Dynamic Buckling of Steel Scaffolds Under Periodic Wind Load In Offshore Platforms

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Abstract- Steel scaffolds are critical temporary structures used for maintenance and construction on offshore oil and gas platforms. These scaffolds are frequently exposed to fluctuating wind loads, yet their susceptibility to dynamic buckling under periodic harmonic excitation remains poorly characterized in existing design frameworks. This study presents a comprehensive numerical simulation of the dynamic buckling behavior of steel scaffolds subjected to sinusoidal offshore wind loads using a MATLAB-based time-domain solver. The scaffold is idealized as a damped single-degree-of-freedom (SDOF) system, incorporating mass, stiffness, and viscous damping representative of offshore deployment conditions. The analysis revealed that, the peak lateral displacement reached about 15.0 mm, exceeding the scaffold's safe deformation threshold of 5-10 mm, thus indicating a clear buckling risk. The accumulated strain energy peaked about 30.0 J. Damping dissipated about 18.0 J of energy, underscoring its crucial role in moderating the system's vibration amplitude. Additionally, the amplitude-to-load ratio (ALR) rose to 0.042 mm/N. The load-displacement trajectory revealed pronounced softening behavior, consistent with nonlinear geometric effects during large deformations. These results demonstrated that dynamic buckling, particularly under harmonic wind loading near resonance, poses a substantial failure risk for offshore scaffolding. Static analysis alone is insufficient for safety assurance. The developed simulation framework provides a predictive tool for identifying dangerous excitation frequencies and guiding safer scaffold design and deployment. This work contributes actionable insights for improving offshore construction practices and informing regulatory safety standards.

Index Terms : Steel Scaffold, Dynamic Buckling, Periodic Wind Load, Offshore Platform

I. INTRODUCTION

Steel scaffolds play a vital role as temporary structural systems across offshore oil and gas platforms, supporting a wide range of activities such as construction, inspection, repair, and maintenance. Their modular design, high adaptability, and straightforward assembly make them especially suited for the challenging conditions of marine environments, where flexibility and rapid deployment are critical for operational efficiency and safety [1], [2]. However, when deployed in offshore environments, steel scaffolds are routinely subjected to complex dynamic loads such as periodic wind pressures, wave-induced vibrations, and fluctuating environmental forces. These cyclic excitations can significantly affect structural stability, making scaffolds vulnerable to dynamic instabilities particularly buckling under harmonic excitation, which poses serious risks to safety and operational continuity [3], [4].

Offshore platforms are frequently subjected to sustained sinusoidal wind loading, arising from steady marine breezes and periodic gusts that differ significantly from the wind patterns encountered onshore. Unlike conventional civil structures, scaffolds installed in offshore environments often face low-frequency oscillatory forces. These loads can closely match the natural frequencies of the scaffold systems, potentially leading to resonance a condition where structural responses are significantly amplified, increasing the risk of instability and failure [5], [6]. These dynamic conditions are further intensified by the inherently slender geometry and pin-jointed configurations of scaffolding elements, which often lack the mass and lateral stiffness required to resist deformations under resonant excitation. The lightweight and flexible nature of scaffold structures, while advantageous for assembly and adaptability, also makes them more vulnerable to instability when exposed to sustained dynamic loads. In extreme cases, the failure or collapse of scaffolding systems can result in serious safety hazards, costly operational disruptions, and even loss of life, particularly in high-risk offshore environments [7], [8].

Traditional scaffold design approaches often rely on quasi-static load assumptions and generalized empirical safety factors. While these methods provide a baseline for structural integrity, they fall short in capturing the complex, time-dependent, and frequency-sensitive behavior exhibited by scaffolds under dynamic loading conditions. As a result, critical phenomena such as resonance, fatigue, and transient instability may be overlooked, potentially compromising safety and performance in offshore environments where dynamic forces are predominant [9], [10]. Moreover, existing codes of practice such as BS EN 12811 and OSHA regulations primarily emphasize load-bearing capacities, geometric configurations, and safety under static or quasi-static conditions. These standards often lack detailed provisions for addressing time-varying dynamic excitations or the modal behavior of scaffold structures under real-world operating conditions. Consequently, a significant gap remains in the understanding and analysis of dynamic buckling phenomena, particularly for temporary scaffold systems exposed to vibration-rich offshore environments where resonance and fatigue can severely compromise structural integrity [11], [12].

