Improved Slender Column Design Models for the SBC 304 Saudi Building Code

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Received: 15 July 2025 | Revised: 5 August 2025 | Accepted: 15 August 2025

ABSTRACT

The study offers an in-depth examination of the current design provisions for slender reinforced concrete columns in the Saudi Building Code (SBC 304) and the development of advanced predictive models for practical application. Current design procedures in modern building codes, including SBC 304, primarily rely on the moment magnifier method, where linear static moments are magnified using empirical values based on slenderness ratios and end conditions. These procedures, nevertheless, fail to capture geometric and material nonlinearities, leading to inaccurate and sometimes unrealistic design predictions. Based on a detailed analysis of 107 test specimens from three large-scale experimental programs, the study identified notable deficiencies in the existing code provisions when compared with test results. To address these shortcomings, the study proposes improved design formulae for estimating lateral deflection and failure load in slender reinforced concrete columns, incorporating both material and geometric nonlinearities through advanced nonlinear regression techniques. Statistical validation confirms that the proposed equations are more accurate and reliable than current code-based procedures, yielding significantly lower prediction errors and improved consistency. The new lateral displacement formula reduced the average absolute error by 58% (from 12.9 mm to 5.4 mm) and the coefficient of variation by 30% (from 63.1% to 44.1%) compared with existing code procedures. Failure load prediction equations were also significantly improved, with average absolute errors reduced by approximately 89% for predictions based on section capacity and 42% for slender column analysis-based predictions.

Keywords-slender columns; nonlinear analysis; lateral displacement; failure load; Saudi Building Code; predictive modeling

I. INTRODUCTION

Columns are primary load-carrying members in reinforced concrete structures intended to resist compressive loads. Dissimilar localized structural zones influenced by beam collapse, column collapse can initiate catastrophic progressive collapse, highlighting their greatest importance in structural safety design [1]. The Saudi Building Code (SBC 304) [2] provides specific design criteria for various structural members, such as columns, which are becoming slender in form because of advances in high-strength concrete technology and architectural needs for optimal structural efficiency.

The most important distinction between the behavior of short and slender columns is their mode of failure and controlling design condition. Short columns' load capacity is a function of cross-sectional geometry and material properties [3]. Slender column behavior is more intricate, with secondary moments imposed by geometric characteristics from transverse deflections, referred to as the P-delta effect. Lateral deflections in eccentrically loaded columns increases effective eccentricity, thereby increasing maximum moments and lowering the ultimate load capacity [4, 5].

The P-delta effect is a geometric nonlinearity that increases with increase in column's slenderness ratios. The secondary moment effect can be very damaging to the ultimate load-carrying capacity, the extent of damage depends on variables including slenderness ratio, applied eccentricity, end restraint conditions, and material properties. For very slender columns, these additional moments may lead to stability-related premature failures under loads below expected failure load [6, 7].

The majority of current international design codes, including SBC 304 [2], ACI 318 [8], and Eurocode 2 [9], adopt the moment magnifier method as the primary approach for the design of slender columns. It deals with the second-order effects by scaling first-order moments by empirical magnification factors depending on slenderness ratios and end conditions. However, this approach is not adequate to account for the complex nonlinear behavior exhibited by slender columns, particularly for the cases of large slenderness ratios (typically greater than 60), large eccentricities, different end conditions, the use of high-strength concrete, and complex loading conditions [10].

Comparisons between the code and experimental responses show very significant discrepancies. There is a need for more advanced design procedures that account for both geometric and material nonlinearities to enhance the safety and economic performance of structural designs featuring slender reinforced concrete columns.

II. THEORETICAL BACKGROUND

A. Deformation Behavior of Slender Columns

Slender columns subjected to eccentric loading exhibit pronounced lateral deformations that fundamentally alter their structural behavior through the P-delta effect. As illustrated in Figure 1, when a column is subjected an axial load P with equal eccentricities e at both ends, bending deformations occur that increase the effective eccentricity at the critical section by an additional deflection Δ. This geometric effect transforms the initial moment ($P.e$) into an amplified moment ($P.(e+\Delta)$), representing a significant increase in internal forces [11]. The figure illustrates how initial eccentricity (e) is amplified by lateral deflection (Δ) in slender columns, resulting in increased moments and reduced load capacity. The P-delta effect represents the fundamental difference between slender and short column behavior [12].

