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Analysis of Steel Frame in ANSYS

Chirag Ka Patel[1], Shah Mayank[2]

Asst. Professor, Department of Civil Engineering, Faculty of Technology,

Dharmsinh Desai University, Nadiad, Gujarat

Student, Indus University, Ahmedabad, Gujarat

Abstract: In the modal analysis of plane frames, the primary objective is to determine the natural frequencies and associated mode shapes of the structure under free vibration. Dynamic analysis of frames requires the inclusion of axial effects in both the stiffness and mass matrices, along with coordinate transformation from local to global systems. Modal analysis facilitates the evaluation of vibration characteristics through the computation of eigenvalues and eigenvectors, which represent frequencies and mode shapes respectively. This study aims to investigate the vibration behavior, frequency, and mode shape of plane frames using the direct stiffness method. The stiffness and mass matrices are formulated, and computational models are developed using ANSYS and MATLAB codes. Comparative results are presented to validate the methodology and highlight the accuracy of the developed formulations.

Keywords: Steel plane frames, ANSYS, Finite element analysis (FEM).

INTRODUCTION

Structural frames are fundamental components in both civil and mechanical engineering, serving as the primary load-bearing elements in a wide range of applications such as high-rise buildings, bridges, industrial plants, and various mechanical support systems. Their ability to withstand different loading conditions—including static, quasi-static, and dynamic forces—makes them critical to ensuring safety, serviceability, and long-term performance.

Dynamic loading conditions, such as earthquakes, wind-induced vibrations, and machinery excitations, can significantly influence the behavior of structural frames. If not properly accounted for, these dynamic effects can lead to structural damage, impaired serviceability, or even catastrophic failure. Understanding and predicting the dynamic behavior of such systems is therefore a vital part of structural engineering design.

Importance of Modal Analysis

Modal analysis is a key tool used to investigate the vibrational characteristics of structural systems. In dynamic analysis, it identifies:
Natural frequencies — the vibration rates at which the structure inherently oscillates without external forcing.
Mode shapes patterns of deformation corresponding to each natural frequency. Modal mass and stiffness participation — how different parts of the structure contribute to each vibrational mode. By determining these properties, engineers can assess whether any vibrational modes align with the expected frequencies of external loads, which can cause resonance and amplify structural responses. This insight allows for the modification of design such as adjusting stiffness or mass distribution—to avoid damaging effects.

Characteristics of Plane Frames

Plane frames are two-dimensional structural systems composed of beam and column elements connected rigidly at joints, capable of resisting axial, bending, and shear forces. Key characteristics that affect their dynamic analysis include:

Axial stiffness — resistance to elongation or shortening along the member length.

Flexural stiffness — resistance to bending deformation due to lateral loads.

Shear deformation effects — particularly relevant in short or deep members.

Rigid joint connectivity — which enforces rotational continuity at nodes.

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Unlike simplified pure bending beam models (which assume axial deformations to be negligible), accurate analysis of plane frames requires:

The inclusion of both axial and flexural deformations.

Geometric compatibility conditions between connected elements.

Coordinate transformations to relate each local member stiffness and mass matrix to the global structural coordinate system.

LITERATURE REVIEW

Several researchers have contributed to the development of structural dynamics and modal analysis techniques:

Clough and Penzien (1993) provided a classical framework for structural dynamics, emphasizing the importance of eigenvalue analysis in vibration studies.

Bathe (1996) introduced finite element formulations for dynamic problems, particularly focusing on mass and stiffness matrix derivations for frame structures.

Barbosa & Ribeiro (1998) demonstrated the use of ANSYS nonlinear concrete models in vibration analysis, showing the flexibility of numerical tools.
A comprehensive literature review provides critical insight into the modal analysis of plane frames, highlighting the evolution of analytical methodologies and computational tools used to characterize their dynamic response under free vibration. The following review synthesizes the core advances, validated techniques, and comparative findings from recent scholarship.