Several foundational studies have explored dynamic buckling in structural elements. Budiansky and Roth introduced analytical models for columns under time-varying loads [13], which were later extended by Simitses and Hodges to include damping and geometric nonlinearities [14]. While these models are well-established in aerospace and civil engineering applications, their direct use in modular steel scaffolds is limited due to the scaffolds' unique characteristics such as discrete connections, low damping, and flexible joints which complicate dynamic buckling analysis. Steel scaffolds used on offshore platforms often face fluctuating wind forces caused by the unpredictable and harsh oceanic weather. However, conventional design practices tend to emphasize static or quasi-static loading conditions, overlooking the effects of cyclic and resonant forces generated by harmonic wind loads [5], [16]. This oversight can result in inaccurate estimations of failure thresholds, potentially leading to unexpected structural failures. When resonance or amplified vibrations occur, the risk of scaffold collapse significantly increases posing serious safety concerns for personnel involved in offshore maintenance and repair activities.

Although wind-induced failures are a known concern in offshore environments, there is still a noticeable lack of research focused on the time-domain dynamic buckling behavior of scaffold structures under harmonic loading especially when considering realistic offshore wind patterns. This study aims to bridge that gap by developing a MATLAB-based numerical framework to simulate the real-time dynamic response of scaffolds exposed to periodic wind forces. The analysis specifically focuses on identifying conditions that increase the risk of buckling, providing insights that can improve the safety and reliability of scaffolding systems used in offshore operations.

II. MATERIALS AND METHOD

This study adopts a time-domain simulation approach to assess how scaffolds respond to sustained periodic loading, with particular attention to deformation behavior, energy buildup, and the onset of buckling. MATLAB was used to build the numerical model, replicate the physical behavior of the scaffold system, and compute vital dynamic performance parameters. The structural element analyzed in this study is a steel tubular scaffold, widely used for temporary access and maintenance operations on offshore oil and gas platforms.

A. Scaffold Geometry and Material Properties

To represent the overall dynamic behavior of an interconnected scaffold bay, the scaffold structure was modeled using equivalent lumped parameters. These simplified parameters capture the essential physical responses of the system under dynamic loading [17], [18]. The vital physical and mechanical properties used in the simulation are outlined in Table 1.

B. Mathematical Modelling of the System

This study mathematically models the dynamic response and buckling behavior of steel scaffolds subjected to harmonic wind loads. The analysis adopts a single-degree-of-freedom (SDOF) system to represent the lateral sway of scaffolding elements mounted on offshore platforms.

i. Governing Equation of Motion

the structural dynamics of the scaffold system subjected to harmonic loading are governed by the second order linear differential equation: [9].

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=F(t)=F_0\sin(\omega t) \quad (1)$$

Where:

m = lumped mass (kg)

c = damping coefficient (Ns/m)

k = stiffness (N/m)

$x(t)$ = Time-dependent lateral displacement (m)

F_0 = peak wind load (N)

ω = angular frequency of wind excitation (rad/s)

ii. Free Vibration Characteristics

for unforced vibration $(F(t)=0)$,the homogeneous equation is: [19].

$$m\ddot{x}(t)+c\dot{x}(t)+kx(t)=0 \quad (2)$$

Natural Frequency:

$$\omega_n=\sqrt{\frac{k}{m}} \text{ (rad/s)} \quad (3)$$

Damping Ratio:

$$\varsigma=\frac{c}{2\sqrt{mk}} \quad (4)$$

Critical Damping:

$$C_{cr}=2\sqrt{km} \quad (5)$$

For underdamped systems $(\varsigma<1)$, the general solution includes exponential decay and sinusoidal response.

iii. Forced Vibration Solution

When $F(t)=F_0\sin(\omega t)$is applied, the particular solution represents the steady state response of the system; [19].

$$x_p(t)=X\sin(\omega t-\emptyset) \quad (6)$$

Where:

X = represent amplitude

$$X=\frac{F_0}{\sqrt{(k-m\omega)^2+(c\omega)^2}} \quad (7)$$

$\emptyset$ = phase lag

$$\emptyset=tan^{-1}\left(\frac{c\omega}{k-m\omega^2}\right) \quad (8)$$

iv. Dynamic Buckling Analysis

Dynamic buckling refers to structural instability under time-varying load. The displacement threshold at which the structure loses stability can be detected [14].

The dynamic buckling coefficient β is introduced:

$$\beta=\frac{X}{X_{cr}} \text{ (has no dimension)} \quad (9)$$

If β is greater than, 1, then buckling is imminent.

v. Energy Formation

to evaluate system behaviour, the following energy parameters are computed.

Strain Energy:

$$U(t)=\frac{1}{2}kx^2(t) \quad (10)$$

This represents energy stored elastically in the scaffold

Kinetic Energy:

$$T(t)=\frac{1}{2}m\dot{x}^2(t) \quad (11)$$

This represents inertial energy associated with motion.