The magnitude of this secondary moment depends on several interrelated factors:

- Slenderness ratio (λ): Higher slenderness ratios result in increased lateral deformations and more pronounced P-delta effects.
- Applied eccentricity (e): Greater initial eccentricities amplify the secondary moment effects.
- End restraint conditions: Boundary conditions significantly influence the deflection pattern and magnitude.
- Material properties: Concrete strength and reinforcement characteristics affect both stiffness and ultimate capacity.
- Loading pattern: The distribution and sequence of applied loads influence the deformation response.

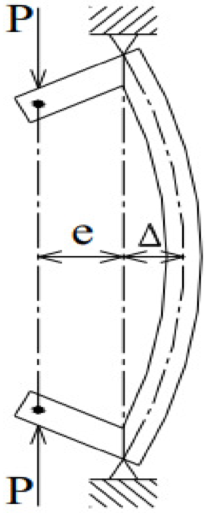

Fig. 1. Deformation mechanism in eccentrically loaded slender column with P-delta effect.

This geometric nonlinearity differentiates slender column behavior from that of short columns: while short columns typically fail due to material strength limitations, slender columns frequently experience stability-related failures before reaching their full material strength capacity. This fundamental difference necessitates design approaches that explicitly account for these geometric effects.

B. Current Code Provisions and Limitations

Contemporary design codes often utilize the moment magnifier method to approximate second-order effects in slender columns. While this method offers a practical and simplified framework for design, it exhibits several limitations:

- Empirical basis: Magnification factors are derived from simplified assumptions that may not accurately reflect actual structural behavior.
- Inadequate consideration of material nonlinearity: The method inadequately accounts for the influence of concrete cracking and steel yielding on structural stiffness.
- Limited scope of applicability: The approach may be inappropriate for columns with very high slenderness ratios or complex loading conditions.

- Over-conservative estimates: Over-conservative predictions can result in inefficient structural designs and increased material consumption.

These shortcomings become particularly evident when analytical predictions are compared against experimental results, underscoring the need for more advanced analytical methods that can capture the combined effects of geometric and material nonlinearities with greater fidelity.

III. EXPERIMENTAL DATABASE AND METHODOLOGY

A. Experimental Database

This study utilized a comprehensive database comprising 107 eccentrically loaded column specimens obtained from three major experimental programs: (1) the El-Gohary Program [13], (2) the Lee and Son Program [14], and (3) the Galano and Vignoli Program [15]. These datasets collectively provide a robust foundation for statistical analysis and model development, covering a wide range of slenderness ratios, concrete strengths, reinforcement configurations, and confinement levels.

1) El-Gohary Program

The study examined 15 models with 100 × 200 mm cross-sections at heights of 2.5, 3.0, and 3.5 m, achieving slenderness ratios of 83.33, 100, and 116.67, respectively. The reinforcement consisted of longitudinal bars of 4Ø10 mm and rectangular ties spaced at 50 mm near the column ends and 100 mm in the middle regions. The concrete strength ranged from 26.5 MPa to 58 MPa, with the focus on high slenderness ratio behavior under eccentric loading.

2) Lee and Son Program

The study examined 32 well-confined specimens with 120 × 210 mm and 120 × 120 mm cross-sections at heights of 0.66, 1.38, and 2.1 m, providing slenderness ratios of 18.33, 49.68, and 58.33 respectively. The reinforcement consisted of 4Ø10 mm and 4Ø16 mm longitudinal bars with Ø10 mm lateral ties at 60 mm spacing for normal-strength specimens and 40 mm spacing for high-strength specimens. Concrete strength ranged from 34.9 MPa to 93.2 MPa, with the focus on high-strength concrete applications with varying confinement levels.

