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Evaluating the Response of Steel frame for Various Wind Load Combinations Using Stochastic Structural Dynamics

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Abstract: The stochastic structural dynamics, probability, random processes, and statistics are used to quantify load uncertainty. Many structural loads are unpredictable and change across time or space. Such forces also cause surprising dynamic behaviour in structures. Thus, stochastic processes and random vibrations are employed to describe such loads and evaluate the structure's response to estimate uncertainty. The Code book's wind load calculation method is deterministic, although some uncertainty always exists. The Young's modulus of Elasticity and wind load will be stochastic variables to account for uncertainty. Analysis will include a multi-storey braced steel frame. The Gust factor technique (IS: 875-2015: Part-III) will calculate wind load, and ANSYS will assess the structure utilising wind load and Young's Modulus as stochastic parameters. The stochastic/probabilistic analysis will create random wind load and Young's modulus of Elasticity values using the Monte Carlo Simulation Technique. Random Variable simulation will use MATLAB. Both studies' deflection values will be tallied and compared to a deterministic model of the same frame. This work aims to understand the structure's behaviour under uncertain wind loads and Young's modulus of Elasticity by conducting a probabilistic analysis and comparing the deflection values with a deterministic analysis.

Keywords: Gust Factor Approach; Monte Carlo Simulation Technique; MATLAB and ANSYS; Statistical Analysis; Finite Element Analysis (FEA); Deterministic Analysis; Dynamic Loads; Uncertainty Analysis.

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1. Introduction

Structural analysis primarily focuses on determining how structures respond to external forces [16]. These forces can include the weight of occupants, equipment, wind, and snow, as well as other stimuli like seismic activity or ground vibrations caused by nearby explosions. In practice, all these loads, including the structure's own weight, vary over time, as they were not present at some point in the past [1]. The distinction between static and dynamic analysis is based on whether the applied force has sufficient acceleration compared to the structure's natural frequency. If a load is applied slowly enough, inertia forces can be disregarded, simplifying the analysis to a static analysis. Consequently, structural dynamics is a branch of structural analysis

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that examines the behaviour of structures when exposed to dynamic loading [2]. Dynamic loads encompass various factors, including occupants, traffic, waves, wind, and earthquakes [3]. These loads can be further classified using various parameters. The simple classification of dynamic loads is either deterministic or probabilistic.

1.1. Uncertainty Analysis

Uncertainty can be analysed by using various techniques and methods [15]. A detailed classification of the various methodologies available for uncertainty analysis is described in Figure 1. Based on the Figure, uncertainty analysis can be broadly classified into two approaches, namely, the probabilistic approach and the non-probabilistic approach. Since our focus is primarily on the probabilistic approach, it has been considered and explained accordingly [4].

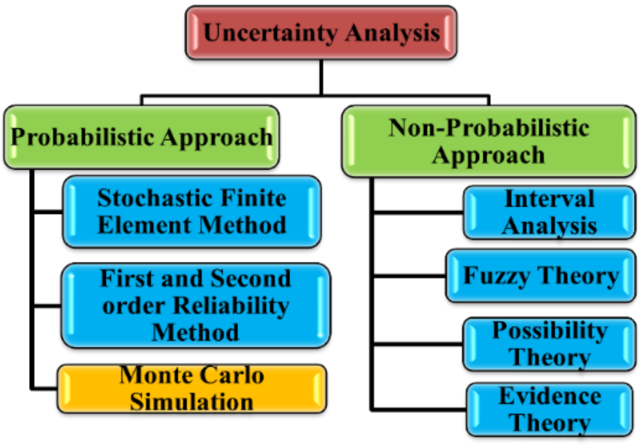

Figure 1: Classification of uncertainty analysis

1.2. Monte Carlo Simulation

Monte Carlo Simulation (MCS) is a robust tool for statistical analysis that finds widespread application in both engineering and non-engineering fields [13]. Its versatility makes it particularly well-suited for addressing complex engineering challenges, as it can effectively handle numerous random variables, diverse distribution types, and highly nonlinear engineering models [17]; [20]. The Monte Carlo methodology encompasses three key components: the digital generation of random variables and functions, statistical evaluation of trial outputs, and techniques for variable reduction [14]; [19].

1.3. Uncertainty in Civil Engineering

In engineering systems design and planning, uncertainties are inevitable. Consequently, engineering analysis tools should incorporate methods and concepts for assessing the impact of uncertainty on system performance and design [12]. Probability principles, along with statistics and decision theory, provide the mathematical foundation for modelling uncertainty and analysing its effects on engineering design [11]; [18]. In the past, idealised assumptions and simplifications of natural processes were used to disregard uncertainty, facilitating deterministic or quantitative approaches. However, these simplifications are often inadequate, as uncertainties are present in nearly all engineering analyses and designs. Regardless of the sophistication of quantitative methods, they are based on idealised assumptions that may not hold in the presence of uncertainty. This is where probability methods become crucial. Mathematical models can be used to determine and quantify uncertainties. Among the various mathematical modelling techniques available, probabilistic (stochastic) modelling is one approach to address these uncertainties. There are many mathematical model techniques available, one of which is probabilistic (stochastic) mathematical modelling [10]; [21].

