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DYNAMIC EFFECTS IN TALL STEEL STRUCTURES WITH DIFERENT PURPOSES

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Abstract

In the initial stages of structure design, precisely defining the loads that a structure must support is of utmost importance. While structures are generally designed to handle live loads effectively, they must also be capable of accommodating other types of loads. The dominant types of loads that a structure must withstand can differ based on the materials used and the type of structure.

For instance, steel structures, which have a lower self-weight, are particularly susceptible to horizontal wind loads. On the other hand, reinforced concrete (RC) structures, due to their higher self-weight, are more affected by horizontal seismic forces. Despite these differences, wind loads are a significant factor for high-rise buildings regardless of whether they are made of steel or reinforced concrete.

This paper explores the impact of wind loads on tall structures, with a particular focus on the role of shape coefficients. It provides a comparison between values obtained through experimental measurements and those specified in regulatory standards. Additionally, the paper includes a practical analysis of various types of structures to illustrate how wind loads affect different designs.

By examining these aspects, the paper aims to shed light on the effectiveness of current regulations and practices related to wind load calculations. It will discuss any discrepancies between experimental data and theoretical predictions, and offer insights into the implications for engineering practice. This analysis is intended to enhance the understanding of wind load effects on high-rise buildings and inform future design approaches.

Keywords: wind, structure, shape coefficients, dampening, steel structures.

1. History

Designing the proper wind speeds for the design of structures is a first and critical step towards the calculation of the wind loads. Moreover, it is also the most inaccurate and uncertain step of the design process for the design of wind loads, and requires a static analysis of written wind speeds over a period of time.

In the 1930es, the dominant school of thought suggested using a symmetrical bell shaped distribution (a Gaussian distribution) to display the extreme wind speeds in order to have a base for the design of the long-term wind speeds which will be used for design. However, this manner for the calculation of the wind load does not take into account earlier theoretical research which take into account the borderline shapes of distribution of the biggest (or smallest) value in a fixed sample. The identification of the three types of distribution of extreme values plays a great role in the development of the probabilistic approach in engineering in general.

The analysis of wind gusts lags behind when using extreme values for wind design speeds. As a result of this circumstance and a number of studies conducted in the 1950s and 1960s, some nations adopted the wind gust principle in accordance with the extreme value analysis as a method of wind speed prediction. Research in the 1960s led to the rapid adoption of probability and statistics by many engineers, which form the foundation of the current method for calculating wind loads.

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Even though, the structure failures of the 1970s and 1980s (the Tracy cyclone in Australia and the strong winds exceeding 60 km/h in Europe) demonstrated that the actual wind loads were significantly higher than those that were planned.

Therefore, additional research was conducted in the following areas:

- errors in gathering data on written value samples (mostly from less than 50 years ago)
- categorizing information from various storm types.

In general, the design's integration of probabilistic methods developed concurrently with their application in wind engineering. This research and development theory, also referred to as the theory of load bearing capability, has been used in design since the 1970s.

2. Introduction

The wind load on structure is very unpredictable and infrequent because of the turbulent nature of the wind speeds. Consequently, a dynamic resonant response of the structures, or segments of them, with a natural frequency below 1Hz could appear. Different wind intensity levels at different times are highlighted by the structure's resonant response. As a result, the resonant response of the structures is dependent on both the wind gust that is occurring at the moment and the wind gusts that have preceded the monitored moment.

The primary focus of the work in this section is upon that the analysis of the dynamic response of the structures to wind, as well as some basis of aero-elasticity and fatigue effects on the structures and the method of equivalent or effective distribution of the static load.

3. Principles of dynamic response

As previously mentioned, the ability of wind loads to vary in terms of force, pressure, and speed can result in a considerable resonant vibration of the structures or their elements if the damping and natural frequencies are low enough.

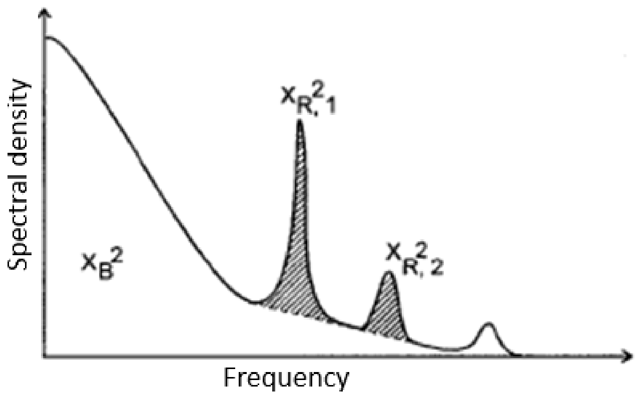

Figure 1. Density of the spectral response under wind loading

There should be a difference between the resonant dynamic response and the background fluctuations that the structure experiences. The density of the spectral response under wind loading is plotted in the figure 1. In reality, the mean square of the fluctuating response is represented by the surface of the entire curve.

