environmentally Constrained and Urbanised Areas, Venice, Italy, 22–24 September 2010*; International Association for Bridge and Structural Engineering (IABSE): Zurich, Switzerland, 2010; pp. 396–397. https://doi.org/10.2749/222137810796025087.
53. Simiu, E.; Scanlan, R.H. *Wind Effects on Structures: Fundamentals and Applications to Design*, 3rd ed.; Wiley Interscience: New York, USA, 1996; ISBN 978-0471121572.
54. Sunaryo, D.; Putra, A. Design the Guyed-Tension Structure of the Influence of the Wind Load on the Radio Antenna Height of 40 Meters. *Int. J. Sci. Eng. Res.* **2020**, *11*, 344–355.
55. Ballaben, J.S.; Guzmán, A.M.; Rosales, M.B. Parametric Studies of Guyed Towers Under Wind and Seismic Loads. *Asoc. Argent. Mecánica Computacional. Mecánica Comput.* **2011**, *XXX*, 1019–1032.
56. *DIN EN 1992-1-1*; Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings. Deutsches Institut Für Normung: Berlin, Germany, 1992.
57. Wommelsdorff, O.; Albert, A.; Fischer, J. *Stahlbetonbau—Bemessung und Konstruktion—Teil 2*, 8 Auflage; Werner Verlag: Neuwied, Deutschland, 2009; ISBN 3-8041-5026-8, 978-3-8041-5026-3.