Evaluation and Sensitivity Analysis of Two-Dimensional Portal Frames under Variations in Geometry and Boundary Conditions Using SAP2000

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Abstract

The stiffness of a two-dimensional portal frame is governed by the interaction among geometry, section properties, joint rigidity, support restraints, and loading pattern. This paper revises and expands an initial SAP2000 analysis of a 2D portal frame by incorporating a unit audit, model-data reconstruction, normalized sensitivity formulations, a verification procedure, and a mechanically consistent interpretation of the results. The baseline model represents a one-story, one-bay rigid portal made of ASTM A992 steel and subjected to vertical and horizontal distributed loads under linear static analysis. The original outputs show maximum raw values of 7086.87 for shear force, 20673.05 for bending moment, -5874.94 for compressive axial force, and 0.2022 for lateral displacement. Because the screenshots do not explicitly preserve the active output units, these values are treated as raw software results; under an N-m unit system, the force values correspond to 7.087 kN and 5.875 kN, while the moment corresponds to 20.673 kN·m. The normalized screening analysis demonstrates that the flexural response is highly sensitive to column height and beam span because displacement scales approximately with the cube of member length. A 10% increase in height is expected to increase lateral displacement by about 33.1%, whereas a 20% increase produces an increase of about 72.8% when flexural action dominates. A 20% reduction in the second moment of area increases deformation by approximately 25%. Support conditions also modify moment redistribution and drift, with fixed-fixed bases providing the highest restraint compared with configurations involving rotational releases. The revised study emphasizes that SAP2000 results should not be used for design decisions before the model units, geometry, reactions, rotations, and section properties have been independently verified.

Keywords: boundary conditions, portal frame, SAP2000, structural stiffness, sensitivity analysis, unit audit.

INTRODUCTION

Two-dimensional portal frames represent fundamental structural idealizations widely employed to investigate load transfer mechanisms, lateral stiffness, bending moment distribution, and deformation behavior in buildings, industrial facilities, and framed components of offshore structures. Although portal frames exhibit relatively simple geometric configurations, their structural responses result from the interaction of axial deformation in columns, flexural deformation in beams and columns, rotational continuity at connections, and translational and rotational restraints at supports. Consequently, relatively small variations in column height, beam span, second moment of area, or support conditions may produce changes in structural response that are not directly proportional to the corresponding parameter variations [3], [8], [9].

Structural stiffness describes the relationship between applied forces and resulting displacements. In linear elastic systems, this relationship is expressed through the global stiffness matrix, whose coefficients depend on the elastic modulus, cross-sectional area, second moment of area, member length, local element orientation, and nodal compatibility conditions [4], [12], [13]. For portal frames dominated by flexural deformation, member length has a particularly significant influence because the lateral flexural stiffness of an individual frame member is proportional to the inverse cube of its length under comparable restraint conditions. As a result, relatively modest geometric variations may substantially increase lateral drift and alter the distribution of internal forces throughout the structural system [6], [10].

SAP2000 provides frame element formulations capable of representing axial forces, shear forces, bending moments, torsion, structural deformation, end releases, rotational springs, P–Delta effects, and various loading combinations [5]. These capabilities make the software suitable for parametric investigations of structural behavior. Nevertheless, successful numerical execution does not automatically establish the validity of a structural model. Reliable analysis requires systematic verification of geometry, unit systems, section properties, local axis orientations, applied loads, boundary conditions, nodal compatibility, support reactions, and overall force equilibrium [21], [26].

The original manuscript reported an analysis of a single-bay, single-story portal frame subjected to uniformly distributed vertical and horizontal loads. The results were presented through shear force diagrams, bending moment diagrams, axial force diagrams, and deformed configurations. However, inconsistencies were identified between numerical values displayed in the figures and the units reported in the accompanying text. For example, force values of 7086.87 and 5874.94 were expressed in kilonewtons (kN), although these values should correspond to approximately 7.087 kN and 5.875 kN, respectively, if the active SAP2000 output unit system was N–m. Furthermore, the geometry table represented the number of stories and bays as 0.1, which

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is physically inappropriate for discrete structural parameters. Such inconsistencies may lead to incorrect interpretations of structural performance and potentially misleading conclusions regarding design safety and adequacy.

Another methodological concern is the use of the term *sensitivity analysis* without a clearly defined matrix of parameter variations. A systematic sensitivity analysis requires the identification of baseline parameters, variation ranges, response indicators, and quantitative sensitivity measures. Evaluating only a single structural configuration is insufficient to establish the sensitivity of structural responses to changes in geometric or boundary parameters. A more appropriate approach involves evaluating multiple structural scenarios or, when complete model data are unavailable, conducting normalized analytical sensitivity screening to provide a preliminary basis for subsequent parametric simulations [14], [17].

To address these issues, the revised study establishes four principal objectives. First, it seeks to reorganize and verify the geometric properties, material characteristics, loading conditions, support restraints, and numerical outputs of the portal frame model. Second, it aims to correct unit interpretations and explicitly distinguish raw SAP2000 output values from converted engineering quantities. Third, it develops a reproducible framework for examining the sensitivity of structural responses to geometric variations and boundary conditions. Fourth, it investigates the structural mechanics implications of variations in column height, beam span, second moment of area, cross-sectional area, and rotational restraint.

The principal contribution of this study lies in the development of a systematic auditing and verification procedure for relatively simple portal frame models. Such a procedure is particularly relevant to the application and teaching of the matrix stiffness method, where errors in unit selection, geometric definition, or boundary conditions may produce numerical outputs that appear plausible but lack physical validity. In offshore structural engineering, two-dimensional portal frames can also serve as preliminary submodels for structural bents, modular frames, deck framing systems, and support structures before more comprehensive three-dimensional modeling and environmental loading analyses are performed [1], [2], [20].

The scope of the investigation is limited to linear elastic structural behavior. Cross-sectional strength verification, local buckling, lateral-torsional buckling, connection design, fatigue assessment, and dynamic loading are not included in the present analysis. Design standards and specifications, including AISC 360, ASCE 7, Eurocode 3, and ISO 19902, are considered conceptual references to emphasize that structural strength and stability verification constitute subsequent design stages distinct from preliminary stiffness and deformation analysis [18]–[20], [25]. Accordingly, the study focuses on establishing a reliable analytical basis for evaluating how changes in geometry and boundary conditions influence the response of two-dimensional portal frame structures.

THEORETICAL BACKGROUND

Axial and Flexural Stiffness of Frame Elements

A two-dimensional frame element has three degrees of freedom at each node: translation along the element axis, translation perpendicular to the element axis, and in-plane rotation. The element formulation combines the mechanical responses of an axially loaded member and a flexural beam. Under linear elastic conditions, axial stiffness is determined by the elastic modulus (E), cross-sectional area (A), and element length (L) [6], [8].

$$k_{ax} = \frac{EA}{L} \tag{1}$$

Equation (1) indicates that increasing the cross-sectional area or elastic modulus produces a linear increase in axial stiffness, whereas increasing the element length reduces axial stiffness inversely. For flexural behavior, one of the principal coefficients of the element stiffness matrix is expressed as follows [4], [9], [12]:

$$k_b = \frac{12EI}{L^3} \tag{2}$$

The cubic relationship in Equation (2) explains why column height and beam span are particularly sensitive geometric parameters. If the element length increases by 10% without changes in E and I, the corresponding flexural stiffness coefficient decreases to approximately 75.1% of its baseline value. Conversely, displacement in an idealized flexure-dominated mechanism increases to approximately 133.1% of the original value.