The graph's hatched area represents the first two modes' resonant response. Low frequencies (generally under the lowest natural frequency) make up the majority of the background response. In fact, it has the largest percentage of wind loading in the wind direction and produces the highest yield in the graph above. With this in mind, the resonant response will become increasingly important after a certain amount of wind loading, to eventually become the dominant effect. This effect happens when the structures are high and slender compared to their cross section, and their mode becomes smaller.

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Figure 2 (a) shows the characteristics of the data at a specific time period of the forces that act in the wind load direction. The figure 2 (b) shows the response of a structure with a high frequency of natural oscillations, while figure 2 (c) shows the response of a structure with a low frequency. It is evident from the graphs that the resonance, as well as vibration component, appears to have a negligible impact on the structure response. The resonance's close proximity to the time variation of the forces acting on the structure explicitly states. The resonant response of the first mode is crucially significant in the second scenario, while the response of the higher modes can be simply ignored.

In actuality, the large percentage of the structures we come across during the design process would figure under 2 (b) and would not respond at all, or only minimally, to a resonant dynamic response. Furthermore, it is common practice to avoid designing buildings with a natural mode lower than 1Hz. In addition, the damping, the aerodynamic characteristics, and the structure itself all affect the amount of the dynamic response.

For illustration, a dynamic response should be used to influence high voltage power lines, which typically have a natural mode well below 1Hz. But because of their extremely high aero dynamical damping value (roughly 25% of the critical), the resonant response is significantly reduced. Because of their low mass, the lattice and truss structures in this impact have a bigger coefficient of aero dynamical damping. Furthermore, the sorts of connections used for such structures enable the emergence of an absorption mechanism in the connections, whereby the forces from the wind loads are dissipated through friction, thereby reducing the resonant response.

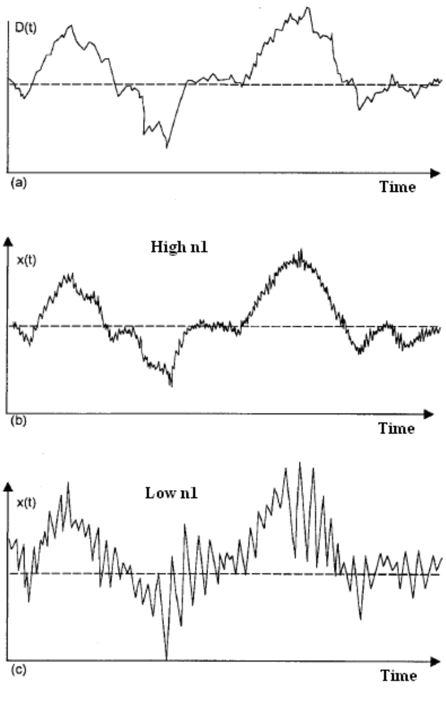

Figure 2. Time response (a) wind load, (b) high period structure response (c) low period structure response

When a resonant response occurs, it may temporarily result in intricate interactions that, when paired with the structure's deflections, may give rise to extra aero-elastic forces. In severe situations, such as the Tacoma Narrows Bridge, this scenario may lead to a structure failure. These are rare scenarios that should, of course, be avoided. However, the dynamic coefficient is superposed over the dominant mean and the background fluctuating response in most cases where the structure has a significant resonant dynamic response.

The primary and most evident cause of the fluctuating wind load is the wind's turbulent flow, which results from the hear effects that occur when the wind passes over non-flat areas of the terrain. The formation of vortexes behind structures with cross sections that produce higher aerodynamic resistance (such as square or circular cross sections) is another main reason of the fluctuating load.

To balance the wind forces, the opposing forces inside the structure will first come into play if it can be altered in a way that produces a dynamic reaction.