1.4. Mathematical Modelling

A mathematical depiction of a random occurrence is known as a probability model. It is characterised by its sample space, events within that space, and associated probabilities. These models serve as statistical analysis tools that forecast the likelihood of an event's recurrence based on historical data [9]. In contrast to deterministic models, probabilistic models incorporate elements of randomness. Consequently, even with identical initial conditions, this type of model may yield varying outcomes. An inherent aspect of chance or uncertainty is always present, suggesting the existence of potential alternative solutions [8]. The probabilistic model comprises both a deterministic component and a random error element. It's important to recognise that deterministic and probabilistic models can yield different outcomes for identical scenarios. While the probabilistic approach enables hypothetical predictions, it doesn't provide exact values, particularly due to the presence of uncertain factors. With respect to structural engineering, a stochastic model is one where in,

- Random properties, e.g. the Young's modulus is a random variable with uniform distribution [E1, E2]; or normal distribution (of a given mean or standard deviation).
- The loads which are applied are also random variables, e.g. Wind Load, earthquake (vibration of random amplitude and displacement) [5].

1.5. Objective of the Study

- The traditional or codal approach to analysis is deterministic in nature, whereas in reality, uncertainty is always present due to various reasons [6].
- An alternative approach to accounting for the uncertainty involved is to consider certain parameters as random or stochastic. Hence, wind load and Young's modulus of Elasticity are considered as stochastic variables.
- The response of the structure obtained through stochastic analysis is to be compared with that of the deterministic analysis, and respective probability charts are plotted.

1.6. Scope of the Study

- The scope of this paper involves understanding the deflection of the structure under consideration through a stochastic/probabilistic analysis [7].
- Maximum deflection values for both deterministic and stochastic analysis shall be calculated using Finite Element Software (ANSYS).
- For the stochastic part of the analysis, random variable generation will be performed using the MATLAB software.
- The values of deflection obtained from the deterministic and the stochastic analysis shall be compared and studied.
- Probabilistic analysis is expected to yield a wider range of values compared to the deterministic output.

2. Methodology

Most of the loads that vulnerably affect structures are uncertain in nature and vary in space or time. Examples include wind, earthquakes and ocean waves. Structures exposed to such forces also exhibit unpredictable dynamic behaviour. Uncertainties are inevitable in any engineering analysis and design. They can be analysed and determined by mathematical models. The probabilistic approach is used here since it can be easily computerised. The aim is to calculate and compare the deflection values using deterministic and probabilistic approaches. A steel-framed structure is modelled using a Finite Element Analysis (FEA) Software, i.e. ANSYS software. The dynamic effect of wind is considered in this paper by calculating wind loads using the Gust Factor approach as per IS: 875-2015 (Part III). The calculated gust loads are applied to the framed structure using ANSYS, and the deflection values obtained are noted and tabulated. To carry out the probabilistic analysis, two random parameters are considered, namely, the wind load and the Young's modulus of the structure. First, a single-column unit subjected to wind load is considered, and random parameters are generated for the load and Young's modulus using MATLAB. The obtained deflection values are tabulated and compared with the deterministic values, and the probability of failure is determined. Further probabilistic (stochastic) analysis is carried out for the entire structure in ANSYS, and deflection values are tabulated and compared.

The first step involves calculating wind load by considering the dynamic effect of wind. This can be achieved by using the Gust Factor approach in accordance with IS: 875-1987(part III). A multi-storey braced steel frame shall be considered for the analysis. The steel frame shall be modelled using Finite Element Analysis (FEA) software – ANSYS. The wind load shall be applied as calculated in accordance with the Gust Factor Approach method, as mentioned earlier. A deterministic analysis is performed on the steel frame, and the deflection value is noted. To conduct the stochastic analysis, a single column member is first considered, with two parameters treated as random: the wind load applied to the column and the Young's modulus of Elasticity. Random generation of variables is performed using the Monte Carlo Simulation method in MATLAB software. The deflection values are studied for various sample generations. The same two parameters mentioned above are considered to be randomly varying, and the entire steel frame is analysed using ANSYS. A stochastic analysis is performed on the already analysed steel frame, and the deflection values are noted and tabulated. The deflection values obtained from both the deterministic and stochastic analyses will be compared, and the variation in these values will be studied. The results from the probabilistic analysis are expected to yield a wider range of deflection values compared to the single value obtained from the deterministic analysis.

3. Deterministic Analysis

Deterministic analysis refers to the analysis conducted by assuming a set of parameters concerning a specific code of practice. In this approach, a partial factor of safety is considered to account for the effects of random variations or uncertainties in boundary conditions, loading patterns, material properties, and other relevant factors. The advantage of this approach is the ease of analysis and design provided by the use of partial safety factors. The use of deterministic models usually leads to partial loss of information, and may lead to incorrect solutions due to the following reasons:

- Using an average value for a parameter
- Variability ignored
- The likelihood of occurrence is ignored
- Extreme combinations not quantified

To conduct a detailed deterministic dynamic analysis, a 30m-high steel-framed structure is considered. The said structure is analysed for the dynamic effects of wind, and the deflection obtained is tabulated and then compared to the output values obtained from the stochastic analysis.