The global equilibrium relationship for a linear elastic structural system can be expressed as:

$$[K]\{d\} = \{F\} \tag{3}$$

After the element stiffness matrices are transformed from local to global coordinates and assembled into the global stiffness matrix, boundary conditions are applied by eliminating or modifying the restrained degrees of freedom. The solution of Equation

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(3) provides the nodal displacement vector. Element end forces are subsequently determined from the element stiffness matrix and local deformation vector, together with the fixed-end forces associated with distributed loading [8], [9], [21].

Influence of Portal Frame Geometry

Column height affects lateral stiffness, base moments, and drift. For columns that mainly work in bending, lateral stiffness is inversely proportional to H^3. Increasing the height can quickly reduce stiffness and increase second-order effects when axial compression forces act at the same time. In real-world design, changes in height also affect the effective length and the stability capacity of columns [16], [27], [28]. Span length affects beam stiffness, positive moments at mid-span, negative moments at connections, and the rotation compatibility between beams and columns. Longer beams with the same cross-section become more flexible, so joint rotations increase. These changes shift the moment distribution between beams and columns and can increase sidesway [3], [10], [22].

The beam-column stiffness ratio is a more informative indicator than a single dimension. Simply put, the ratio can be expressed as $\frac{EI}{L}$_beam compared to $\frac{EI}{H}$ column. A relatively stiff beam restrains the column top rotation and enhances the frame action, while a relatively flexible beam allows larger joint rotations. Therefore, sensitivity studies should ideally change the geometry and cross-section properties separately before evaluating their interaction.

Boundary Conditions and Connection Stiffness

Boundary conditions determine the degrees of freedom permitted at the base of a portal frame. A fixed support restrains both translation and rotation, a pinned support restrains translation while permitting rotation, and a roller support allows translation in one direction while restraining displacement in another. In frame analysis, releasing rotational restraints changes the bending moment transfer mechanism and may increase lateral displacement. Therefore, the selected support conditions should represent the actual physical characteristics of the foundation and connections rather than being chosen solely for computational convenience [8], [9].

In practice, connection stiffness exists along a continuum between ideal pinned and fully fixed conditions. Semi-rigid connections can be represented using rotational springs. A very small rotational spring stiffness approximates pinned behavior, whereas a sufficiently large stiffness approaches a rigid connection. Parametric analysis of rotational stiffness can identify the range beyond which further increases in connection stiffness produce only limited reductions in structural drift [3], [16]. For unbraced portal frames, the combination of support restraints and connection stiffness has a substantial influence on lateral stability. A structural model may develop a mechanism when excessive end releases are introduced. Although SAP2000 generally provides instability or matrix singularity warnings, users must still examine unrealistic deformation patterns and unconstrained degrees of freedom [5], [26].

Definition and Indicators of Sensitivity

Sensitivity describes the variation in structural response resulting from a change in an input parameter. For a parameter p and a structural response R, normalized sensitivity can be expressed using a differential formulation or a finite-difference approximation. Normalization enables comparisons among parameters having different physical units [14], [17]. The differential form of normalized sensitivity is:

$$S_p^R = \left(\frac{p}{R}\right)\left(\frac{\partial R}{\partial p}\right) \tag{4}$$

For discrete parametric scenarios, normalized sensitivity may be approximated as:

$$SI = \frac{\left[\frac{R_i - R_o}{R_0}\right]}{\left[\frac{p_i - p_0}{p_0}\right]} \tag{5}$$

where:

S_p^R = Normalized sensitivity of response R to parameter p.
R_0 = Baseline structural response.
R_i = Structural response under variation scenario i.
p_0 = Baseline parameter value.
p_i = Parameter value under scenario i.

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A greater absolute sensitivity value indicates that the structural response is more sensitive to the corresponding parameter. A positive sensitivity indicates that the response increases as the parameter increases, whereas a negative sensitivity indicates an inverse relationship.

For an idealized relationship in which displacement is proportional to the cube of element length, (\delta \propto L^3), the theoretical normalized sensitivity to length is +3. Conversely, for stiffness (k\propto L^{-3}), the sensitivity is −3. For the relationship (\delta\propto 1/I), the normalized sensitivity to the second moment of area is −1.

These analytical relationships provide a preliminary basis for understanding structural response trends before conducting detailed numerical parametric simulations.

Unit Auditing and Mechanical Consistency

SAP2000 allows users to change the displayed unit system without modifying the underlying structural model. Consequently, numerical values displayed in the software can only be interpreted correctly when the active output units are known. Forces, moments, stresses, masses, and displacements must be converted consistently. Common interpretation errors include treating forces expressed in newtons (N) as kilonewtons (kN), moments expressed in N·m as kN·m, or displacements expressed in millimeters as meters.

An equilibrium check represents a minimum requirement for verifying structural analysis results. The sum of vertical support reactions must balance the total applied vertical loads, while horizontal reactions must balance the total applied horizontal loads. The total support and applied moments must also satisfy global moment equilibrium. Furthermore, the signs and distributions of axial forces, shear forces, and bending moments should be consistent with the applied loads and boundary conditions [4], [21]. In this study, unit auditing was treated as an integral component of the methodology rather than a purely administrative verification procedure. This consideration is essential because incorrect unit interpretation can produce substantial errors in calculated drift ratios, stresses, or safety factors, potentially extending over several orders of magnitude.

DATA AND METHODOLOGY

Data Sources and Baseline Model Reconstruction

The baseline data were obtained from the original manuscript and screenshots of SAP2000 analysis outputs. The structural configuration consisted of two columns and one beam forming a single-story, single-bay portal frame. The beam-column connections were modeled as rigid joints.

The original geometry table contained several decimal values that were inconsistent with the physical interpretation of the structural parameters. Therefore, the revised investigation distinguished between documented model information and parameters requiring further verification using the original SAP2000 model file (.sdb).

Table 1. Reconstruction of baseline model parameters and verification status.

Parameter	Revised working value	Verification status and remarks
Number of stories	1	Originally reported as 0.1; reconstructed as one story
Number of bays	1	Originally reported as 0.1; reconstructed as one bay
Portal frame height	3.0 m	Working reconstruction based on model context; verification against the .sdb file is required
Beam span	6.0 m	Working reconstruction based on model context; verification against the .sdb file is required
Element type	2D frame	Resists in-plane axial forces, shear forces, and bending moments
Upper connections	Rigid joints	Full moment transfer between beams and columns
Analysis type	Linear static	Excludes P–Delta effects and material nonlinearity

The reconstructed parameters provide a preliminary basis for the analytical discussion and proposed sensitivity scenarios. However, the dimensions and other assumptions requiring verification should not be regarded as confirmed original model properties until they have been checked against the corresponding SAP2000 model.

