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Dynamic Analysis of a Slender Building Using Two Parallel Spectral Analysis Methods

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Abstract **-** Wind action is crucial in the design of slender and flexible structures, as both height and wind load can induce worrisome dynamic responses in such constructions. The Paraguayan Standard NP 196 addresses wind action and recognizes its effects on rigid structures but lacks an analysis that includes dynamic effects for buildings susceptible to this wind action. International regulations such as the Euro Code 1: “Actions on Structures” incorporate the dynamic effect of wind through a Gust Response Factor, analyzing the theoretical spectrum of the fluctuating wind component. The objective of this study was to apply two parallel spectral analysis methods, Davenport and Galindez, to analyze a representative slender structure and evaluate the susceptibility of the gust response factor. This assessment was conducted based on the methodological variables proposed in the literature. The research indicates that the difference between both methods lies in the cross-correlation coefficient and the application of the equivalent static force in wind load calculations, with Davenport's method being suggested for its simplicity, or alternatively, Galindez's method which yields more conservative estimates of the equivalent static force.

Keywords**:** Wind, Dynamic Effect, Spectral Analysis, Slender

1. Introduction

The rapid urbanization and advancements in engineering have fueled a high demand for commercial and residential spaces, leading to the vertical expansion of structures. While these innovations offer numerous benefits, they also present significant challenges arising from increased structural flexibility, slenderness, lack of sufficient damping, and low natural frequencies [1]. The influence of dynamic wind action on slender and/or flexible structures is of paramount importance, and its comprehensive analysis is essential to ensure the safety, integrity, and service life of buildings [2]. The Paraguayan standard NP 196: “Wind Action on Constructions” [3] considers wind speed as the sum of a mean velocity component and a fluctuating velocity component, commonly referred to as a gust. These gusts can induce significant deflections in flexible and slender structures. However, the standard mentioned lacks a design methodology for calculating the dynamic effects of wind loads on slender and flexible buildings, which are highly susceptible to these effects.

Mathematically, it is typical to model wind as consisting of two components, with respect to its velocity: a constant component and a fluctuating irregular component. The constant velocity component gradually increases with height, while the fluctuating component exhibits a random variation that cannot be treated deterministically. Instead, the analysis of the fluctuating component requires the use of probability theory and statistical averages. The need to express the properties of turbulence in statistical terms was first recognized by G. I. Taylor [4], through a seminal paper discussing diffusion in the atmosphere. Taylor's theory was subsequently expanded upon by himself in 1935 [5] and further developed by Von Karman and Tsien in 1938 [6]. The spectrum of a turbulent velocity component is defined by the resulting energy distribution as a function of frequency. This energy is equivalent to the variance; therefore, the total variance due to fluctuations across various frequencies directly defines the spectrum [7].

The statistical approaches that enable the prediction of a structure's response to wind are schematically illustrated in Fig. 1. Relationships exist between velocity, force, and gust response, both in the time domain and the frequency domain. Having the velocity spectrum as input data, the force and response spectra of the studied structure can be obtained through the implementation of aerodynamic admittance and mechanical admittance functions, respectively [7]. While this theory applies to systems related to a single degree of freedom, it has been extended to various complex structures with multiple degrees of freedom, susceptible to being excited in various modes of vibration [8], [9].

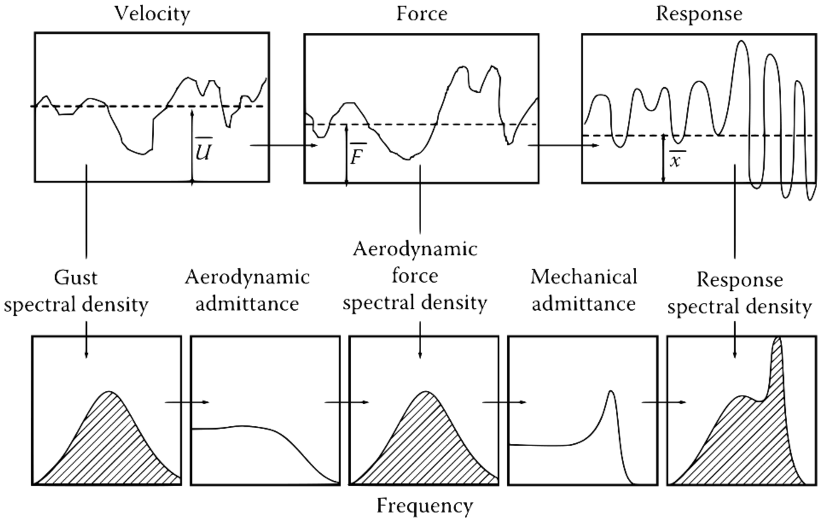

Fig. 1: Statistical approach to determining the response of a structure to wind action [10].