3.1. Gust Factor approach

The dimensions of the structure are chosen such that the dynamic effects of wind can be considered (Table 1). The dimensions and other parameters of the structure considered are as follows (Table 2):

- Length, L= 3 m
- Width, B= 3 m
- Height, H = 30 m
- Place: Chennai
- Wind speed = 50 m/s
- H/B = 30/3 =10 > 5

Hence, the dynamic effect of wind should be taken into consideration (Figure 2).

(From Clause 7.1 of IS: 875-2015 (Part III)

Table 1: Section sizes considered in the analysis

Member	Section used
Column	ISMB 300
Beam	ISMB 250
Brace	ISMC 100

For the analysis, a completely braced multi-storied steel frame is considered. The member sections considered are as follows (Table 1).

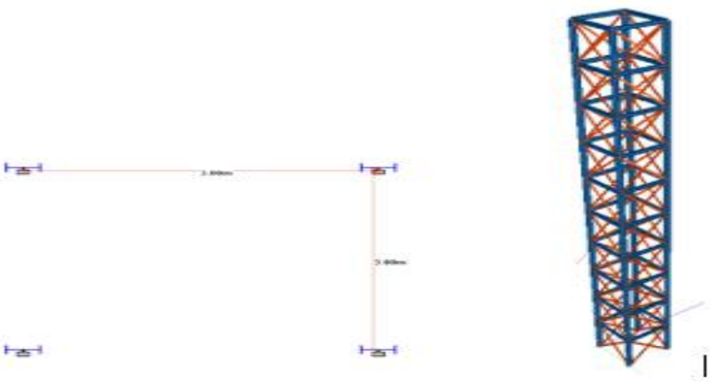

Figure 2: Plan and 3D model of the steel structure considered for analysis

Table 2: Gust factor calculation at different heights of the structure

Height above ground (m)	Design wind speed Vz (m/s)	Design wind pressure pz = 0.6vz2(N/m2)	Gust factor G
10	33.5	700	3.21
15	36	800	3.41
20	37.5	850	3.53
30	39.5	950	3.67

For the above calculations, the following values were used (Table 3),

- Solidity ratio, φ = 0.27
- Force coefficient, C_t 1.7
- Frame spacing ratio, β = 0.9

Table 3: Load calculations on all the member sections

Height	Gust factor	Wind pressure	Column		Beam		Brace	
	G	pz	frame 1	frame 2	frame 1	frame 2	frame 1	frame 2
(m)	-	(kN/m^2)	kN/m	kN/m	kN/m	kN/m	kN/m	kN/m
10	3.21	0.7	0.53	0.48	0.95	0.86	0.38	0.34
15	3.41	0.8	0.65	0.58	1.16	1.04	0.46	0.42
20	3.53	0.85	0.71	0.64	1.28	1.15	0.51	0.46
30	3.67	0.95	0.83	0.75	1.48	1.33	0.59	0.53

3.2. Analysis of A Single Column Member Subjected to Wind Load

A single column unit of height 3m is considered in the analysis. The column is fixed at its base and hinged at the other end to account for the effect of beam-column connections at that end. This gives us a propped cantilever case (Figure 3).

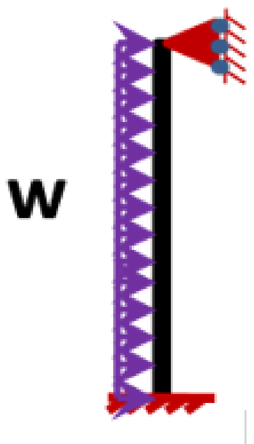

Figure 3: A propped cantilever column subjected to a uniformly distributed load

The deflection equation for the propped cantilever column is given by:

$$\delta = \frac{wl^4}{185\ EI} \qquad (1)$$

4. Analysis Using FEA Software (Ansys) for the Entire Frame

After conducting a deterministic analysis on a single column unit, the entire steel-framed structure needs to be analysed. To achieve this, FEA software is utilised. ANSYS is a Finite Element Analysis (FEA) software that is widely used for structural analysis applications. Using this software, an analysis is carried out for the considered steel frame structure (Figure 4).