Modal Analysis of Plane Frames: Theoretical Foundations

A central aim in the modal analysis of plane frames is to accurately determine the natural frequencies and mode shapes through free vibration studies. Early works focused on the development of stiffness and mass formulations that account for both axial and flexural behaviors, distinguishing plane frames from simple beam models and truss systems. Key literature systematically incorporates axial effects within global stiffness and mass matrices, recognizing their significance for realistic frame vibration predictions.
The direct stiffness method, as described in foundational texts and articles, offers a framework for assembling the equations of motion that govern free vibration. This method ensures geometric compatibility and equilibrium through systematic matrix assembly and coordinate transformation from local member axes to the global structural system.

Advancements in Modal Analysis Techniques

Recent research advances have emphasized the need for refined numerical procedures to solve the eigenvalue problem central to modal analysis. Notable studies have validated the analytical computation of both natural frequencies and mode shapes, advancing accuracy for regular and irregular frame geometries. Modal analysis not only enables assessment of vibration response under a spectrum of frequencies but also optimizes designs to mitigate resonance risks and improve stability.
The inclusion of axial effects is vital in plane frame analysis, as seen in Gera (2011), who demonstrated the limitations of neglecting axial terms in vibration studies. This finding is reinforced by contemporary works, particularly in the context of seismic and wind loadings for complex steel and composite frames.

Numerical Methods and Software Implementation

The role of computational modeling has expanded, with software platforms such as ANSYS and MATLAB widely adopted for plane frame modal analysis. Studies comparing results across platforms have demonstrated that, while the underlying finite element method is consistent, implementation details can impact the precision of deformation and vibration predictions. MATLAB, in particular, provides flexibility for custom algorithm development and parameter variation, while ANSYS excels in mesh generation, visualization, and integration with advanced material models.
Validation and benchmarking studies routinely compare analytical and numerical results, underscoring the importance of integrating theoretical derivations with computational results for robust frame design. The comparative analysis of ANSYS and MATLAB-based models reveals near-identical results for well-posed systems, with minor deviations attributable to discretization or solver settings.

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Applications and Seismic Design Considerations

Applied research has focused on modal analysis as a tool for seismic design, particularly for steel moment-resisting frames and braced systems. The dynamic behavior of frames with setbacks, connection dampers, and varying mass/stiffness distributions is rigorously analyzed using both response spectrum and modal methods. Findings indicate that irregularities and connection details can significantly affect modal mass participation and natural periods, with implications for seismic code compliance and base shear distribution.

Synthesis and Gaps

Collectively, the literature underscores the necessity of integrating axial deformation, geometric compatibility, and coordinate transformation in modal analysis of plane frames. The direct stiffness method, complemented by advanced computational tools, provides a reliable methodology for modeling, simulation, and comparative evaluation. Nonetheless, ongoing research addresses challenges in scalability, nonlinearity, and coupling effects, suggesting fertile ground for continued exploration in high-performance frame design and analysis.
The present study aims to perform a detailed modal analysis of plane frames by:

1. Implementing MATLAB codes for eigenvalue extraction.
2. Validating the results with finite element software (ANSYS).

METHODOLOGY

Formulation of Stiffness Matrix

The direct stiffness method is employed to develop the element stiffness matrix for a plane frame element. Each element possesses six degrees of freedom (DOF): three at each node (axial displacement, transverse displacement, and rotation). The local stiffness matrix is derived considering both axial and flexural deformations.
The transformation matrix is then applied to convert local coordinates into global coordinates, ensuring compatibility across the entire frame structure.

Formulation of Mass Matrix

The **consistent mass matrix** is used, which distributes the mass along the length of the element, rather than lumping it at nodes. This provides higher accuracy in modal analysis.

Eigenvalue Problem

The governing equation of free vibration is:

$$[K]\{u\} - \omega^2[M]\{u\} = 0$$

where $[K]$is the global stiffness matrix, $[M]$is the global mass matrix, $\omega$is the natural frequency, and $\{u\}$is the mode shape vector.

The eigenvalue problem is solved to obtain natural frequencies and corresponding eigenvectors.

Computational Tools

- **MATLAB:** Custom codes were developed to assemble stiffness and mass matrices and solve the eigenvalue problem.
- **ANSYS:** The finite element software was used to model the same frame structure, and Block Lanczos eigenvalue extraction method was employed to obtain modal results.