The gust response factor, G, proposed by Davenport [11] can be described as the ratio of the expected maximum response of a structure over a defined time period (e.g. 10 minutes) to the average response, within that same defined time period. This approach has led to the estimation of equivalent static wind load by the multiplication of mean wind with the gust response factor mentioned previously, and has been adopted as a standard method in many design codes and standards worldwide such as [12], [13].

The research aims to analyze the suitability of two parallel methodologies found in the literature for assessing the dynamic effect of wind on slender and flexible structures. The two methodologies studied were proposed by Davenport and Galindez, respectively. The primary objective was to identify the main cause of the discrepancy in the gust response factor between these two methods. Both methods are fundamentally based on the spectral analysis of wind, employing procedures to calculate the dynamic amplification factor of the corresponding structure.

2. Methodology

In order to compare Davenport and Galindez methods, a representative high-rise building was selected. Subsequently, the calculation of the dynamic wind effect acting on the structure considered was carried out by applying the two parallel spectral analysis methodologies. Finally, a comparison of the values obtained through both approaches was conducted, contrasting their influences, with the aim of obtaining equations that adequately represent the phenomenon being investigated.

2.1. Description of the structure and the environment

In this study, a representative residential structure from Cachuço's [14] research was selected for analysis, as shown in Fig. 2. The building is characterized by a reinforced concrete framework comprising slabs, pillars, beams, and substantial screens. Standing at an elevation of 81 meters, it boasts a floor plan measuring 25 meters in the x-axis and 12 meters along the y-axis. With 27 floors above ground, each floor is 3 meters high, resulting in a total typical floor area of 319.4 m^2. The total mass of the building, estimated at 7290 tons, is evenly distributed at 270 tons per floor. This choice was made due to the building's dynamic characteristics and its representation of common features found in high-rise reinforced concrete structures throughout the Paraguayan capital.

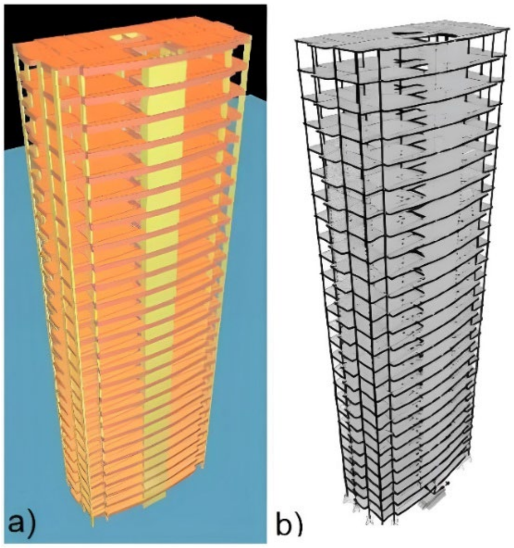

Fig. 2: 3D view of the analyzed building [14].

For the study, the location of the analyzed structure was considered according to Category II: “Open or approximately level terrain, with few isolated obstacles such as trees and low-rise construction”, as established in NBR 6123 [15]. Terrain roughness coefficients were determined by the Category II previously stated. A discrete model of the structure was considered using precise floor location information of the building, as illustrated in Fig. 3. This resulted in the subdivision of the structure into discretized points, with 27 separate nodes spaced at 3-meter intervals. Each node was assigned a point mass of 270 000 kg.