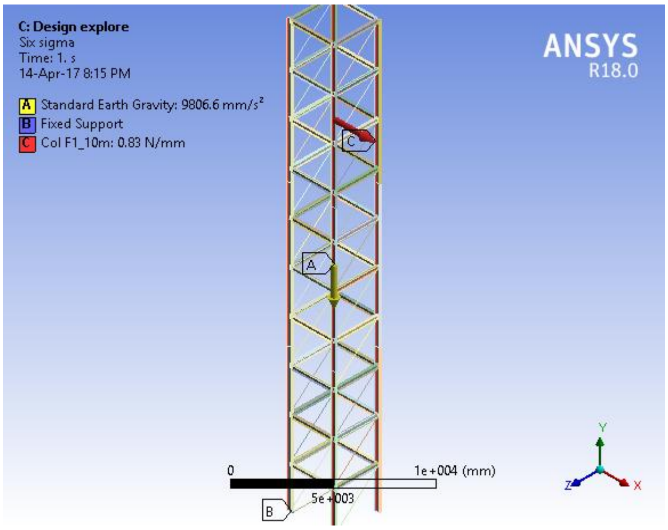

Figure 4: Modelling of the steel-framed structure

5. Stochastic Analysis

A stochastic process refers to a random phenomenon that changes over time. In the field of probability theory, it specifically denotes a time-based sequence that represents the changes in a system, where the variable's alterations are subject to random fluctuations. This concept stands in contrast to a deterministic process. While a deterministic process follows a single, predictable path, a stochastic or random process involves uncertainty: even when the starting conditions are known, the process can unfold in numerous (often infinite) ways. Many stochastic processes exhibit a property where the transition to the next state or position is solely dependent on the current state, without influence from previous states or values. In this research, Monte Carlo Simulation (MCS) will be employed to conduct uncertainty analysis.

5.1. Monte Carlo Simulation (MCS)

Unlike physical experiments, Monte Carlo simulation employs computer-based random sampling to conduct numerous virtual trials. The statistical properties of these simulated experiments (model outputs) are then analysed to conclude the model's performance. In each trial, potential values for the input random variables are generated based on their respective distributions. Subsequently, the output variable Y is computed using the performance function applied to the sampled input random variables. By repeating this process multiple times, a collection of output variable Y samples is obtained for statistical analysis, enabling the estimation of Y's characteristics. The first step in MCS is to identify the distribution type that needs to be selected for a random variable. This is done based on the references available in the literature. In the next step, a sample set is generated from the considered distribution. This generation of sampling sets can be done via the following software: MATLAB. In the final step, a small or large number of simulations are conducted on the generated sampling set, and the appropriate results are arrived at. Two variables are considered as random variables in the analysis. First, the wind load, w, and the other random variable are the Young’s Modulus of Elasticity, E. The wind load is considered to have a normal distribution since load values can be positive or negative, and the Young’s Modulus of Elasticity is considered to have a lognormal distribution since it cannot take any negative values. The following mean and standard deviation values are assumed for this analysis, as shown in Table 4 below.

Table 4: Mean and standard deviation values for the propped cantilever

Input parameters	Random Variable 1 Wind Load (kN/m)	Random Variable 2 Young’s Modulus (MPa)
Mean	100	2 x 105
Standard Deviation	25	0.1 x 105
COV	0.25	0.05

Using the above data, a detailed code was written in MATLAB to generate sampling sets for the required deflection. The analysis is conducted for 10, 100, 1000, and 10000 samples to determine the probability of failure and to obtain converging values. Figure 5 is a snapshot of the code written in MATLAB.

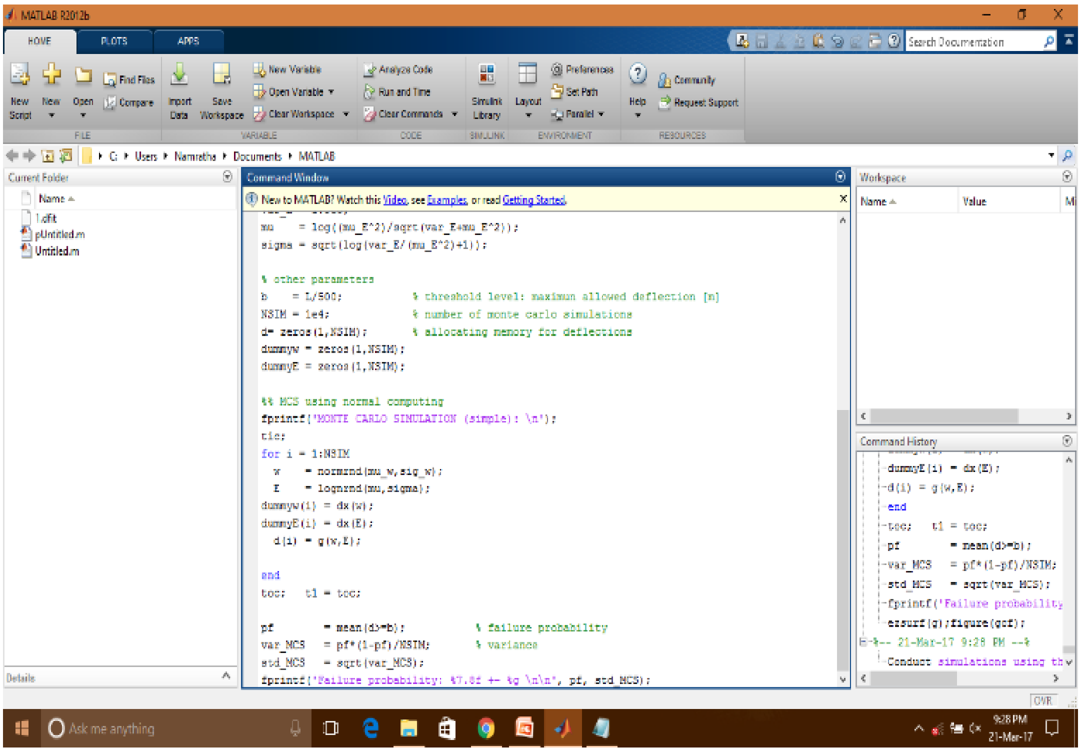

Figure 5: Coding using MATLAB software

Based on the input parameters defined in MATLAB, the following two histograms have been generated, as shown in Figures 6 and 7. The histogram indicates that the chosen random variable follows the assigned distribution, and henceforth, the written code is verified.