3) Galano and Vignoli Program

The study examined 60 eccentrically loaded specimens with 100 × 100 mm cross-sections at a height of 2.0 m, providing a slenderness ratio of 66.67. The reinforcement consisted of 4Ø8 mm and 4Ø12 mm longitudinal bars with 6 mm diameter square stirrups at 80 mm or 40 mm spacing. Concrete strength ranged from 40.16 MPa to 113.32 MPa, with the focus on medium slenderness behavior with systematic variation of parameters.

B. Analysis Methodology

The evaluation of current SBC 304 provisions was conducted using comparative analysis between code predictions and experimental results. Column capacities were calculated using fundamental equilibrium equations implemented in Microsoft Excel, with cross-sectional analysis based on strain compatibility and force equilibrium principles.

1) Nominal Capacity Calculations

The nominal axial capacity was determined using cross-sectional equilibrium:

$$P_n = C_c + C_s - T = 0.85 f_c' \cdot a \cdot b + A'_s f_s' - A_s f_s \quad (1)$$

$$M_n = P_n \cdot e = C_c\left(\frac{h}{2} - \frac{a}{2}\right) + C_S\left(\frac{h}{2} - d'\right) + T\left(d - \frac{h}{2}\right) \quad (2)$$

where f_c' is the cylinder strength of concrete, a is the depth of equivalent rectangular concrete stress block, b is the column width, A_s' is the area of compression steel, A_s is the area of tension steel, f_s' is the stress in compression steel, f_s is the stress in tension steel, d is the distance from extreme compression fiber to centroid of tension steel, and d' is the distance from extreme compression fiber to centroid of compression steel.

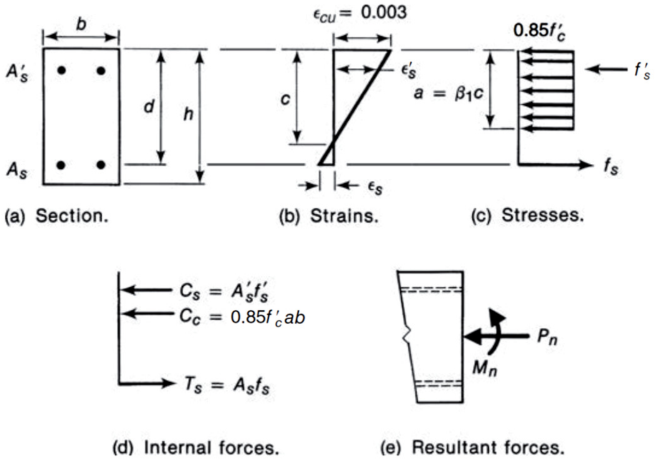

Fig. 2. Cross-sectional analysis for eccentric compression.

Figure 2 shows the stress and force distribution in a reinforced concrete cross-section under eccentric compression, illustrating the compression force (C_c), compression steel force (C_s), and tension steel force (T) used in the equilibrium equations.

2) Deflection Analysis

Total eccentricity at failure was computed as $\delta_f = \frac{M_n}{P_f}$, with mid-height deflection determined as $\delta_{cal} = \delta_f - e_{int}$, where e_{int} represents the initial eccentricity.

IV. RESULTS AND ANALYSIS

A. Evaluation of Current Code Provisions

Statistical analysis of code predictions compared with experimental results revealed significant limitations in current methodologies:

1) Lateral Displacement Predictions

The current code approach for lateral displacement prediction exhibited a mean value of 26.3 mm with a standard deviation of 16.6 mm, resulting in a coefficient of variation of

63.1% and an average absolute error of 12.9 mm. These statistics indicate substantial scatter and systematic bias in displacement predictions, with the high coefficient of variation suggesting poor consistency across different structural configurations.

The scatter plot in Figure 3 shows the relationship between code-predicted and experimentally measured lateral displacements. The 45° line represents perfect agreement, while the deviation of data points indicates the level of prediction accuracy. The substantial scatter demonstrates limitations in current code provisions.

2) Load Capacity Predictions

Two approaches were evaluated for load capacity prediction:

a) Approach 1: Section Capacity Method

$$P_n = 0.85\, fc'\left(A_g - A_{st}\right) + f_y A_{st} \qquad (3)$$

where A_g is the gross cross-sectional area, A_{st} is the total longitudinal steel area, and f_y is the yield strength of reinforcing steel.