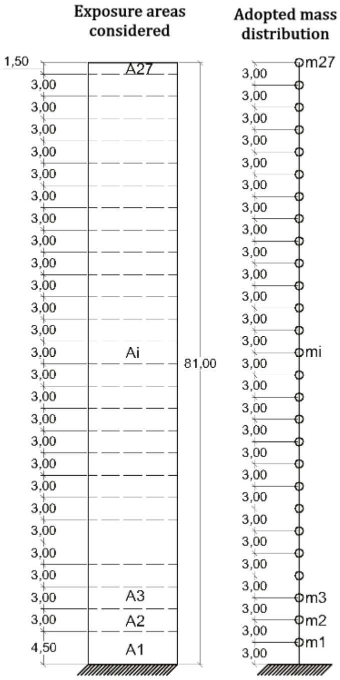

Fig. 3: Discretized model of the structure [16].

The natural frequency of the building was determined to be 0.339 Hz, pointed out on Fig. 4. Vibration modes were analyzed using SAP2000 software, revealing modes of translation along the y-axis at 0.339 Hz and the x-axis at 0.341 Although these frequencies are closely aligned, the primary natural frequency indicates a lesser rigidity along the y-axis. thorough analysis of the building, categorized as a framed structure with reinforced concrete screens designed to absorb horizontal forces, unveiled a critical damping ratio ζ equal to 0.015.

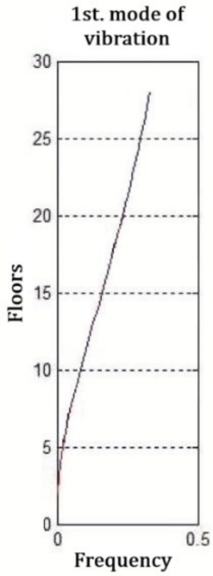

Fig. 4: Vibration mode of the building [16].

2.2. Reference heights for spectral analysis

Davenport [11] defines 'G' as one value associated with a specific building. However, various authors argue that this value depends on the elevation considered, indicating it is not constant as established by Davenport. Simplification for calculation codes, such as the American standard ASCE/SEI 7-22: "Minimum Design Loads and Associated Criteria for Buildings and Other Structures" [13], and "Guidelines for Electrical Transmission Line Structural Loading" [17], adopts a single 'G' value for each structure. In this regard, several authors proposed adopting a reference height at the wind pressure center. Solari [18] recommended using 2/3H, where H is the total height of the analyzed building. Davenport [11] used the total height H of the building, while Franco [19] considered 0.9H in his research, stating it as the most unfavorable height. This study investigated the impact of the reference height on the gust response factor 'G'. To assess this influence, reference heights of h1 = 0.5H; h2 = 2/3H; h3 = 0.9H; and h4 = H were adopted for the dynamic analysis of the analyzed building.

3. Results

3.1. Gust Response Factor

Gust response factors 'G' have been determined by the general statistical method and simplified method, both by Davenport, and the Galindez method, which is the one adopted in the Brazilian standard NBR 6123 [15].

The gust response factor values are shown using the general statistical method for a basic wind speed equal to 30 m/s, according to the functions of power spectral density of Davenport [20], Harris [21], Kaimal [22], and Von Karman [23], and its behavior according to the reference heights by Fig. 5.