The primary offenders are:

- The internal forces are proportionate to the structure's mass.
- The damping or energy-absorbing forces are proportional to speed in their purest form, although this is not always the case.
- Rigid or elastic forces that are proportionate to the structure's deflection

Regarding mostly horizontal loads, it is crucial to note the primary differences between the dynamic responses of structures to earthquakes and wind. The following are the primary differences between these forces:

- Earthquakes are regarded as incident loads since they have a substantially shorter duration of impact than wind loads.
- An earthquake's dominant frequency is typically 10–50 times higher than that of a full-fledged storm. This explains why some structures up to a certain height can react significantly to wind loads while remaining totally inert to seismic loads.
- There will be a direct correlation between the height of the structure and the movement of the earthquake load along it. However, the wind load will be partially correlated because of the vortices that form along the height of the structure.

The figure 3 also illustrates the range of frequencies that cause structures to be excited by earthquake and wind loads.

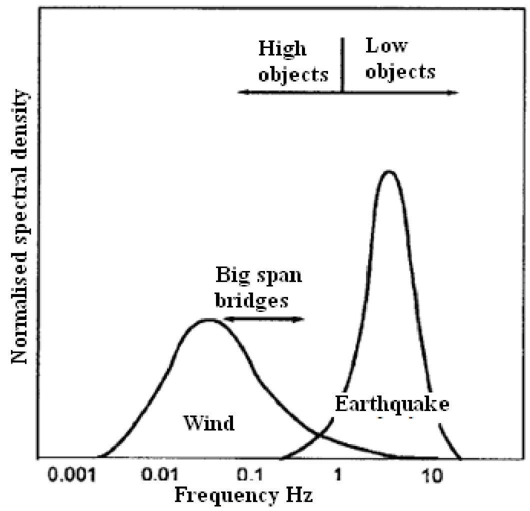

Figure 3. Dynamic response of structures to wind and earthquake loads

4. Calculation

A comparative analysis of multiple structures made of different materials (steel and RC) and for various uses (a 50m mast, a 200m industrial chimney, a 30m radar, and 30m silos) was conducted for the purposes of this work. Under the influence of wind loads, the elements were analyzed both as linear and shell elements, taking into account the shapes of the structure as well as the used method to determine wind intensity. Of course, in order to obtain data about the main loads in the structures dimensioning, the structures were loaded with additional loads that are typical for their respective purposes.

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For all the structures at hand, the analysis has been done with the aid of the program SAP2000 according to EUROCODE2.

4.1. Analysis of mast elements

The 3D model used for determining of the influence of the loads on the use of the structure, was made of shell elements, of which the dimensions are shown in Table 1. In the calculation done in tower, frame elements were used.

From the results obtained, shown on figure 4, one can conclude that the horizontal wind loads W have a dominant role in the use of the mantles from the chimney, which entails 80%. On the other hand, the seismic loads Sx and Sy have an insignificant influence of 5% and 10%. The effect of the vertical loads is inversely proportional to the mantle thickness, where the mantle thickness of 5mm takes only 30% in the participation of the elements use.

Table 1. Mast's mantle thickness

dp=9mm – Mantle thickness 9mm (segment 0m-10m)
dp=8mm – Mantle thickness 8mm (segment 10m-20m)
dp=7mm – Mantle thickness 7mm (segment 20m-40m)
dp=5mm – Mantle thickness 5mm (segment 40m-50m)