Material and Cross-Sectional Properties

The original manuscript specified ASTM A992 structural steel with an elastic modulus of 200 GPa, a Poisson's ratio of 0.30, a density of 7,850 kg/m³, and a minimum yield strength of 345 MPa. These properties are consistent with the general characteristics of structural steel used in linear elastic modeling. However, the original document did not specify the beam and

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column cross-sectional types or dimensions. Because the second moment of area and cross-sectional area directly determine flexural and axial stiffness, respectively, the absence of these properties limits the reproducibility of absolute numerical response predictions [6], [18].

Table 2. Material properties and required cross-sectional data.

Property	Symbol	Value	Application in the structural model
Elastic modulus	E	200 GPa	Axial and flexural stiffness
Poisson's ratio	ν	0.30	Material lateral deformation relationships
Density	ρ	7,850 kg/m³	Self-weight calculation
Yield strength	Fy	345 MPa	Reference for strength capacity; not directly evaluated
Cross-sectional area	A	Not documented	Required for EA and axial response
Second moment of area	I	Not documented	Required for EI and lateral drift

The material properties were retained as reported in the original manuscript, while the missing cross-sectional parameters were explicitly identified as essential inputs for further numerical verification.

Loading, Boundary Conditions, and Analysis Cases

The original manuscript reported vertical and horizontal distributed loads of 10 kN/m. However, another section identified a reference load of 1 ton-force per meter. Since 1 ton-force/m is approximately equivalent to 9.81 kN/m, these two loading values are relatively close but not identical. The revised assessment adopted 10 kN/m as the nominal reference value while retaining the discrepancy as an input requiring verification. Structural self-weight was included through the self-weight multiplier assigned to the relevant gravity load pattern in SAP2000 [5].

The support conditions reported in the original manuscript were also inconsistent. One section specified fixed supports at both column bases, whereas other sections referred to pinned-roller and fixed-fixed configurations. The available output figures displayed similar support symbols at both bases, but the rotational restraints could not be determined reliably from the low-resolution images. Therefore, the fixed-fixed condition was adopted as the working baseline assumption for interpretation, while fixed-pinned and pinned-pinned arrangements were considered conceptual boundary-condition sensitivity scenarios.

Table 3. Loading and boundary-condition cases for baseline modeling and sensitivity assessment.

Component	Baseline model	Sensitivity variation
Uniform vertical load	10 kN/m applied to the beam	Constant across scenarios
Uniform horizontal load	10 kN/m applied to the relevant element	Constant; exact location to be verified in the .sdb file
Self-weight	Included	Constant
Base restraints	Fixed-fixed	Fixed-pinned, pinned-pinned, and rotational springs
Nonlinearity	Not included	P–Delta recommended for future investigation
Load combinations	Single linear analysis case	Separate V, H, and V + H cases recommended for verification

The reference loading and boundary conditions establish the proposed basis for structural interpretation. However, the exact application of horizontal loading and the rotational restraints at the column bases must be verified before definitive numerical conclusions are drawn.

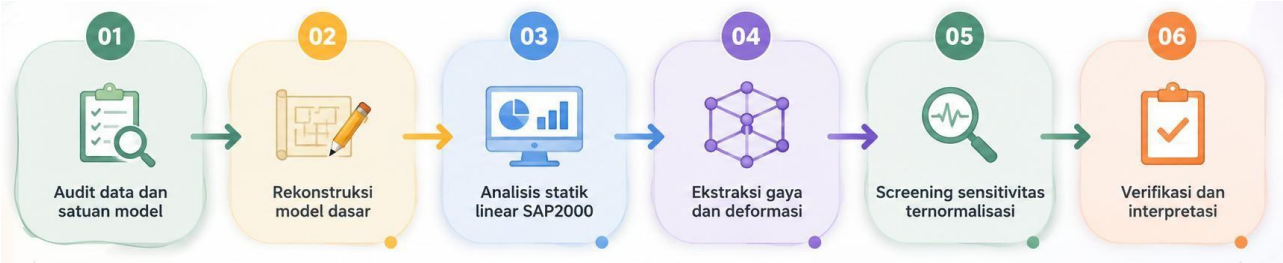


Figure 1. Workflow of the revised study, from input data auditing to structural sensitivity interpretation.

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Parameter Variation Matrix

Geometric sensitivity was examined through an analytical screening approach using parameter ratios of 0.80, 0.90, 1.00, 1.10, and 1.20 relative to their respective baseline values. This corresponds to a variation range of ±20%, allowing preliminary identification of response trends without introducing excessively large changes to the structural configuration. The screening analysis was based on normalized relationships derived from linear elastic structural mechanics and was not presented as the result of additional SAP2000 simulation runs. Actual SAP2000 parametric analyses should be conducted only after the baseline geometry, cross-sectional properties, loading conditions, and boundary restraints have been verified.

Table 4. Recommended parameter variation matrix for structural sensitivity assessment.

Parameter group	Parameter	Scenario range	Principal response indicators
Geometry	Column height, H	0.80–1.20 H_0	Lateral drift, base moment, joint rotation
Geometry	Beam span, L	0.80–1.20 L_0	Beam moment, deflection, rotation
Cross-section	Second moment of area, I	0.80–1.20 I_0	Drift and moment redistribution
Cross-section	Cross-sectional area, A	0.80–1.20 A_0	Axial shortening and relative axial response
Boundary conditions	Rotational stiffness, Kθ	Zero to a very large value	Drift, support moment, and stability
Analysis assumptions	P–Delta effects	Off/On	Drift and moment amplification

The proposed parameter matrix provides a structured basis for identifying the relative influence of geometric characteristics, member stiffness, and boundary conditions on portal frame response. Individual parameter variations should initially be evaluated independently to isolate their respective effects. Subsequent analyses may investigate interactions among parameters once a reliable baseline numerical model has been established.

Verification Procedure

The model verification procedure was organized into four levels.

The first level involved verifying the input data and unit system, including geometric dimensions, material properties, cross-sectional parameters, applied loads, and active SAP2000 output units.

The second level consisted of checking support reactions and structural responses against simplified analytical calculations. This stage was intended to confirm global equilibrium and assess whether the predicted displacement and internal force patterns were mechanically reasonable.

The third level addressed numerical modeling considerations, including member end releases, local axis orientations, joint connectivity, deformation characteristics, and potential instability warnings. These checks were intended to identify modeling inconsistencies that could produce unrealistic or misleading analysis results.

The fourth level involved evaluating structural responses against applicable design criteria after the preceding verification stages had been completed [5], [18], [26].



Figure 2. Hierarchical verification procedure before numerical results are used for structural design decisions.

This hierarchical procedure establishes a distinction between numerical model verification and structural design assessment. A model that satisfies equilibrium and compatibility requirements may provide reliable elastic response predictions,

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but additional strength, stability, and serviceability checks are still required before conclusions regarding structural safety can be established.