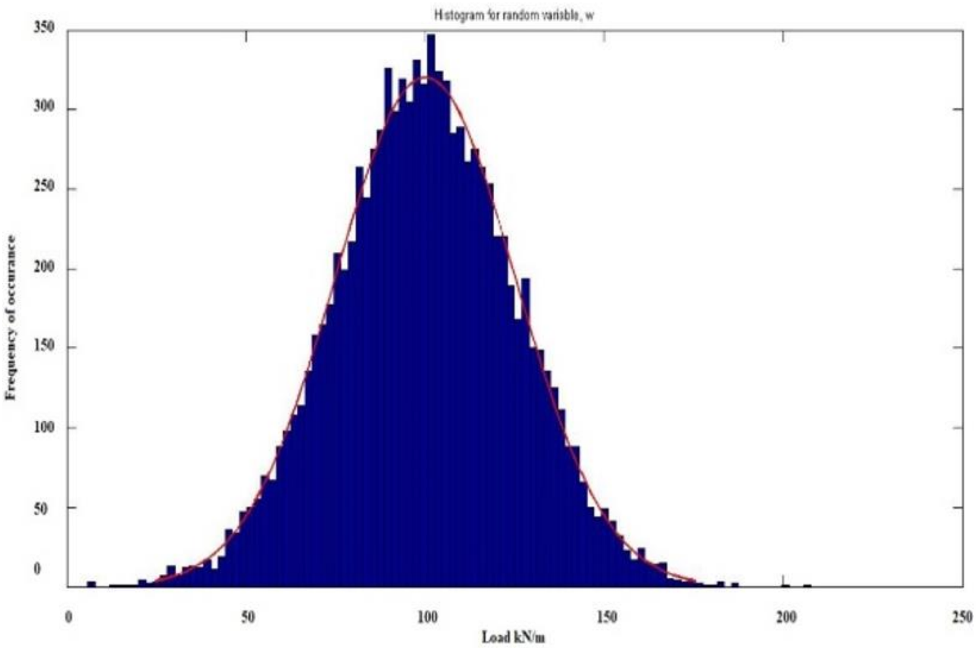

Figure 6: Histogram for wind load

In probability analysis, after conducting numerous sampling experiments on a structural component, a failure probability is determined to assess the credibility or reliability of the structure. The probability of failure (POF) refers to the state or condition of not meeting a desirable or intended objective, and may be viewed as the opposite of success.

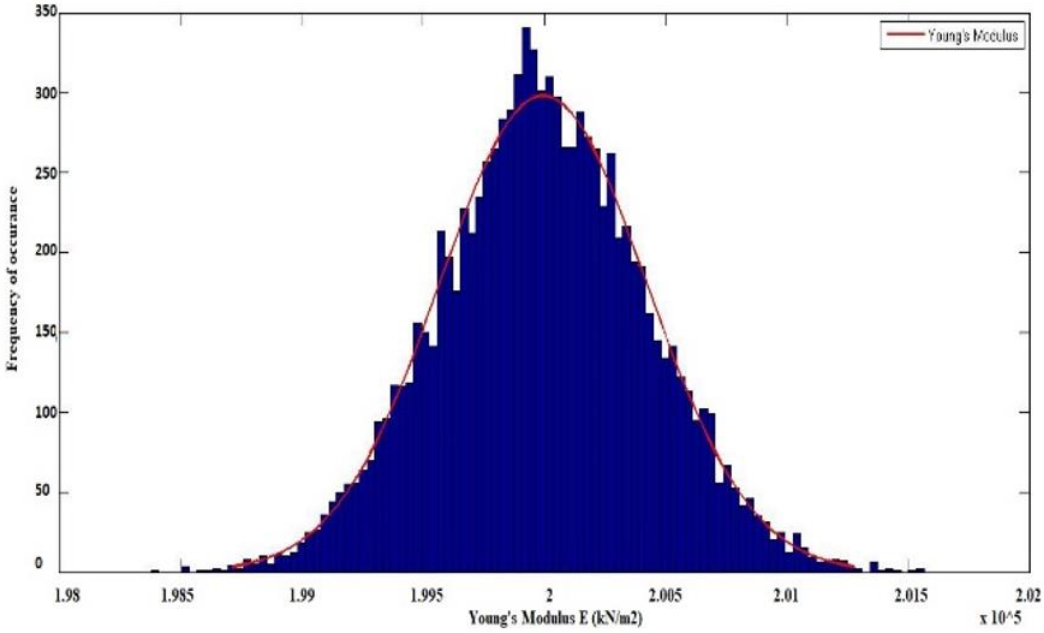

Figure 7: Histogram for Young's modulus of elasticity

The probability of failure can be expressed as a value between 0 and 1, where 0 indicates zero failure and 1 indicates 100% failure. By varying the number of samples generated in the MCS approach, the probability of failure is calculated and tabulated. Based on this data, a converging value of the probability of failure is determined, and the number of samples that need to be generated is finalised. Table 5 below shows the probability of failure for different sample sizes.