Results demonstrated a mean value of 931.4 kN with a standard deviation of 211.2 kN, resulting in a coefficient of variation of 22.7% and an average absolute error of 602.5 kN.

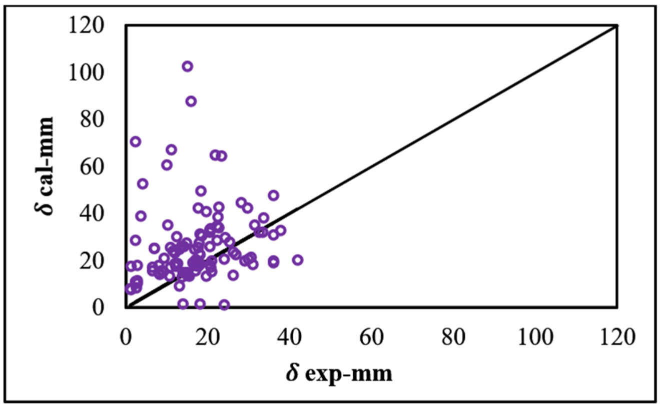

Fig. 3. Correlation between calculated and experimental lateral displacement.

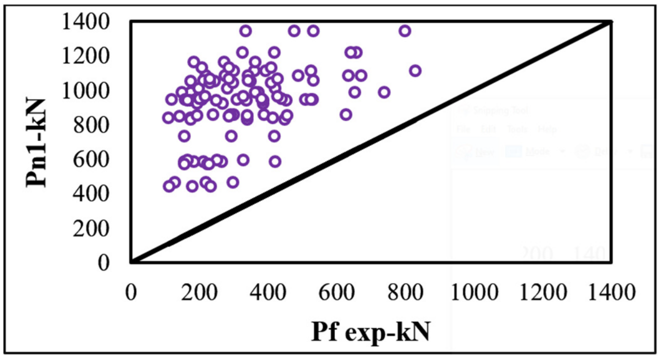

Fig. 4. Correlation between calculated and experimental lateral displacement.

The scatter plot in Figure 4 shows the comparison between section capacity-based predictions and experimental failure loads. The large deviations from the 45° line indicate significant overestimation by the current code method, highlighting the need for improved predictive models.

b) Approach 2: Slender Column Analysis

This approach considers initial eccentricity and lateral deflection effects, yielding a mean value of 464.4 kN with a standard deviation of 281.5 kN, resulting in a coefficient of variation of 60.6% and an average absolute error of 147.2 kN. The scatter plot in Figure 5 shows improved correlation compared to the section capacity method but still exhibits significant scatter and bias. The data demonstrate the limitations of current slender column analysis methods in accurately predicting failure loads.

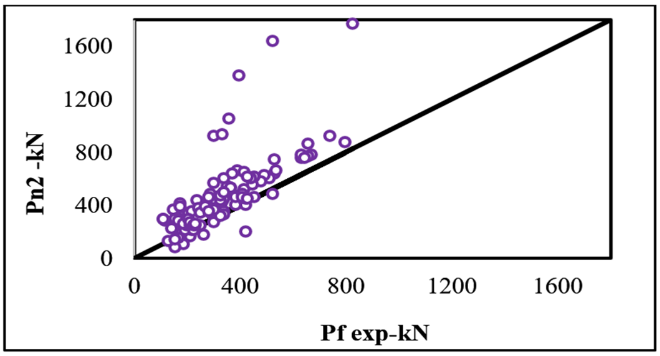

Fig. 5. Correlation between calculated and experimental lateral displacement.

B. Development of Enhanced Predictive Models

Based on comprehensive parametric analysis, enhanced predictive models were developed using nonlinear regression techniques to account for the complex interaction between key design parameters.