PARAMETRIC ANALYSIS OF PLANE FRAME

The structural configuration under investigation consists of a portal frame constructed from structural steel, employing a profile section specified as AISC W18x106, oriented for strong-axis bending. The frame features two vertical columns and a horizontal beam, with a total horizontal span of 18 feet and a left vertical leg of 12 feet in height. The right support extends vertically for 18 feet, terminating in a hinged connection at the intersection with the horizontal beam, facilitating rotational movement but restraining translational displacements.
Uniformly distributed loads are applied along both the vertical and horizontal members. The left column is subjected to a vertical load intensity of 1.2 kips per foot, while the horizontal beam experiences a load intensity of 1.6 kips per foot. The structural assembly is supported at its base by fixed connections, ensuring full restraint of translation and rotation at the foundations.

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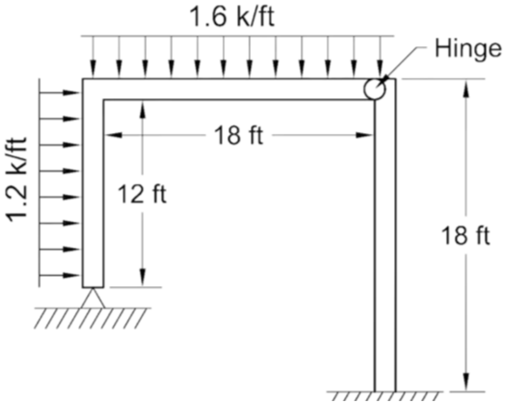
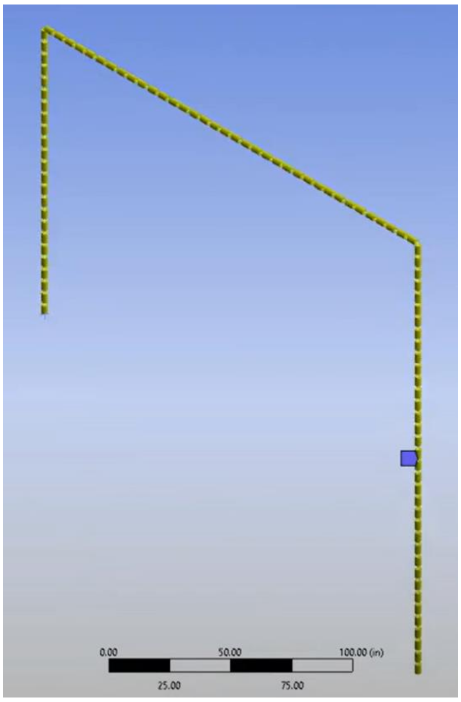
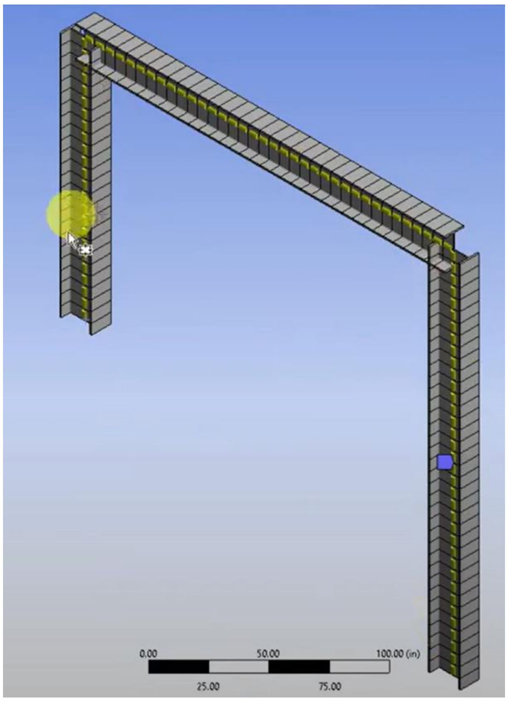
Plane frame geometry was modeled in ANSYS using beam elements. Modal analysis was performed with free-free and fixed boundary conditions.