BASELINE MODEL RESULTS AND OUTPUT AUDIT

Portal Frame Configuration and Load Transfer Mechanism

The portal frame model illustrated in Figure 3 consists of two columns connected by an upper beam. The original structural diagrams indicate the presence of horizontal support reactions and lateral sidesway deformation. Vertical loads applied to the beam are transferred to the columns through compressive axial forces and end moments, whereas horizontal loading generates story shear forces, joint moments, and base moments. Because the upper beam-column connections are assumed to be rigid, rotational compatibility must be maintained between the connected structural members [8], [9].

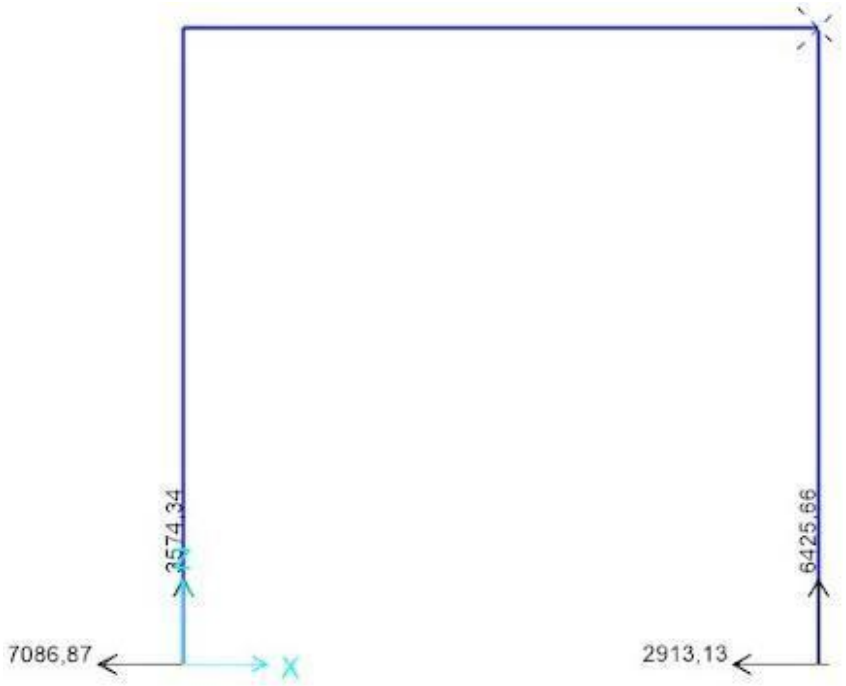


Figure 3. Two-dimensional portal frame model and support reactions displayed in the SAP2000 output.

Shear Force and Bending Moment Distribution

The shear force diagram indicates a maximum raw output value of 7086.87 at the base of the left column and approximately 2913.13 at the right column. If the active SAP2000 unit system is N–m, these values correspond to 7.087 kN and 2.913 kN, respectively. The shear force distribution along the beam varies linearly under uniformly distributed loading. The difference in force values between the left and right sides suggests that the loading configuration or structural restraints may not be entirely symmetrical.

The bending moment diagram presents raw values of 20673.05 at the base of the left column and 14070.35 at the base of the right column. A negative moment of approximately −2281.3 was also identified at one of the beam-column connections, while a positive moment of approximately 1060.96 was observed in the beam region. Assuming that the active moment unit is N·m, the corresponding base moments are 20.673 kN·m and 14.070 kN·m, respectively. The greater base moment in the left column is consistent with its higher reported shear force. However, overall moment equilibrium must be verified using the support reaction tables rather than relying exclusively on graphical force and moment diagrams [4], [22].

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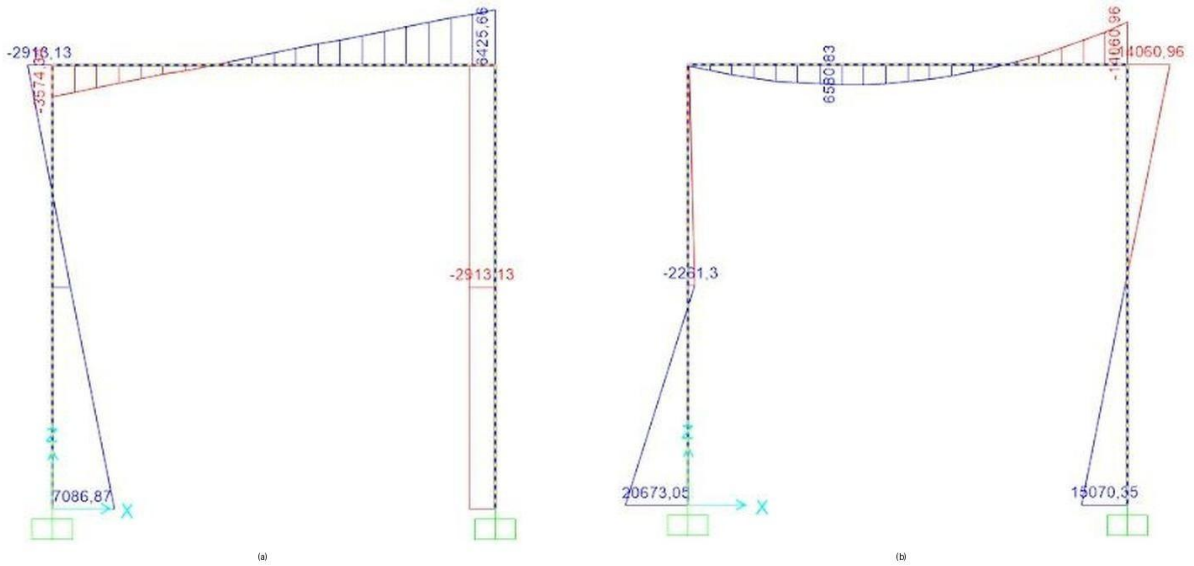


Figure 4. Internal force distributions: (a) shear force 2-2 and (b) bending moment 3-3.

Axial Force Distribution

The axial force diagrams indicate raw values ranging approximately from −3574.94 to −6425.66 in the left and right columns, whereas the original manuscript reports values of −5425.66 and −5874.94.The discrepancies between these values may indicate differences in the selected nodes, load cases, or interpretation of the graphical outputs. Under the adopted SAP2000 sign convention, negative axial forces represent compression. If the active output force unit is the newton, the corresponding compressive forces are on the order of several kilonewtons rather than thousands of kilonewtons. Because vertical loads applied to the beam are transferred to both columns, a relatively uniform axial force distribution along the column height is consistent with the expected response of a portal frame without additional vertically distributed loads applied directly to the columns [6], [14].