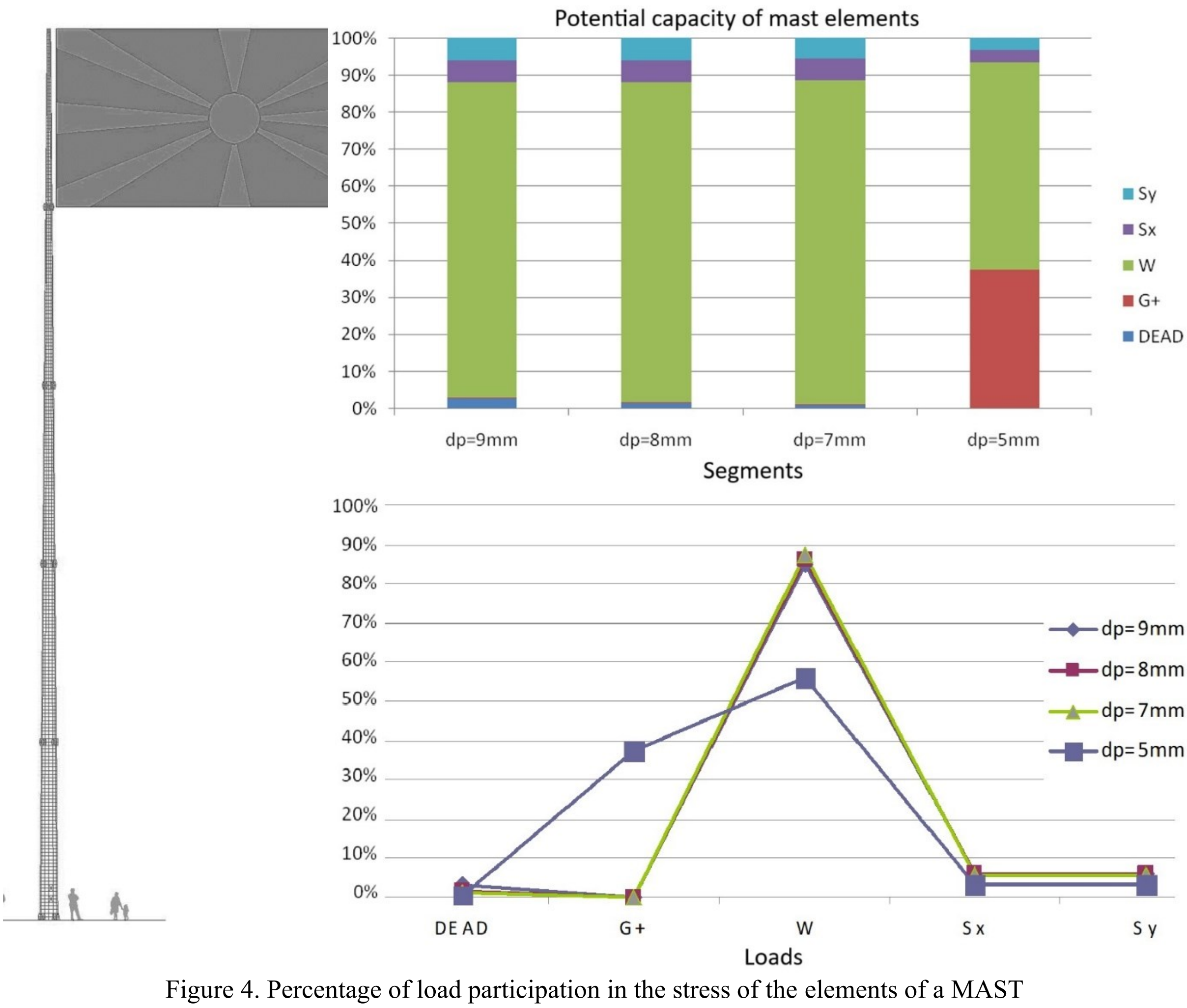

Figure 4. Percentage of load participation in the stress of the elements of a MAST

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4.2. Analysis of radar tower elements

In the static analysis for radar tower, the elements are modeled as frame elements. In this static calculation own weight of the elements has been applied directly through the program and the other loads were applied manually – the other permanent loads (the radar itself); operational and survival wind loads; temperature and ice coating. In table 2 the naming of the constructive elements is shown.

On figure 5, the results of the analysis, i.e. the usage of the elements in percentages is shown, for every constructive elements for every different load case. From this analysis it can be concluded that the biggest percentage of the use of the constructive elements entiles to the horizontal wind loads W_{maxX} и W_{maxY}. On the other hand, the bigger use from vertical load cases is displayed only in the columns(C 24-30).

Table 2. Radar tower elements

C 0-12 – Column 0-12	HD – Horizontal beam Down
C 12-24 – Column 12-24	HU – Horizontal beam Up
C 24-30 – Column 24-30	BD – Bracing Down
	BU – Bracing Up