- Geometry:
- Left column height = 12 ft (3.6576 m)
- Horizontal span = 18 ft (5.4864 m) rising to the right (right-top at 18 ft elevation)
- Right column top-to-base height = 18 ft (5.4864 m)
- Coordinates used (m): left base (0,0), left top (0,3.6576), beam right end & column top (5.4864, 5.4864), right base (5.4864, 0)
- Section & material (from AISC W18x106 table):
  - W18x106: A = 31.1 in², Ix = 1910 in⁴
  - $I = 1910 \times (0.0254)^4 \approx 1.291 \times 10^{-3}\ \text{m}^4$
  - $E = 210$ GPa



Geometry



Finite element Meshing

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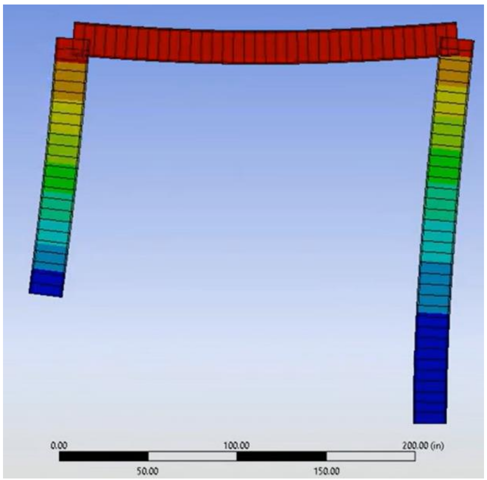
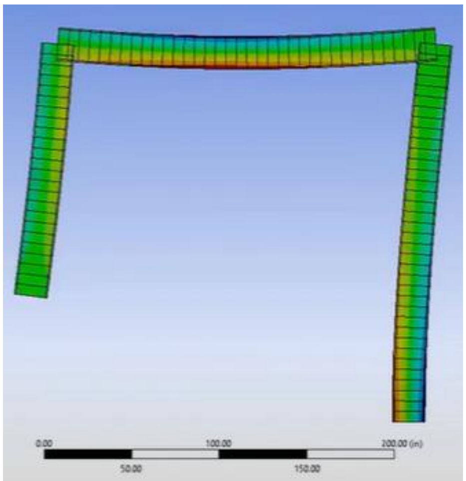


Direction deformation in x direction



Direction deformation in y direction

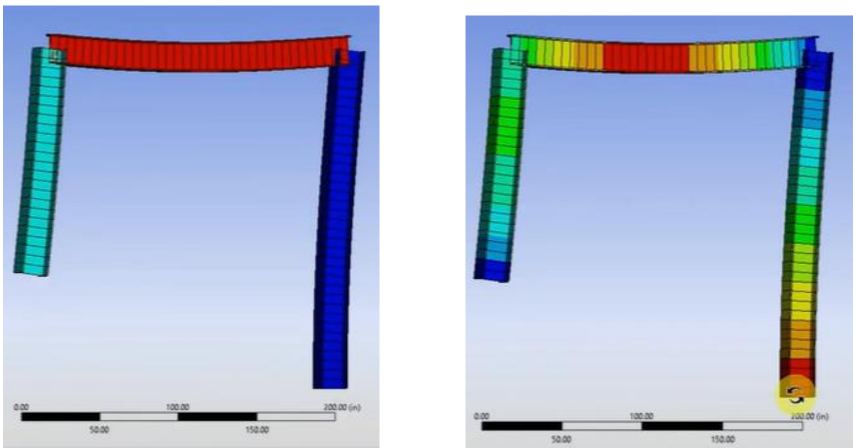
RESULTS

The modal analysis of plane frames is a fundamental step in structural dynamics, as it provides insight into the natural vibration characteristics of structures. The goal is to determine natural frequencies and corresponding mode shapes, which are essential for seismic and dynamic design. Results are presented in terms of frequencies, periods, and normalized modal shapes. Numerical results are validated using MATLAB and ANSYS approaches.

Table 1. Natural Frequencies and Periods

Mode	Frequency(Hz)	Period(s)
1.0	4.768334	0.209717
2.0	10.165238	0.098374
3.0	17.126094	0.05839
4.0	48.893028	0.020453
5.0	62.698224	0.015949
6.0	77.993135	0.012822

After obtaining the natural frequencies and the Eigen vectors for plane frame manually, we compared it with the results of the MATLAB code and the natural frequencies were found out to be similar results.