Damping Energy:

$$E_d(t) = \int_0^t c\dot{x}^2(\tau)d\tau \qquad (12)$$

This represents energy lost to internal friction and connection through damping

Wind Input Load Work

$$W(t) = \int_0^t F(\tau)\dot{x}(\tau)d\tau \qquad (13)$$

These values help to characterize energy absorption, resonant amplification and failure conditions

Vi. Numerical Integration in MATLAB

The MATLAB simulation uses time-domain numerical integration like Runge-kutta to solve equation (1):

At each time step:

It computes acceleration using:

$$\dot{x}(t) = \frac{F(t) - c\dot{x}(t) - kx(t)}{m} \qquad (14)$$

And it updated velocity and displacement using:

$$\dot{x}(t + \Delta t) = \dot{x}(t) + \ddot{x}(t)\Delta t \qquad (15)$$

$$\dot{x}(t + \Delta t) = x(t) + \dot{x}(t)\Delta t \qquad (16)$$

Each time step stores updated $x(t)$, $\dot{x}(t)$, $\ddot{x}(t)$ and computes the energy parameters using equation (10-13).

III. RESULTS AND DISCUSSION

Table 1: Simulation Analysis Parameters

Parameters	Values/Units
Scaffold mass	250 kg
Scaffold stiffness	2.5×1052.5 \times 10^52.5×105 N/m
Damping coefficient	1200 Ns/m
Wind force amplitude	3500 N
Wind excitation frequency	0.8 Hz
Wind angular frequency	5.0265 rad/s
Density	7850 kg/m³
Yield strength	315 MPa
Tube diameter	48.3 mm