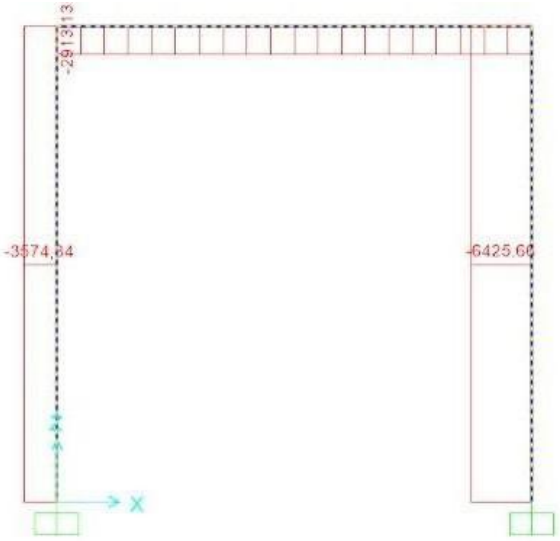


Figure 5. Axial force diagrams for the two portal frame columns.

Structural Deformation and Displacement

The deformed configurations indicate lateral sidesway toward the right and downward deflection of the beam. One output image displays a nodal displacement U1 of approximately 0.202, a displacement U3 of approximately −0.0004, and a rotation R2 of approximately 0.01422. Another output image indicates U1 of approximately 0.319 and R2 of approximately 0.00377.These values are inconsistent with the original displacement table, which reports zero rotations at all nodes. Therefore, the nodal displacement and rotation tables should be re-exported directly from SAP2000 using consistent load cases and explicitly displayed output units.

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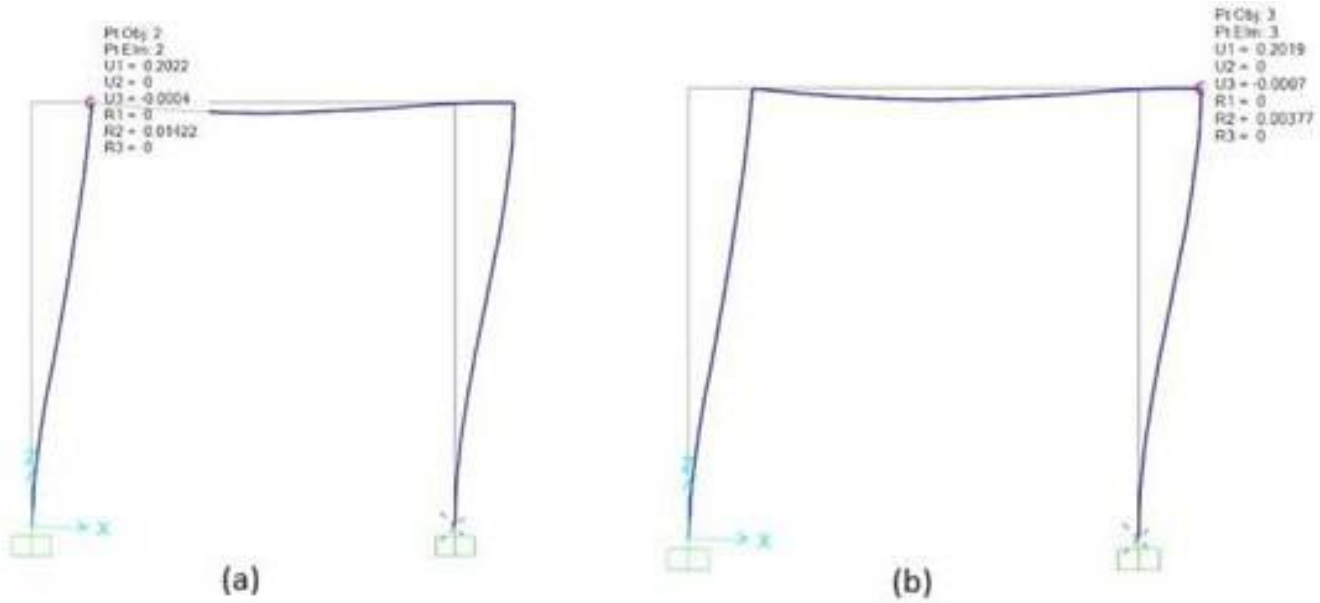


Figure 6. Deformed configurations and nodal displacement/rotation values obtained from two SAP2000 output views.

The maximum lateral displacement of 0.2022 can only be evaluated against drift after the height of the story is confirmed. If the height is 3.0 m, the drift ratio is about 0.2022/3.0 = 0.0674 or 6.74%, which is very large for typical steel structures. If 0.2022 is in mm, the ratio becomes very small. This example shows that safe or unsafe conclusions should not be made before the units and geometry are locked in. Drift criteria in design standards also depend on the function of the structure, type of load, and service conditions [19], [25].

Summary of Numerical Output Audit

The audit indicates that the baseline results remain useful for identifying qualitative structural response patterns but are insufficient for establishing structural safety or design adequacy. The minimum information required for reliable numerical verification includes active units, section names, section properties, load patterns, load cases, self-weight multipliers, support restraints, frame releases, geometric coordinates, and support reaction tables. Without these inputs, the absolute numerical results cannot be reproduced reliably or compared with structural member resistance.

Table 5. Audit of data inconsistencies and interpretations of baseline model outputs.

Structural response	Raw value	Original interpretation	Revised interpretation
Maximum shear force	7086.87	7086.87 kN	7.087 kN if the force unit is N
Left column base moment	20673.05	20673.05 kN·m	20.673 kN·m if the moment unit is N·m
Compressive axial force	−5874.94	−5874.94 kN	−5.875 kN if the force unit is N
Lateral displacement U1	0.2022	0.2022 m	Unit must be verified from active units
Rotation R2	0 in the original table	No rotation	Nonzero rotation shown in the graphical output
Geometry	0.1; 0.3; 0.6	Directly adopted	Potential decimal or transcription errors

NORMALIZED SENSITIVITY ANALYSIS

Sensitivity to Column Height

For a flexure-dominated lateral sidesway mechanism, lateral displacement can be approximated as proportional to the cube of column height. Table 6 presents the theoretical stiffness and displacement ratios corresponding to column height variations of ±20%. These values represent analytical sensitivity screening rather than additional SAP2000 simulation results. Nevertheless, the relationships provide a preliminary basis for identifying parameters that should receive priority in subsequent numerical parametric studies.

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Table 6. Analytical sensitivity screening of column height for flexural response.

H/H₀	Lateral stiffness ratio, k/k₀	Displacement ratio, Δ/Δ₀	Change in Δ
0.80	1.953	0.512	−48.8%
0.90	1.372	0.729	−27.1%
1.00	1.000	1.000	0.0%
1.10	0.751	1.331	+33.1%
1.20	0.579	1.728	+72.8%

A 10% reduction in column height decreases the theoretical displacement to approximately 72.9% of the baseline value. Conversely, increasing column height by 10% increases the displacement to approximately 133.1% of its initial value. A 20% increase in height produces a displacement ratio of 1.728, corresponding to an increase of 72.8%. Thus, the normalized theoretical sensitivity of lateral displacement to column height is approximately +3 under ideal flexure-dominated conditions. In an actual portal frame, however, the sensitivity may differ because of axial deformation, beam stiffness, support restraints, and second-order P–Delta effects.