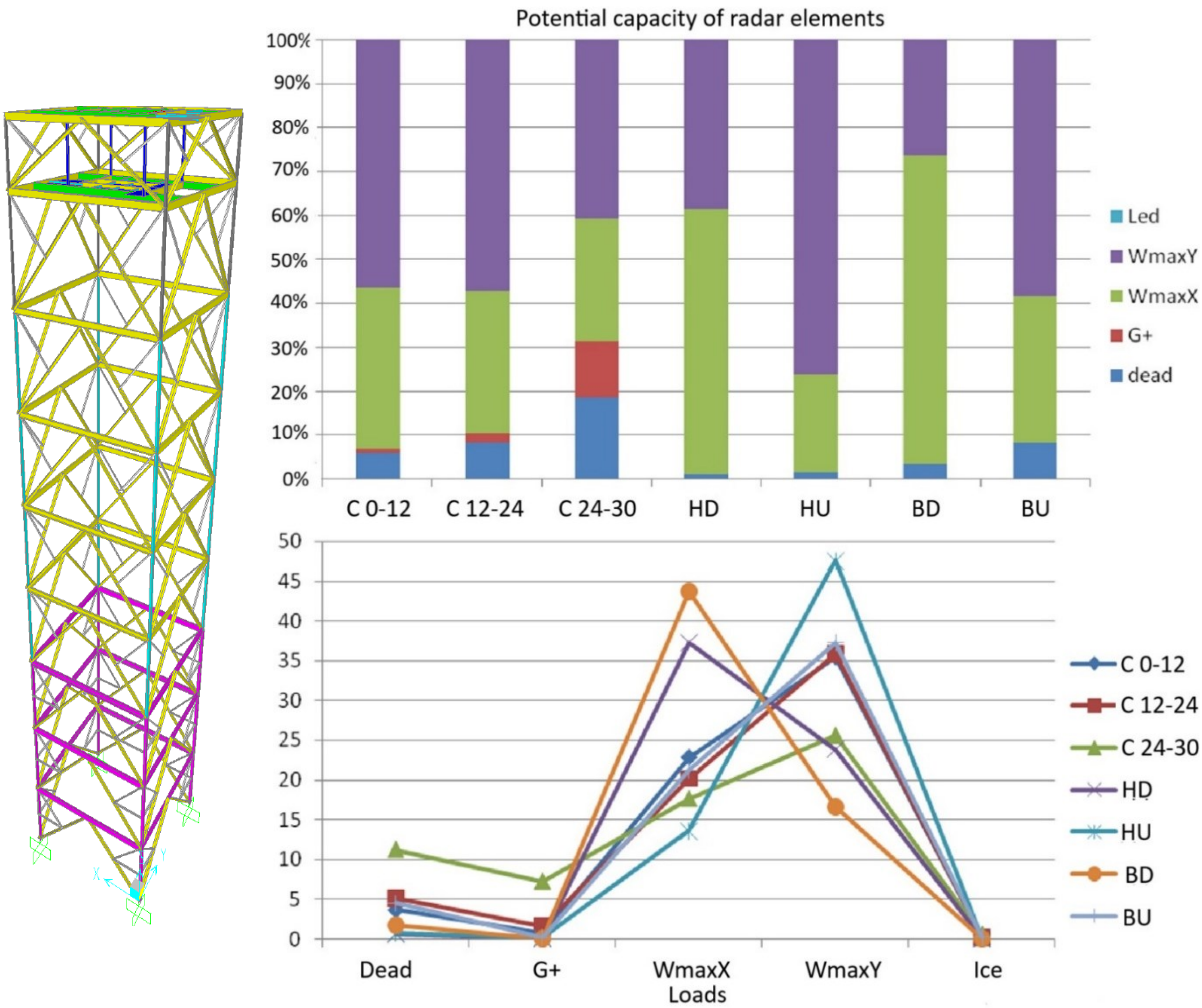

Figure 5. Percentage of load participation in the stress of the elements of a RADAR TOWER

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4.3. Analysis of silo elements

The mathematical analysis model is designed as a spatial system made of frame elements (table 3), with joint connections with the foundations, while the silos are modeled as shell elements (table 4). In this analysis case, different constructive elements have different behavior on outside influences. On figure 6 the percentage use of the steel elements of the structure are displayed for different load cases.

On the mantle of the silo (figure 7), the horizontal dynamic pressure has a dominant influence on the use of up to 80%, and as such (albeit reduced) again as dominant is transferred to the load bearing structure.

Table 3. Silo elements

ECD – End Column Down	MCU – Middle Column Up
ECU – End Column Up	BD – Beam Down
MCD – Middle Column Down	BU – Beam Up
Mantle thickness 8mm and 6mm	B – Bracing

Table 4. Silo's mantle thickness

dp=9mm – Mantle thickness 9mm (segment 0m-10m)
dp=8mm – Mantle thickness 8mm (segment 10m-30m)
dp=7mm – Mantle thickness 7mm (segment 30m-40m)
dp=5mm – Mantle thickness 5mm (segment 40m-50m)