Table 5: Probability of failure for different numbers of samples generated

Number of Samples	Probability of Failure (p_f)
10	0.10000000 ± 0.0948683
100	0.07000000 ± 0.0255147
1000	0.05300000 ± 0.00708456
10000	0.05250000 ± 0.00223033

As seen from the above data, the value of p_f converges at 10,000 samples. Hence, the entire analysis is conducted using 10,000 samples.

6. Result and Discussion

6.1. Results for a Single Column Member (Deterministic Results)

For the deterministic part of the analysis, a single base column has been considered. The column considered is a propped cantilever. Wind load obtained from Gust calculations is applied on the column, and the deflection value is arrived at as follows,

$$\delta = 4.26 \text{ mm} \quad (2)$$

6.2. Results For a Single Column Member (Stochastic Results)

On analysing a single column member subjected to wind load and by considering two random parameters, viz. Young's modulus of elasticity and the lateral wind load yielded the following results. These results were obtained by writing a detailed code in MATLAB software for the deflection equation of a propped cantilever beam subjected to a uniformly distributed load. The random generation of variables has been simulated for different sample sizes in MATLAB, specifically 10, 100, 1000, and 10,000 (Figure 8).

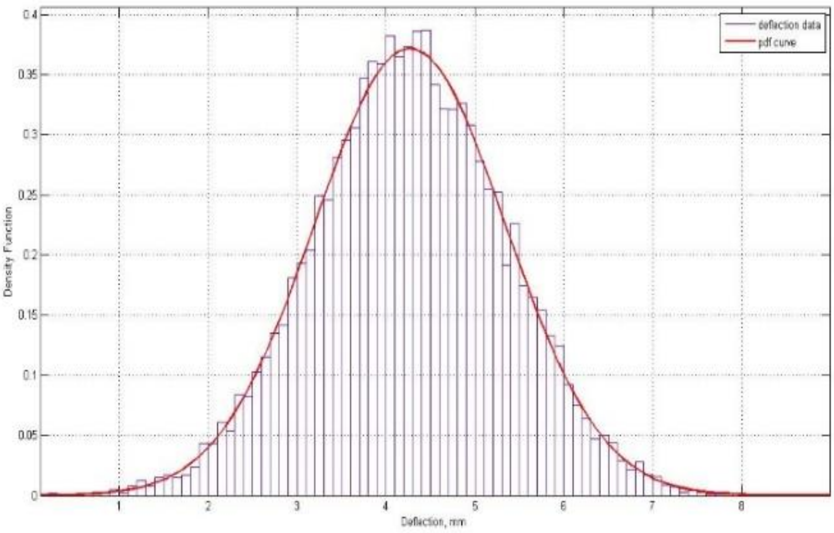

Figure 8: A PDF graph for the deflection value obtained for a single column

From the above graph, it is evident that the obtained deflection values follow a probability density function. The mean, variance, and standard deviation for these have been tabulated in Table 6.

Table 6: Deflection values obtained from MATLAB

Output parameters	Deflection values (mm)
Mean	4.261
Variance	1.127
Standard Deviation	1.062

As seen from the table above, a mean deflection value of 4.261mm is obtained. The variation in deflection is 1.062mm from the mean. This is also evident in the PDF plot, as shown in Figure 7.

6.3. Comparison of Deterministic and Probabilistic Deflection

From the results obtained through deterministic and stochastic analysis of a single column member, the following findings have been tabulated in Table 7.

Table 7: Comparison of deterministic and probabilistic deflection

Deflection Value (mm) Deterministic	Deflection values (mm) Probabilistic
4.266	4.261 ± 1.062

As seen from the table above, the probabilistic analysis yields more variation in the deflection values compared to the deterministic value.

6.4. Results for the Entire Steel Framed Structure

6.4.1. Deterministic Results

The entire steel-framed structure is analysed for wind loads using ANSYS software, and the results obtained are shown in Figure 9 below.