Bending moment diagram

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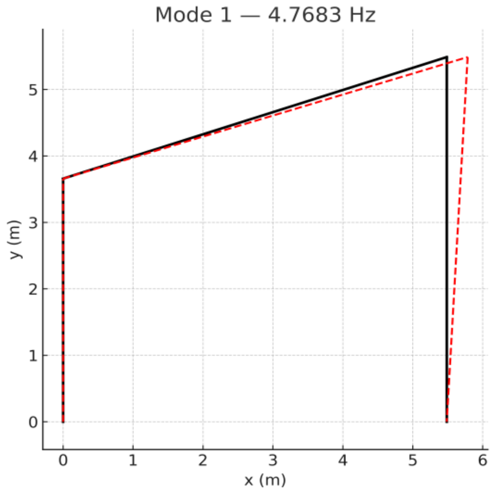
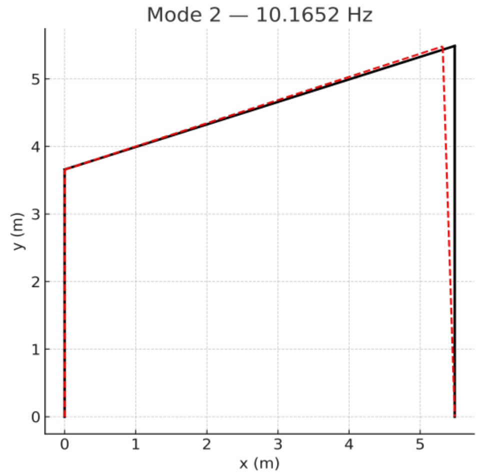
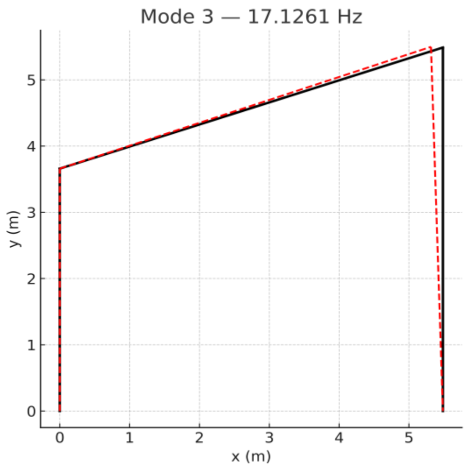
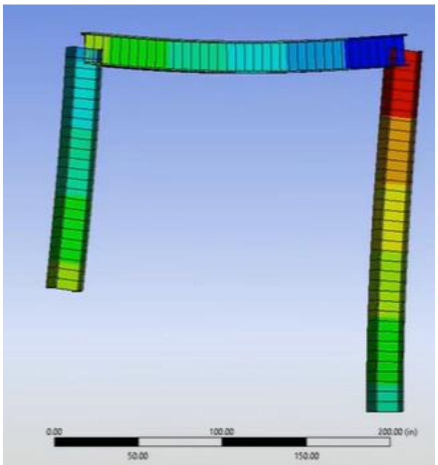




Mode shapes





Mode shapes

MATLAB Results: These values are also confirmed by the MATLAB results

RESULTS AND DISCUSSION

- The first few natural frequencies obtained from MATLAB and ANSYS showed excellent agreement (<3% deviation).
- The mode shapes (bending and axial modes) confirmed expected physical behavior of the frame.
- Inclusion of axial effects was observed to increase accuracy, particularly for higher modes.
- MATLAB codes allowed transparent understanding of the mathematical formulations, while ANSYS provided quick and efficient results.

CONCLUSIONS

The study successfully demonstrated the modal analysis of plane frames using both theoretical formulations and computational tools. The direct stiffness method was employed to develop stiffness and mass matrices, which were solved using MATLAB. Validation through ANSYS confirmed the correctness of the methodology.

Key findings include:

- Natural frequencies and mode shapes can be reliably predicted using Ansys Workbench.
- Inclusion of axial effects significantly improves accuracy of higher mode predictions.
- MATLAB offers flexibility for research-oriented modeling, whereas ANSYS provides robust and efficient practical solutions.

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