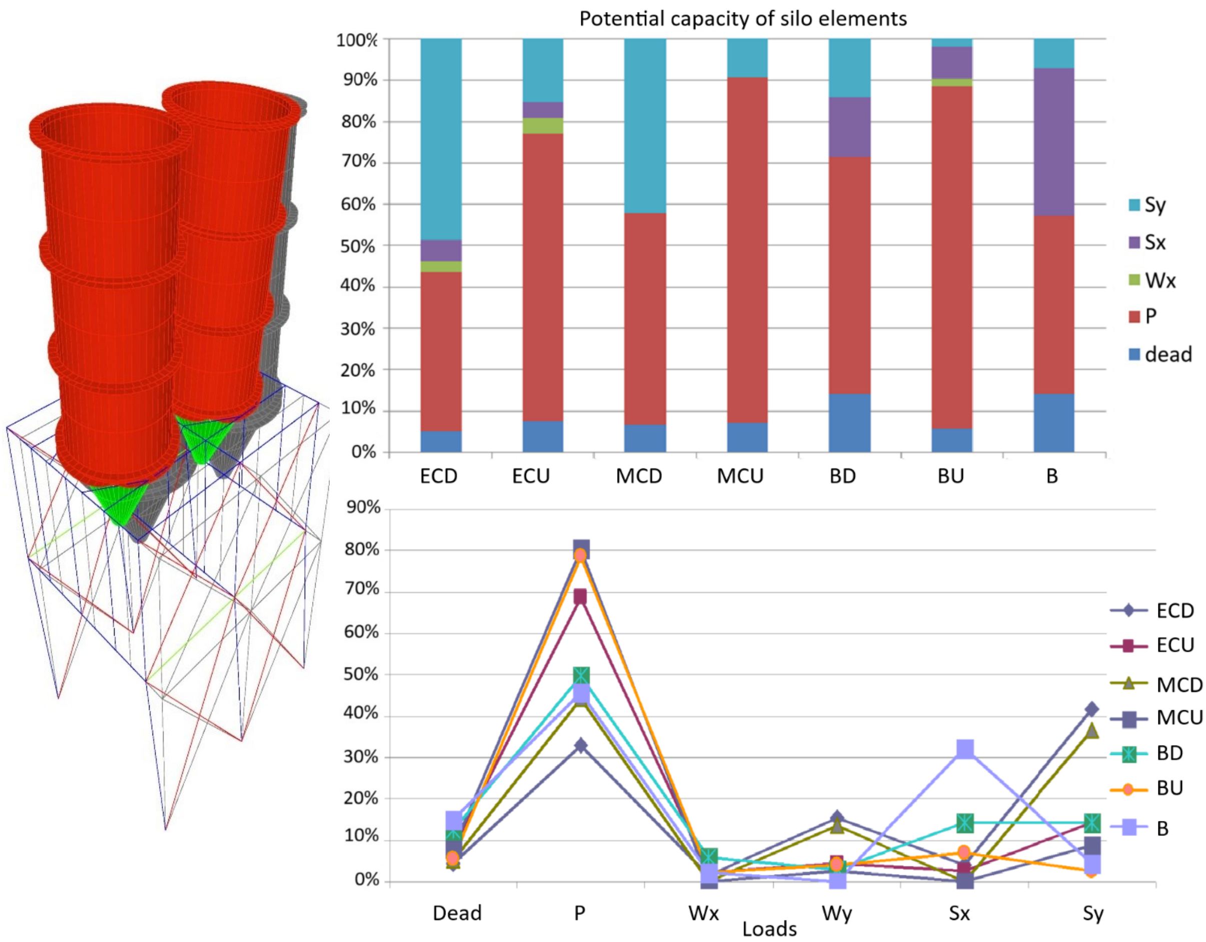

Figure 6. Percentage of load participation in the stress of the elements of a SILO