Sensitivity to Beam Span

Beam deflection and joint rotation are also sensitive to changes in beam span. For a beam subjected to uniformly distributed loading with unchanged cross-sectional properties, characteristic flexural deflection increases strongly with span, while the flexural stiffness coefficients of the element are inversely proportional to the cube of its length. In a portal frame, increased joint rotation affects the distribution of column end moments. Consequently, the sensitivity of internal bending moments to beam span may be more complex than the sensitivity associated with column height alone [10], [22]. As a preliminary analytical screening relationship for a frame component, the following expression was considered:

$$\frac{\Delta}{\Delta_0} \approx \left(\frac{L}{L_0}\right)^3 \tag{6}$$

Using identical length ratios, this approximation produces the same normalized values presented in Table 6.

However, the deflection response of a beam under uniformly distributed loading can follow different length-dependent relationships depending on the loading assumptions and structural restraints. For numerical analysis using SAP2000, two loading scenarios should therefore be distinguished: constant distributed load intensity and constant total applied load. This distinction is necessary to isolate the effects of geometric changes from variations in the total applied loading.

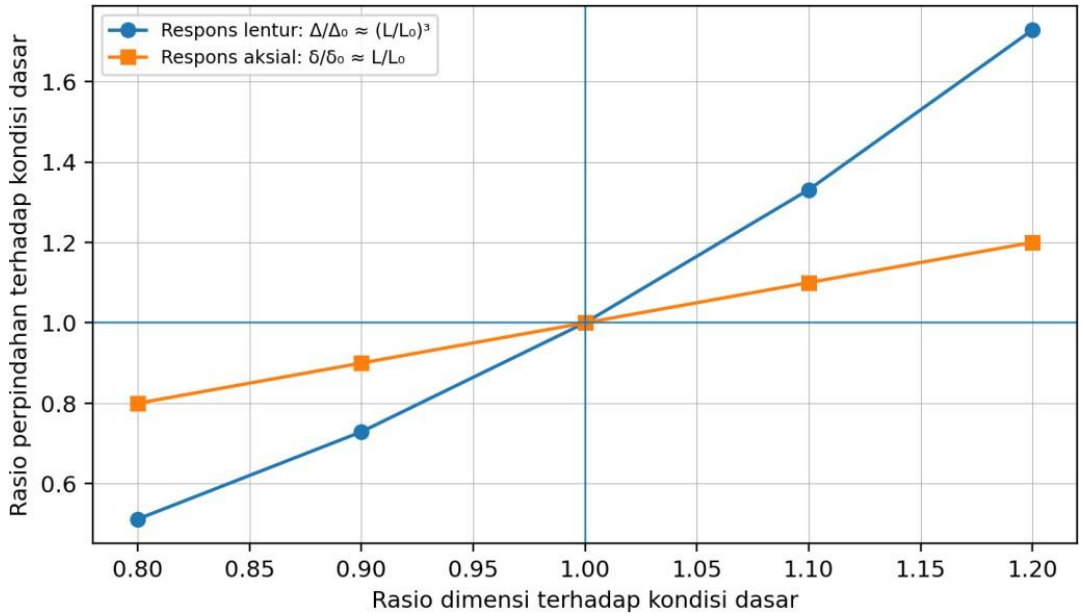


Figure 7. Comparison of axial and flexural displacement sensitivity under variations in member length.

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Sensitivity to the Second Moment of Area and Cross-Sectional Area

In linear bending behavior, displacement is inversely proportional to EI. If E remains constant, changes in I directly affect bending stiffness. A 20% decrease in I increases deformation to 1/0.8 = 1.25 times the baseline. A 20% increase in I reduces deformation to about 0.833 times the baseline. The impact on internal moments depends on the degree of static indeterminacy; in indeterminate portals, changes in relative stiffness alter the moment distribution, not just the deformation [9], [14].

Table 7. Analytical sensitivity screening of the second moment of area for flexural deformation.

I/I_0	Flexural stiffness ratio, k/k_0	Displacement ratio, Δ/Δ_0	Change in Δ
0.80	0.800	1.250	+25.0%
0.90	0.900	1.111	+11.1%
1.00	1.000	1.000	0.0%
1.10	1.100	0.909	−9.1%
1.20	1.200	0.833	−16.7%

The cross-sectional area mainly affects axial shortening and axial stiffness. In models with vertical loads, reducing A increases column shortening and can amplify the P-Delta effect. However, if the section profile is actually changed, A and I usually change together. So, for practical studies, it's better to use the SAP2000 section list rather than changing A and I independently without a physical section.

Sensitivity to Boundary Conditions

The pinned supports prevent the rotation at the base of the two columns, giving the frame the most lateral stiffness and relatively high base moments. When one of the bases is made a hinge, some of the base moment is released and the rotation increases. In a hinge-hinge setup, the frame can still have lateral stiffness because of the rigid beam-column joints, but the drift is usually larger and the moment distribution changes. If extra releases are applied at the top connections, the model can approach a mechanism.

Table 8. Qualitative influence of boundary conditions on portal frame response.

Base condition	Relative stiffness	Base moment	Lateral drift	Remarks
Fixed-fixed	Highest	Significant at both columns	Lowest	Suitable for highly rigid foundations
Fixed-pinned	Intermediate	Concentrated at the fixed base	Increased	Asymmetric structural response
Pinned-pinned	Lower	Approaches zero at the bases	Higher	Stability depends on frame action
Rotational springs	Continuous variation	Depends on $K\theta$	Depends on $K\theta$	Represents semi-rigid connections or foundations

The rotational spring parameter can be normalized against EI/H. A very small $K\theta/(EI/H)$ value represents a hinge, while a very large value approaches a clamp. The drift curve against that ratio generally decreases nonlinearly and then levels off. The transition point can be used to determine whether increasing the foundation or joint stiffness is still structurally effective.remain structurally effective.

Parameter Interactions and Simulation Priorities

The sensitivity effects associated with individual parameters cannot always be combined through direct linear addition. For example, increasing column height while simultaneously reducing the second moment of area may amplify lateral displacement through two interacting mechanisms. Similarly, increasing compressive axial forces may introduce additional second-order effects that amplify moments and lateral displacements. Therefore, following single-parameter sensitivity screening, two-parameter interaction studies should be considered for combinations such as column height and second moment of area, column height and rotational restraint, and beam span and second moment of area. Experimental design methods or response surface approaches may be considered when the number of investigated parameters increases [14], [17].

Table 9. Recommended priorities for subsequent SAP2000 parametric simulations.

Priority	Parameter combination	Engineering rationale
1	Column height and column I	Direct influence on lateral stiffness through H^3/EI

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Priority	Parameter combination	Engineering rationale
2	Column height and base rotational stiffness Kθ	Controls lateral sidesway and base moment response
3	Beam span and beam I	Influences joint rotation and beam bending moments
4	Column area and axial force	Affects axial shortening and potential P–Delta behavior
5	Loading pattern and support conditions	Determines response symmetry and internal force redistribution

DISCUSSION

Consistency of Structural Response with Portal Frame Mechanics

The reported internal force and deformation diagrams exhibit characteristic behavior associated with rigid portal frames. These characteristics include nonzero bending moments at beam-column connections, base moments at restrained supports, compressive axial forces in the columns, and lateral sidesway resulting from horizontal loading components or structural asymmetry. Qualitatively, these response patterns are consistent with the fundamental principles of the matrix stiffness method [8], [9]. However, the mechanical consistency of diagram shapes does not establish the accuracy of the absolute numerical values. Differences in shear forces and bending moments between the left and right columns may result from variations in horizontal load location, unequal support restraints, or differences in local element axis orientation.