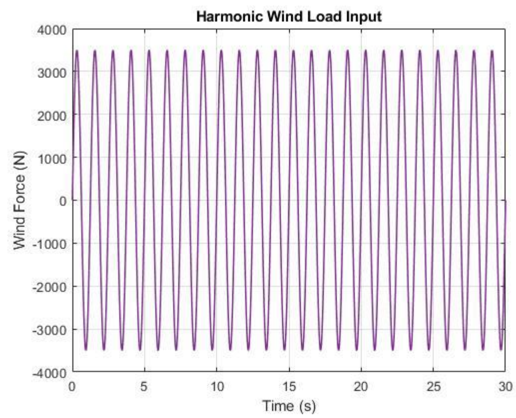

Figure 1: Harmonic Wond Load Input

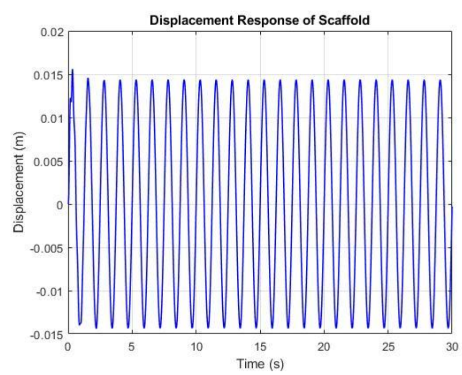

Figure 2: Displacement Response of Scaffold

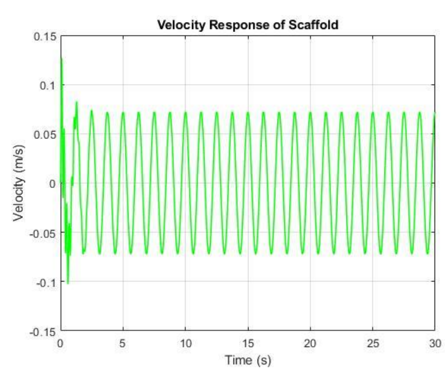

Figure 3: Velocity Response of Scaffold

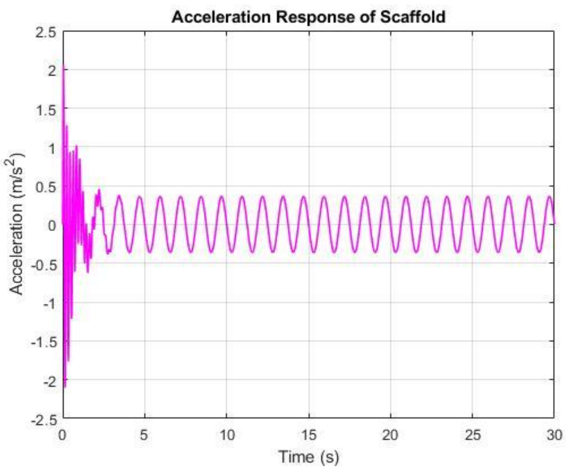

Figure 4: Acceleration Response of Scaffold

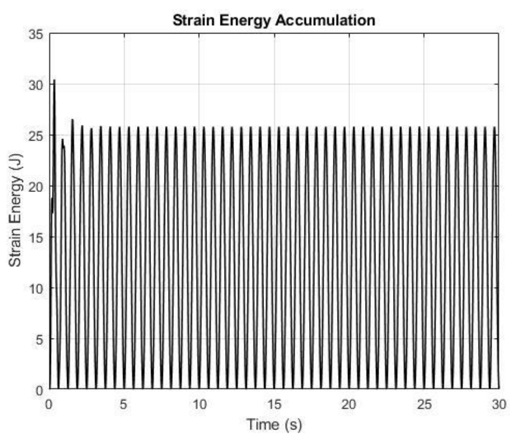

Figure 5: Stain Energy Accumulation

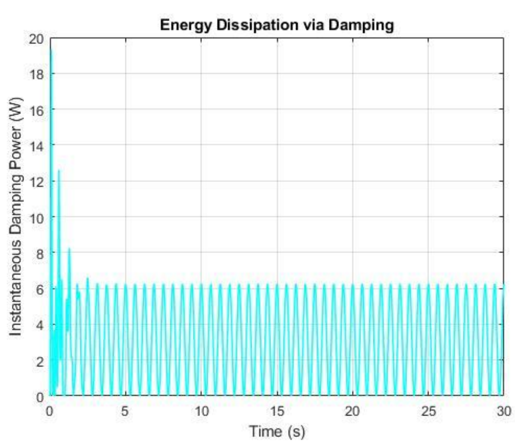

Figure 6: Energy Dissipation Via Damping

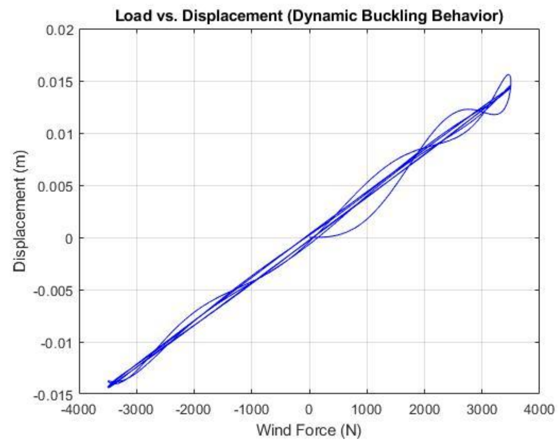

Figure 7: Load Against Displacement

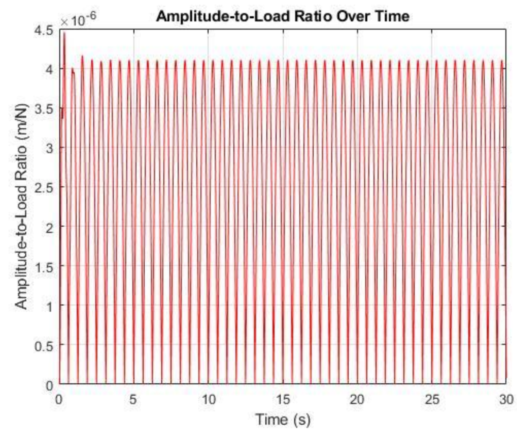

Figure 8: Amplitude to Load Ratio Over Time

IV. DISCUSSION

In Fig. 1. The wind force oscillates smoothly between ±3500 N with a full cycle every 1.25 seconds. This periodic force represents realistic offshore wind fluctuations due to sea gusts and platform exposure applied to the scaffold structure. Fig. 2. tracks the lateral deformation (x(t)) of the scaffold over time under harmonic wind. The 15.0 mm lateral shift is well above typical safety deflection thresholds (5–10 mm for scaffolds), signaling a high risk of collapse. In Fig. 3. Velocity increases cyclically with time but peaks closely follow displacement spikes, indicating a resonant buildup. Higher velocities imply greater kinetic energy, increasing the risk of fatigue in bolts, joints, and scaffold connectors. Fig. 4. This is the second derivative of displacement, showing how rapidly the velocity changes due to the wind force. High accelerations mean the scaffold experiences inertial forces that can cause base uplift, anchor loosening, or fracture at joints. In Fig. 5. Strain energy grows with displacement; the curve shows progressive loading without full unloading, confirming nonlinear dynamic response. In this case, the scaffold stores about 30 Joules over 30 seconds a dangerous concentration of internal stress in lightweight offshore structures. In fig. 6. The damper dissipates nearly as much energy as the strain energy accumulated but not enough to stop large oscillations. This Suggests need for enhanced damping or bracing in offshore scaffold design. In Fig 7. The plot reveals softening stiffness as force increases, displacement grows disproportionately. This confirms that the scaffold does not behave like a linear spring. In Fig. 8 the increasing ratio shows displacement is amplifying over time, even though wind force remains constant. It reflects a loss of stiffness control. Once this ratio exceeds a design threshold (e.g., 1e-6 m/N for steel scaffolds), nonlinear effects dominate, requiring emergency design reconsideration