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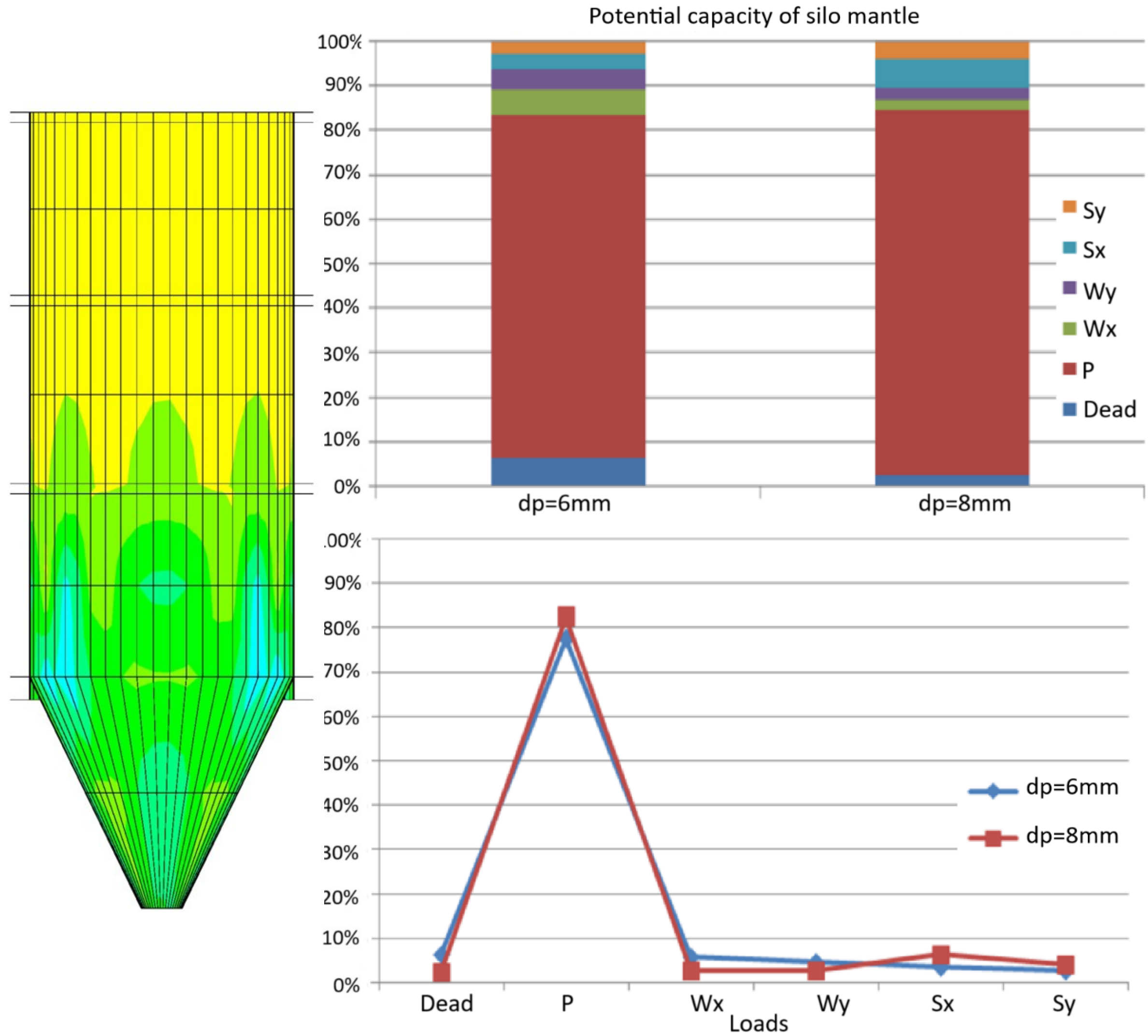

Figure 7. Percentage of load participation in the stress of the elements of a SILO MANTLE

4.4. Analysis of chimney elements

All chimney elements are with 30cm thickness, but in order to achieve finer transparency, the chimney is divided in segments in regard with the different wind loads along the height of the chimney. From the analysis one can conclude that as the height of the chimney increases, the influence of the dynamic horizontal loads is more dominant, with the seismic load of up to 50% in the overall use of the load capacity of the elements, and on second place is the dynamic wind load with 30% (figure 8). With the decrease of the height of the chimney and the increase of the thickness of the mantle, the influence of the vertical loads in the overall use of the elements increase, but only up to 15%.