If the frame geometry and applied loading are intended to be symmetrical, an asymmetric response may indicate that one or more modeling inputs require further verification. A mirrored structural model or reversal of the applied horizontal load direction may be used to examine numerical symmetry and identify inconsistencies. The presence of nonzero rotation R2 in the graphical output, despite the original table reporting zero rotation, provides an important example of data inconsistency. Such discrepancies may arise when output tables and figures represent different load cases, joints, analysis steps, or display settings. For scientific reporting, each numerical table and graphical output should therefore identify the corresponding load case, analysis step, and unit system consistently.

Interpretation of Drift and Structural Adequacy

The original interpretation that a lateral displacement of 0.2022 m remains structurally acceptable cannot be supported without a verified story height and an applicable drift criterion. Lateral drift should be evaluated as the ratio between relative horizontal displacement and story height, and subsequently compared with the appropriate serviceability requirements. Furthermore, the deformation scale factor used in SAP2000 visualization may exaggerate the displayed structural deformation. Consequently, the graphical appearance of the deformed frame should not be used to estimate actual displacement without consulting the numerical output tables. If the working frame height is 3.0 m and U1 genuinely represents a horizontal displacement of 0.2022 m, the resulting drift ratio is 6.74%. Such a value indicates substantial lateral flexibility and suggests that second-order effects may warrant further investigation.

Conversely, if U1 represents 0.2022 mm, the corresponding drift ratio is approximately 0.0067%. The difference between these two interpretations is a factor of 1,000, demonstrating that unit verification is essential to the validity of structural conclusions. For structural strength assessment, internal forces and bending moments must also be compared with the corresponding member resistance values. Specifications such as AISC 360 and Eurocode 3 require consideration of axial-flexural interaction, local and global stability, and appropriate stability analysis procedures. Because the present study does not include complete cross-sectional information, demand-to-capacity ratios were not calculated [18], [25]. Accordingly, the available results should be interpreted as a preliminary structural response assessment rather than a definitive evaluation of structural safety.

Implications for Offshore Structures and Engineering Education

Although the investigated model represents a conventional portal frame, the analytical and verification procedures are relevant to framed components used in maritime and offshore engineering. Potential applications include structural bent frames, topside modules, support frames, and preliminary submodels of offshore structural systems. In maritime environments, additional factors such as environmental loading, corrosion, fatigue, and foundation conditions introduce further complexity. Nevertheless, reliable numerical analysis continues to depend on the accurate definition and verification of geometry, unit systems, structural stiffness, boundary conditions, and load transfer mechanisms [1], [2], [20]. From an educational perspective, two-dimensional portal frames provide a useful bridge between manual structural analysis and computational modeling.

Students can determine support reactions, joint rotations, and bending moments using slope-deflection or matrix stiffness methods and subsequently compare their calculations with SAP2000 results. Single-parameter variations also help demonstrate the physical significance of axial rigidity (EA), flexural rigidity (EI), member end releases, and support restraints. This approach provides greater instructional value than reporting software screenshots without explaining the underlying structural mechanics

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[7], [11]. The revised study also emphasizes computational reproducibility. SAP2000 model files, joint coordinate tables, section properties, loading definitions, and exported numerical results should be preserved as supplementary research materials. Providing these materials would allow other researchers to reproduce the analysis, verify unit interpretations, and investigate additional structural configurations.

Recommended Numerical Validation Plan

Mesh refinement in frame element analysis does not necessarily require highly refined element subdivisions for linear elastic structural responses. Nevertheless, structural members should be subdivided at locations involving changes in loading, connection conditions, or important output evaluation points. For prismatic members subjected to distributed loading, conventional frame element formulations can provide accurate linear elastic responses using a single element per member when the load formulation is appropriate. Additional subdivisions may be useful for resolving internal force distributions or addressing nonprismatic, nonlinear, or more complex loading conditions [5], [21].

Table 10. Recommended verification checklist for SAP2000 model validation.

No.	Verification item	Acceptance criterion
1	Active units	Explicitly identified in each table and figure
2	Joint coordinates	Story height and beam span agree with the methodology
3	Section properties	A, I2, I3, J, and member self-weight are documented
4	Applied loads	Total loads agree with distributed load intensity multiplied by the loaded length
5	Support reactions	ΣFx, ΣFz, and ΣM satisfy global equilibrium
6	End releases and restraints	No unintended unconstrained degrees of freedom
7	Mesh sensitivity	Changes in principal outputs remain below 2–5%
8	P–Delta effects	Amplification is reported when axial forces are significant
9	Analytical cross-check	Basic support reactions and response trends agree with structural theory
10	Output consistency	Figures and tables use consistent load cases, analysis steps, and units

This verification framework is intended to improve the reliability and reproducibility of structural analysis results before they are used for design interpretation.

Research Limitations

The principal limitation of this study is the unavailability of the original SAP2000 model file, preventing direct verification of active units, joint coordinates, section properties, load patterns, and support restraints. The reconstructed portal height of 3.0 m and beam span of 6.0 m represent working assumptions inferred from the available model context. These values must be revised if the original SAP2000 model indicates different dimensions. The quantitative sensitivity analysis presented in Section 5 is based on normalized linear elastic mechanical relationships. Although these relationships are useful for identifying the direction and approximate magnitude of structural response trends, they do not substitute for actual parametric SAP2000 simulations. Definitive numerical sensitivity results require a verified baseline model in which individual parameters are systematically varied while other relevant variables remain controlled. Furthermore, the study does not evaluate cross-sectional resistance, structural buckling, connection behavior, material nonlinearity, second-order effects, geometric imperfections, or dynamic loading.

For frames exhibiting substantial lateral drift or significant compressive axial forces, first-order linear static analysis may underestimate bending moments and lateral displacements. Therefore, P–Delta analysis and appropriate advanced structural analysis procedures should be considered in subsequent investigations [16], [18], [28]. Another limitation concerns the incomplete specification of the horizontal distributed load location. To improve reproducibility, future work should provide a clearly defined structural diagram identifying global coordinate directions, load application locations, load cases, and loading combinations. Separating vertical and horizontal load cases would also facilitate a clearer understanding of their individual contributions to axial forces, bending moments, and lateral drift. Overall, these limitations indicate that the present findings should be interpreted as a structured numerical output audit and preliminary analytical sensitivity assessment rather than a fully validated parametric study of portal frame performance.