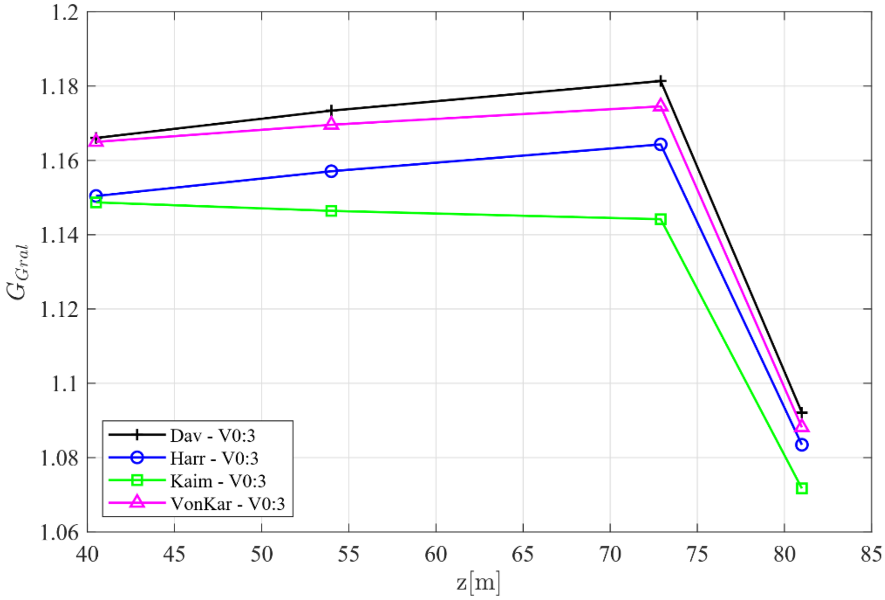

Fig. 5: Gust Response Factor (Davenport General Statistical Method) variation according to reference heights for spectral analysis, for basic wind speed equal to 30 m/s.

The gust response factor values are shown using the simplified method for a basic wind speed equal to 30 m/s, according to the functions of power spectral density of Davenport [20], Harris [21], Kaimal [22], and Von Karman [23], and its behavior according to the reference heights by Fig. 6.

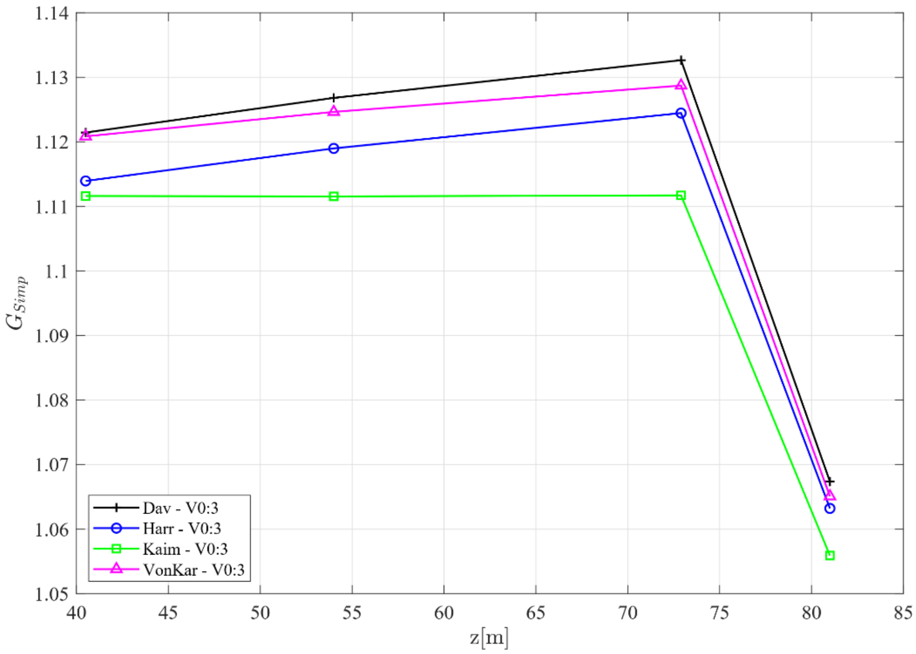

Fig. 6: Gust Response Factor (Davenport Simplified Method) variation according to reference heights for spectral analysis, for basic wind speed equal to 30 m/s.

The gust response factor values are shown using the Galindez method for a basic wind speed equal to 30 m/s, according to the functions of power spectral density of Davenport [20], Harris [21], Kaimal [22], and Von Karman [23], and its behavior according to the reference heights by Fig. 7.