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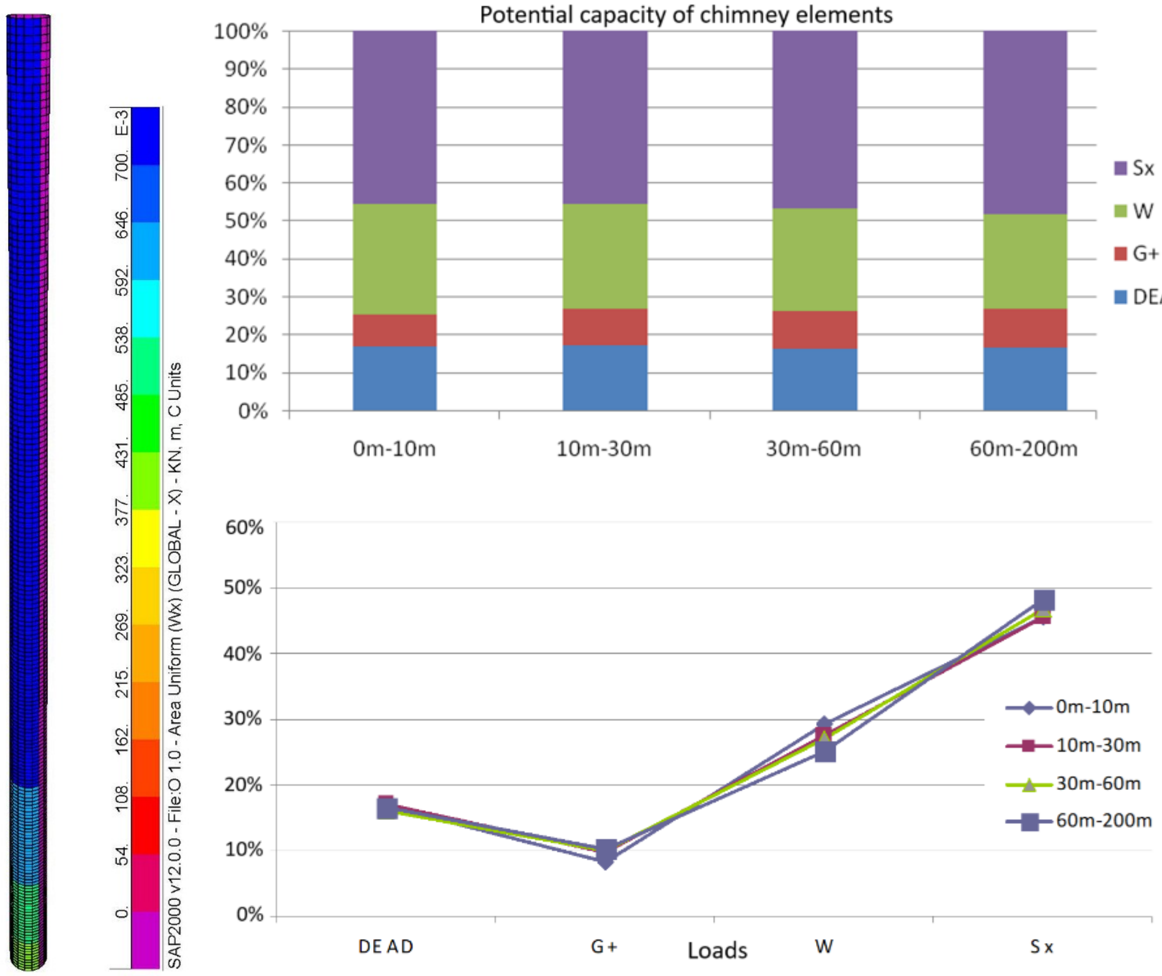

Figure 8. Percentage of load participation in the stress of the elements of a CHIMNEY

5. Conclusion

The following conclusions can be drawn from the experimental and the theoretical research:

- An overall analysis of the entire structure with all of its elements and loads should be preferred over generalizing the wind load on the overall design of the elements for individual objects (such as columns, beams, girders, etc.). Specifically, the mantle will experience significant deformations if only empty silos with wind load are examined. On the other hand, the loads cancel each other out if the mantle is examined with wind and live load.
- Compared to reinforced concrete, the wind load has a far greater impact on the design of steel structural elements. Specifically, steel structures are far more vulnerable to wind loads than concrete ones (which are more vulnerable to seismic loads) because of their small mass. However, the wind load effect can be minimized to be less than the seismic load effects when choosing the constructive solution for a steel structure.
- Additionally, the structures can be significantly stabilized with minor interventions. The silo mantle, in particular, shows a rapid increase in stiffness after adding horizontal rings as stiffeners (just 2% more material), which decreased the material's deformation and stress.
- The stress of the constructive elements also depend by the type of structure, whether it is open or closed. The material experiences less stress in closed objects than in directly exposed elements of open structures because of the interaction between the cladding and the constructive elements.

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- The height and width of a structure determine how the wind affects it. In other words, wind increases the stress on tall building's materials than it does on low, wide structures. According to the previously mentioned calculations, the mast had the highest material stress while the silos had the lowest. However, compared to open structures (like radar towers or power lines), closed structures, where the surface for wind load application is precisely defined, can be designed with much more precision and certainty. The effect that ice and snow deposits have on the increase of the surface for wind loads is one topic that was not covered in this work and that provides room for additional study. Specifically, as was the case with numerous power lines during the winter of 2012–2013, these deposits have the potential to drastically increase the surface area for wind loads and even completely change the structure from an open to a closed type, which can lead to failure. The stress would have been lowest in a typical warehouse, according to the analysis.

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