CONCLUSION

The revised analysis demonstrates that the qualitative response patterns of the two-dimensional portal frame are consistent with the fundamental behavior of a rigid frame, as indicated by compressive axial forces in the columns, the development of

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bending moments at beam-column connections and column bases, and lateral sidesway resulting from horizontal loading or asymmetric load distribution. However, the interpretation of numerical results requires careful verification of the active SAP2000 unit system. Raw force values of 7086.87 and −5874.94 cannot be directly interpreted as thousands of kilonewtons without confirming the corresponding output units. If the model employs the N–m unit system, these values are equivalent to approximately 7.087 kN and −5.875 kN, respectively, while the raw bending moment of 20673.05 corresponds to 20.673 kN·m. Similarly, the reported displacement of 0.2022 cannot be considered structurally acceptable without confirming its unit and the actual portal height. If the displacement is expressed in meters and the portal height is 3.0 m, the resulting drift ratio is approximately 6.74%, indicating the need for further assessment of structural stiffness and potential P–Delta effects.

The normalized analytical sensitivity screening indicates that column height and beam span are important geometric parameters influencing structural response. Under an idealized flexure-dominated mechanism, a 10% increase in member length may produce an approximately 33.1% increase in displacement, whereas a 20% increase may result in a displacement increase of approximately 72.8%. A 20% reduction in the second moment of area may also increase flexural deformation by approximately 25%. In addition, more flexible support conditions may reduce bending moments at certain column bases while simultaneously increasing joint rotation and lateral drift. These findings demonstrate that structural sensitivity assessment should not rely solely on a single baseline model but should incorporate a clearly defined parameter variation matrix, consistent response indicators, and quantitative sensitivity measures. The reported sensitivity values represent theoretical screening estimates and require confirmation through verified numerical simulations before being applied to specific portal frame configurations.

Before the numerical results are used for structural design decisions, the original SAP2000 model file (.sdb) should be systematically verified with respect to geometric dimensions, cross-sectional properties, active units, applied loading, support restraints, member end releases, support reactions, joint rotations, and analysis load cases. The proposed parameter variation matrix provides a structured basis for subsequent SAP2000 parametric analyses aimed at validating the theoretical sensitivity trends. Following model verification, further investigations should evaluate structural strength, stability, deformation limits, and nonlinear effects in accordance with the relevant design standards. Overall, this study highlights the importance of integrating numerical output auditing, structural mechanics principles, and systematic sensitivity analysis to improve the reliability, reproducibility, and engineering interpretation of two-dimensional portal frame assessments.

REFERENCES

[1] American Petroleum Institute, API RP 2A-WSD: Planning, Designing and Constructing Fixed Offshore Platforms. Washington, DC, USA: API, 2007.
[2] R. Bhattacharyya, Dynamics of Marine Structures. Hoboken, NJ, USA: Wiley, 2011.
[3] S. L. Chan and P. P. T. Chui, Non-Linear Static and Cyclic Analysis of Steel Frames. Oxford, U.K.: Elsevier, 2000.
[4] R. D. Cook, D. S. Malkus, M. E. Plesha, and R. J. Witt, Concepts and Applications of Finite Element Analysis, 4th ed. New York, NY, USA: Wiley, 2002.
[5] Computers and Structures, Inc., SAP2000 Analysis Reference Manual, Version 22. Berkeley, CA, USA: CSI, 2020.
[6] J. M. Gere and B. J. Goodno, Mechanics of Materials, 8th ed. Stamford, CT, USA: Cengage Learning, 2012.
[7] R. R. Husaini, M. Yazid, A. D. Islami, T. J. Gunawan, and M. D. Wahyudi, "Analisis struktur rangka batang 2D dengan metode matriks kekakuan," Jurnal Rab Construction Research, vol. 8, no. 2, pp. 322-338, 2023.
A. Kassimali, Matrix Analysis of Structures, 2nd ed. Stamford, CT, USA: Cengage Learning, 2012.
[8] W. McGuire, R. H. Gallagher, and R. D. Ziemian, Matrix Structural Analysis, 2nd ed. New York, NY, USA: Wiley, 2000.
[9] S. P. Timoshenko and D. H. Young, Elements of Strength of Materials. Princeton, NJ, USA: D. Van Nostrand, 1965.
[10] S. T. Zulfikar, Dasar-Dasar Metode Elemen Hingga untuk Teknik Mesin. Ambarawa, Indonesia: Universitas Muhammadiyah Ambarawa, 2019.
[11] J. N. Reddy, An Introduction to the Finite Element Method, 3rd ed. New York, NY, USA: McGraw-Hill, 2006.
[12] O. C. Zienkiewicz, R. L. Taylor, and J. Z. Zhu, The Finite Element Method: Its Basis and Fundamentals, 7th ed. Oxford, U.K.: Elsevier, 2013.
[13] T. H. G. Megson, Structural and Stress Analysis, 3rd ed. Oxford, U.K.: Butterworth-Heinemann, 2014.
[14] Y. C. Fung and P. Tong, Classical and Computational Solid Mechanics. Singapore: World Scientific, 2001.
[15] W. F. Chen and E. M. Lui, Structural Stability: Theory and Implementation. New York, NY, USA: Elsevier, 1987.
[16] S. S. Rao, The Finite Element Method in Engineering, 5th ed. Burlington, MA, USA: Butterworth-Heinemann, 2011.
[17] American Institute of Steel Construction, ANSI/AISC 360-22: Specification for Structural Steel Buildings. Chicago, IL, USA: AISC, 2022.
[18] American Society of Civil Engineers, ASCE/SEI 7-22: Minimum Design Loads and Associated Criteria for Buildings and Other Structures. Reston, VA, USA: ASCE, 2022.
[19] International Organization for Standardization, ISO 19902:2020, Petroleum and Natural Gas Industries Fixed Steel Offshore Structures. Geneva, Switzerland: ISO, 2020.
[20] K. J. Bathe, Finite Element Procedures, 2nd ed. Watertown, MA, USA: Klaus-Jürgen Bathe, 2014.

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[21] R. C. Hibbeler, Structural Analysis, 10th ed. Hoboken, NJ, USA: Pearson, 2018.
[22] R. W. Clough and J. Penzien, Dynamics of Structures, 3rd ed. Berkeley, CA, USA: Computers & Structures, Inc., 2003.
A. K. Chopra, Dynamics of Structures: Theory and Applications to Earthquake Engineering, 5th ed. Boston, MA, USA: Pearson, 2017.
[23] European Committee for Standardization, EN 1993-1-1:2005+A1:2014, Eurocode 3 Design of Steel Structures Part 1-1: General Rules and Rules for Buildings. Brussels, Belgium: CEN, 2014.
[24] Computers and Structures, Inc., SAP2000 Verification Manual, Version 22. Berkeley, CA, USA: CSI, 2020.
[25] S. P. Timoshenko and J. M. Gere, Theory of Elastic Stability, 2nd ed. New York, NY, USA: McGraw-Hill, 1961.
[26] R. D. Ziemian, Ed., Guide to Stability Design Criteria for Metal Structures, 6th ed. Hoboken, NJ, USA: Wiley, 2010.

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