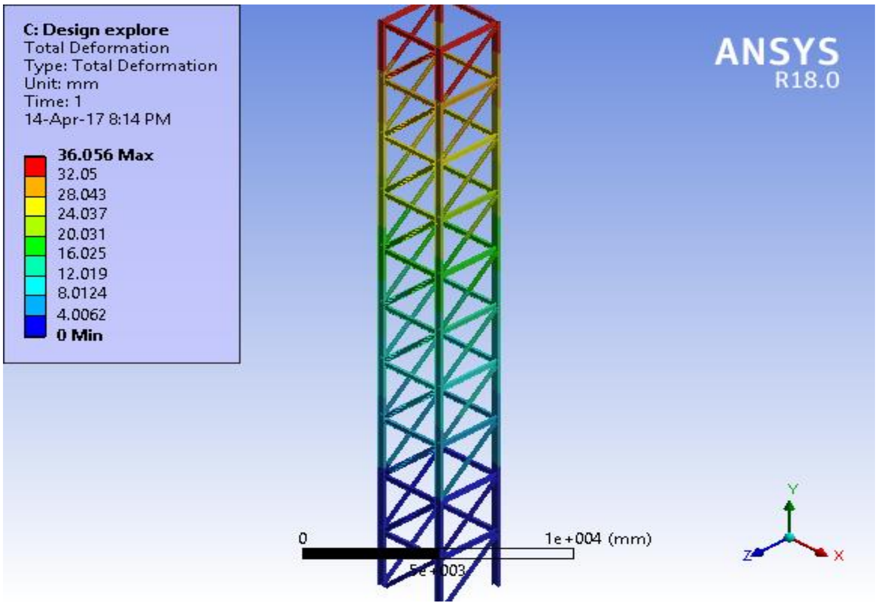

Figure 9: Deflection value obtained after deterministic analysis

The maximum value of deflection, as shown in Figure 8, is 36.056mm.

6.4.2. Stochastic Results

After performing a detailed deterministic analysis on the steel-framed model, a stochastic analysis is conducted on the same model by considering two random parameters as before, namely, wind load and the Young's modulus of Elasticity. Random values are generated for the parameters considered. The different distribution functions obtained in ANSYS are shown in Figures 10 to 12 below.

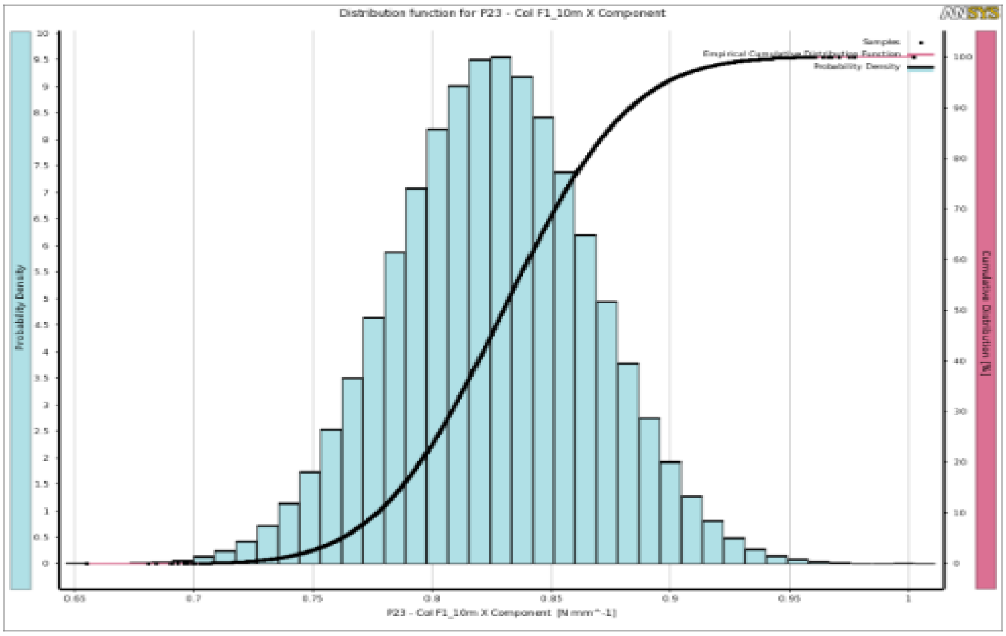

Figure 10: The PDF and CDF plots for Young's Modulus of Elasticity

The above Figure shows the PDF and CDF plots of the Young's modulus of Elasticity obtained after the stochastic analysis is performed.