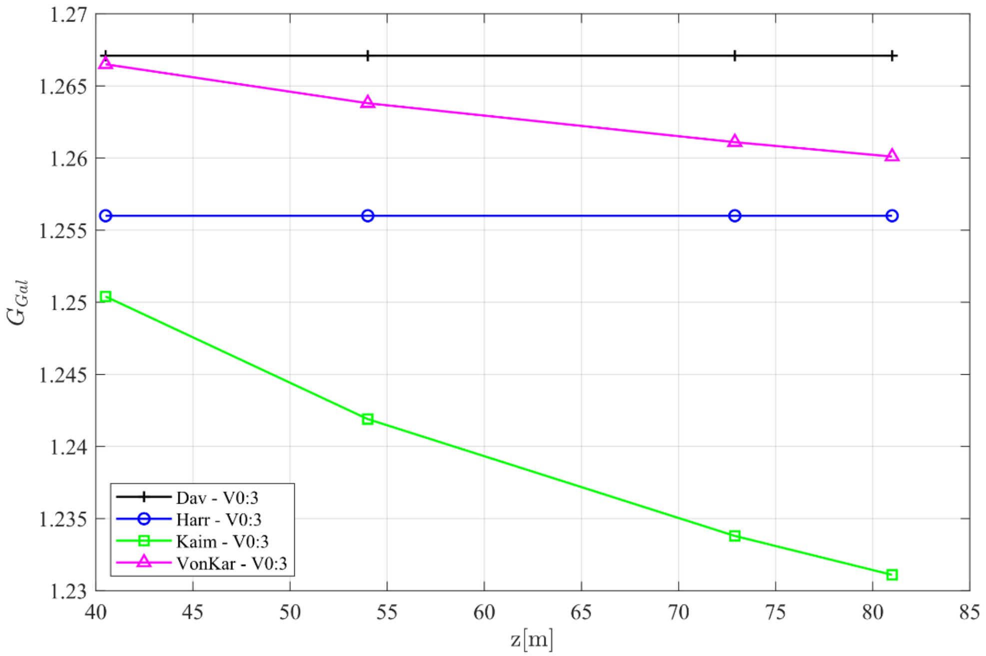

Fig. 7: Gust Response Factor (Galindez Method) variation according to reference heights for spectral analysis, for basic wind speed equal to 30 m/s.

3.2. Comparison Criteria

Each gust response factor ‘G’ was analyzed for both Davenport and Galindez’s methods, taking note of basic wind speeds ranging from 10 m/s up to 50 m/s and reference heights h1, h2, h3 and h4, stated previously. A comparative analysis was conducted across all cases, examining the maximum variability between the minimum and maximum values of the gust response factor under consideration. Additionally, the functions for the power spectral density were evaluated for their influence into the gust response factor.

4. Conclusion

This research examined the behavior of the gust response factor ‘G’ for two parallel spectral analysis methods, Davenport's general statistical method and Galindez's method. These methods were applied for the assessment of a slender flexible building structure with a natural frequency of 0.339 Hz, susceptible to dynamic wind action. Additionally, a simplified version of Davenport's method was evaluated. A maximum difference of 6.4% was found between Davenport's general method and Galindez's method, and a 9.2% difference between Galindez's method and Davenport's simplified method. Also, there was a difference of 3% between Davenport’s general and simplified method.

The sensitivity of the reference height used for calculating the gust response factor ‘G’ was also assessed, with a maximum variation of 4.5% observed between each case. Based on the results of this work, the application of a reference height equal to 2/3 of the total height of the structure is recommended, as this approach is endorsed by many widely accepted design codes and standards.

Additionally, it is worth noting that, while Davenport’s function for the power spectral density is identified with the highest resonant peak, approximately at the natural frequency of the structure, it was the first spectrum proposed in the literature and is not commonly used in various standards. Therefore, the recommended function was Von Karman’s, due to its second highest prominent resonant peak, particularly when compared to other methods such as Davenport, Harris, and Kaimal, bringing the second highest values of the gust response factor 'G'.

The key difference between the spectral analysis methods studied, Davenport's and Galindez's, lies in the cross-correlation coefficient and the application of the equivalent static force in wind load calculations. It can be concluded that that both methodologies provide reliable and similar values, affirming that there is not much sensitivity and influence of the of the method used in the equivalent static force. Additionally, Davenport's method is convenient for its simplicity, but alternatively, Galindez's method could be applied when conservative values of the equivalent static force are of interest.

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References

[1] A. Sharma, H. Mittal, and A. Gairola, "Mitigation of wind load on tall buildings through aerodynamic modifications: Review," *Journal of Building Engineering*, vol. 18, pp. 180–194, 2018, doi: https://doi.org/10.1016/j.jobe.2018.03.005.

[2] A. Kareem, "Mitigation of wind induced motion of tall buildings," *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 11, no. 1, pp. 273–284, 1983, doi: https://doi.org/10.1016/0167-6105(83)90106-X.

[3] N. y M. (INTN) Instituto Nacional de Tecnología, *NP 196: Acción del viento en las construcciones*, 1st ed. Asunción, 1991.