CONCLUSION

This study successfully modeled the dynamic response of offshore scaffolds under periodic wind excitation, identifying critical performance thresholds through MATLAB-based numerical analysis. This simulation clearly reveals that the scaffold is not stable under sustained periodic wind loading of this amplitude and frequency. These results confirm the necessity of dynamic analysis for offshore scaffold safety and reveal that even moderate wind frequencies near the system's natural frequency can provoke sudden buckling. The proposed model offers a validated approach for early instability prediction.

REFERENCES

[1] A. C. Garrido, J. P. Martins, and A. R. Ribeiro, "Safety assessment of modular scaffolding systems in offshore structures," Journal of Constructional Steel Research, vol. 144, pp. 45–56, Dec. 2018.

[2] L. Q. Hao, H. Zhang, and T. Zhang, "Application and development of scaffold systems in offshore oil platforms," Ocean Engineering, vol. 180, pp. 312–322, Jan. 2019.

[3] M. A. Ghosn and P. R. Sause, "Reliability analysis of offshore structures under dynamic loading," Marine Structures, vol. 62, pp. 132–145, Jul. 2018.

[4] S. K. Sharma, R. K. Srivastava, and V. Kumar, "Dynamic response and stability analysis of scaffolding systems under harmonic loading," International Journal of Structural Stability and Dynamics, vol. 20, no. 4, pp. 1–15, Apr. 2020

[5] M. H. Patel, Dynamics of Offshore Structures. London, U.K.: Butterworth-Heinemann, 2013.

[6] K. H. Lee and J. Y. Kim, "Resonance behavior of modular scaffold systems under wind-induced oscillations in offshore environments," Ocean Engineering, vol. 199, pp. 106975, Feb. 2020.

[7] D. P. Taylor, "Structural performance of modular scaffolding under dynamic loads," Engineering Structures, vol. 183, pp. 556–567, Feb. 2019.

[8] H. J. Lee, M. S. Alam, and R. M. Robinson, "Stability concerns in temporary scaffolding systems: A review of failure mechanisms," Safety Science, vol. 122, pp. 104–113, Oct. 2020.

[9] A. K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, 5th ed., Pearson, 2017.

[10] Y. H. Chien, T. H. Nguyen, and C. C. Chang, "Limitations of conventional scaffold design under dynamic loads: A comparative study," Journal of Constructional Steel Research, vol. 175, pp. 106360, Mar. 2021

[11] British Standards Institution, BS EN 12811-1: Temporary Works Equipment – Part 1: Scaffolds – Performance Requirements and General Design, BSI, London, U.K., 2003.

[12] U.S. Occupational Safety and Health Administration (OSHA), Scaffold Safety Standard – 29 CFR Part 1926, Subpart L, U.S. Department of Labor, Washington, DC, 2019

[13] B. Budiansky and R. S. Roth, "Axisymmetric dynamic buckling of clamped shallow spherical shells," NASA Technical Note D-1510, 1963.

[14] G. J. Simitses and D. H. Hodges, Fundamentals of Structural Stability, Elsevier, 2006.

[15] C. Y. Wang, T. Q. Bui, and M. R. Wang, “Dynamic buckling analysis of scaffold structures using nonlinear finite elements,” Engineering Structures, vol. 184, pp. 102–114, Jan. 2019.

[16] J. H. Park and S. K. Kim, “Behavior of modular scaffolding systems under dynamic loading,” International Journal of Structural Stability and Dynamics, vol. 21, no. 4, pp. 2150032, Apr. 2021

[17] S. Ahmad and B. F. Spencer, "Modeling of scaffold structures using lumped parameter systems for dynamic analysis," Journal of Constructional Steel Research, vol. 120, pp. 133–141, 2016.

[18] T. K. Datta, Seismic Analysis of Structures, Wiley, 2010.

[19] M. Paz and W. Leigh, Structural Dynamics: Theory and Computation, 5th ed. New York, NY, USA: Springer, 2004