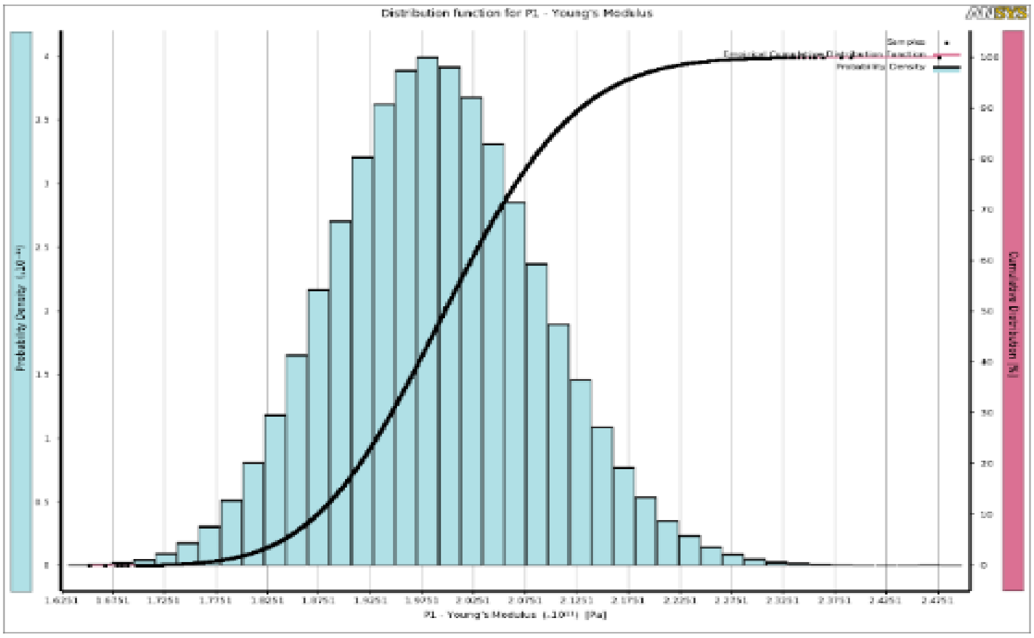

Figure 11: The PDF and CDF plots for lateral wind load

Figure 12 below is the PDF plot of the deflection value obtained after analysis.

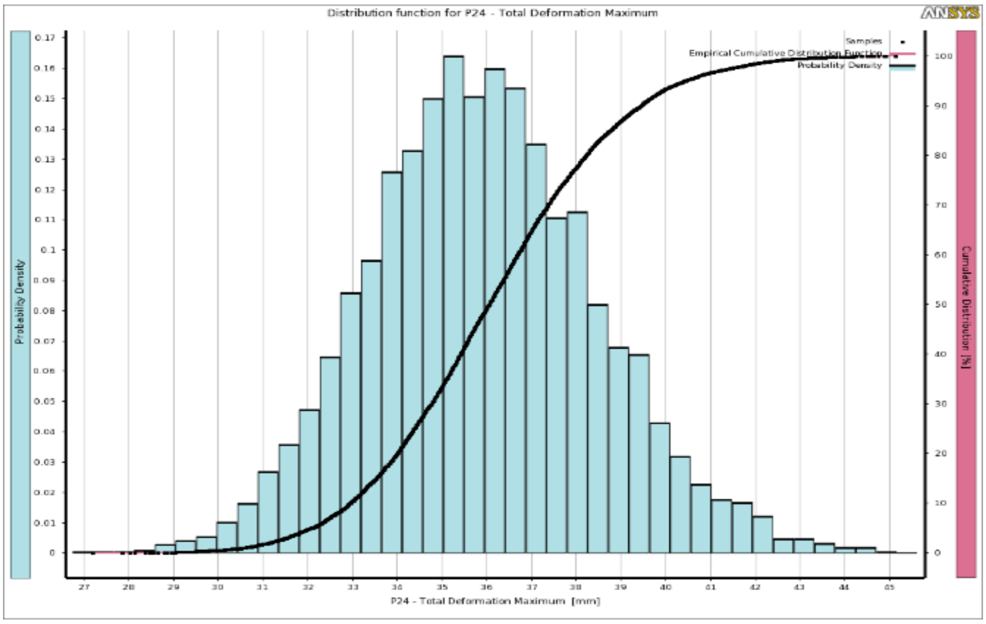

Figure 12: The PDF and CDF plots for deflection

The value of deflection varies from 26.242mm to 48.572mm, as shown in the above plot. The mean and standard deviation values have been tabulated in Table 8.

Table 8: Mean and standard deviation values of deflection

Output parameters	Deflection values (mm)
Mean	36.146
Variance	2.544
Standard Deviation	1.594

Table 9: Comparison of deterministic and probabilistic deflection for the entire steel frame

Deflection Value (mm) Deterministic	Deflection values (mm) Probabilistic
36.056	26.242 to 48.572

6.5. Comparison of Deterministic and Probabilistic Deflection

The results obtained from deterministic and stochastic analyses of the entire steel-framed structure are tabulated in Table 9. As seen from the table above, the probabilistic analysis yields more variation in the deflection values compared to the deterministic value.

7. Conclusion

The analysis yields numerous major conclusions. The probabilistic approach to structural analysis offers a more comprehensive understanding of the system's behaviour compared to the deterministic method. The deterministic technique gives one value of deflection based on set input parameters. At the same time, the probabilistic approach takes into account the inherent uncertainties in material properties, loading circumstances, and boundary limitations. This results in a broader spectrum of deflection values, mirroring the genuine diversity seen in real-world situations. Also, the probabilistic analysis is more accurate and reliable since it takes these uncertainties into account instead of only using nominal or average values. Because of this, it gives a more accurate and reliable picture of how the structure will work in different situations. This deeper understanding makes it easier to improve structural designs, which makes them safer and more cost-effective. Another key result is that the standard partial safety factors that are usually required by design standards may need to be changed when a full probabilistic analysis is done. If there is enough statistical proof and reason, variations from typical codal safety factors can be explained, which can lead to better design options without hurting the structural integrity. So, using probabilistic methods in structural analysis not only makes predictions more accurate, but it also helps create structures that are more suited to real performance expectations and are more cost-effective.

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Ethics and Consent Statement: The authors confirm that the research was conducted in accordance with ethical standards, with informed consent obtained and confidentiality maintained for all participants.

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