[4] G. I. Taylor, "Diffusion by continuous movements," *Proceedings of the London Mathematical Society*, vol. 20, pp. 196–212, 1921.

[5] G. I. Taylor, "Statistical theory of turbulence," *Proceedings of the Royal Society of London. Series A*, vol. 151, no. 873, pp. 421–444, Sep. 1935, doi: 10.1098/rspa.1935.0158.

[6] Th. Von Karman and H. S. Tsien, "Boundary Layer in Compressible Fluids," *Journal of the Aeronautical Sciences*, vol. 5, no. 6, pp. 227–232, Apr. 1938, doi: 10.2514/8.591.

[7] A. G. Davenport, "The buffeting of large superficial structures by atmospheric turbulence," *Annals of the New York Academy of Sciences*, vol. 116, no. 1, pp. 135–160, 1964.

[8] A. G. Davenport, "Buffeting of a Suspension Bridge by Storm Winds," *J. Struct. Div.*, vol. 88, no. 3, pp. 233–270, Jun. 1962, doi: 10.1061/JSDEAG.0000773.

[9] A. G. Davenport, "The response of slender, line-like structures to a gusty wind.," *Proceedings of the Institution of Civil Engineers*, vol. 23, no. 3, pp. 389–408, Nov. 1962, doi: 10.1680/iicep.1962.10876.

[10] J. D. Holmes, *Wind loading of structures*. CRC Press, 2015. [Online]. Available: https://books.google.com.py/books?id=y4WbBgAAQBAJ

[11] A. G. Davenport, "Gust loading factors," *Journal of the Structural Division*, vol. 93, no. 3, pp. 11–34, 1967.

[12] E. C. for Standardization (CEN), "Eurocode 1: Actions on structures—Part 1–4: General actions—Wind actions." European Committee for Standardization Brussels, Belgium, 2005.

[13] American Society of Civil Engineers, *Minimum design loads and associated criteria for buildings and other structures: ASCE/SEI 7-16*. in American Society of Civil Engineers. Reston, Virginia: Published by American Society of Civil Engineers Reston, Virginia, 2017.

[14] F. B. Cachuço, "Estudo da incerteza em estimativas de frequências naturais de vibração livre de edifícios altos em concreto armado," 2014.

[15] ABNT, *NBR 6123: Forças devidas ao vento em edificações*, 2nd ed. Associação Brasileira de Normas Técnicas, 2023.

[16] R. I. Silva, "Análisis dinámico y comparativo de la respuesta de una edificación sometida a la acción del viento en el dominio de la frecuencia para futura propuesta a la NP-196," Universidad Nacional de Asunción - UNA, 2019.

[17] Task Committee on Electrical Transmission Line Structural Loading, *Guidelines for Electrical Transmission Line Structural Loading*, Fourth Edition. Reston, VA: American Society of Civil Engineers, 2020. doi: 10.1061/9780784415566.

[18] G. Solari, “Design wind loads,” *Journal of Wind Engineering and Industrial Aerodynamics*, vol. 11, no. 1–3, pp. 345–358, 1983.

[19] M. Franco, “Direct along-wind dynamic analysis of tall structures,” *Boletim técnico da Escola Politécnica da Universidade de São Paulo BT/PEF/9303, São Paulo*, 1993.

[20] A. G. Davenport, “The spectrum of horizontal gustiness near the ground in high winds,” *Quarterly Journal of the Royal Meteorological Society*, vol. 87, no. 372, pp. 194–211, Apr. 1961, doi: 10.1002/qj.49708737208.

[21] R. I. Harris, “The nature of the wind,” in *Seminar in the Modern Design of Wind-Sensitive Structures, Construction Industry Research and Information Association*, 1970, pp. 29–55.

[22] J. C. Kaimal, J. C. J. Wyngaard, Y. Izumi, and O. R. Coté, “Spectral characteristics of surface-layer turbulence,” *Quarterly Journal of the Royal Meteorological Society*, vol. 98, no. 417, pp. 563–589, 1972.

[23] T. Von Karman, “Progress in the statistical theory of turbulence,” *Proceedings of the National Academy of Sciences*, vol. 34, no. 11, pp. 530–539, 1948.