1) Enhanced Lateral Displacement Model

Parametric analysis revealed that lateral displacement exhibits power-law relationships with relative eccentricity (*e/h*), slenderness ratio (λ), and reinforcement ratio (ρ). The proposed model takes the form:

$$\delta = c_1 \left(\frac{e}{h}\right)^{c_2} \lambda^{c_3} \rho^{c_4} \qquad (4)$$

The log-log plot shown in Figure 6 demonstrates a power-law relationship between relative eccentricity, slenderness ratio, reinforcement ratio, and lateral displacement. The trend line confirms the suitability of the power-law formulation for model development. Through nonlinear regression analysis using IBM SPSS Statistics-26 [16], the following enhanced equation was derived:

$$\delta = 0.086 \left(\frac{e}{h}\right)^{0.44} \lambda^{1.44} \rho^{0.32} \qquad (5)$$

The proposed model demonstrates substantially improved accuracy with a mean value of 21.9 mm and a standard deviation of 9.7 mm, resulting in a coefficient of variation of 44.1% and an average absolute error of 5.4 mm.

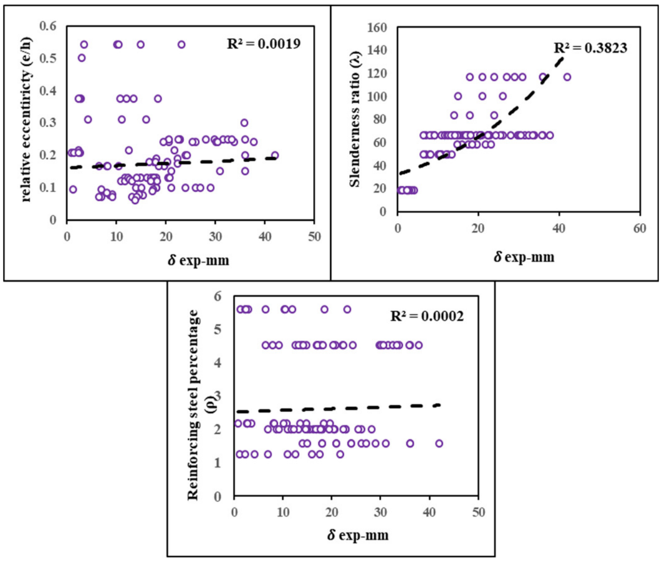

Fig. 6. Relationship between relative eccentricity (*e/h*) slenderness ratio, reinforcement ratio and experimental lateral displacement.

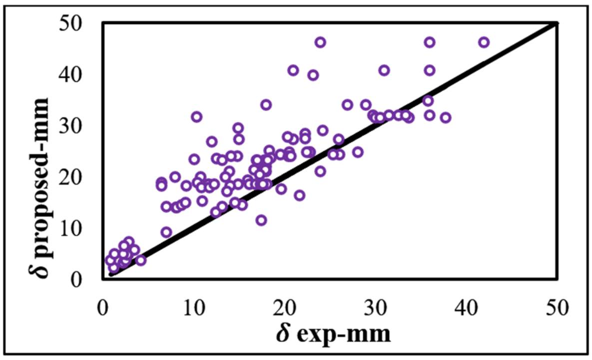

Fig. 7. Validation of proposed lateral displacement model against experimental results.

The scatter plot in Figure 7 shows excellent correlation between proposed model predictions and experimental lateral displacements. The data points cluster closely around the 45° line, demonstrating the superior accuracy of the enhanced model compared to the current code provision.

2) *Enhanced Load Capacity Models*

The Figure 8 illustrates the correlation between section capacity-based nominal load, slender column analysis-based nominal load, relative eccentricity, reinforcement ratio, slenderness ratio, and experimental failure loads. The relationship provides the foundation for developing the enhanced predictive model.

$$\mathrm{Pf} = c_1 P_n \left(\frac{e}{h}\right)^{c_2} \rho^{c_3} \lambda^{c_4} \qquad (6)$$

Two enhanced models were developed for failure load prediction:

a) Model 1: Section Capacity-Based Approach

$$Pf_{P1} = \frac{0.5P_n}{\left(\frac{e}{h}\right)^{0.6} \rho^{0.07} \lambda^{0.35}} \qquad (7)$$

where P_n is calculated using the section capacity method (3).

Performance metrics:

- Mean value: 328.3 kN
- Standard deviation: 116.8 kN
- Coefficient of variation: 35.5%
- Average absolute error: 66.2 kN

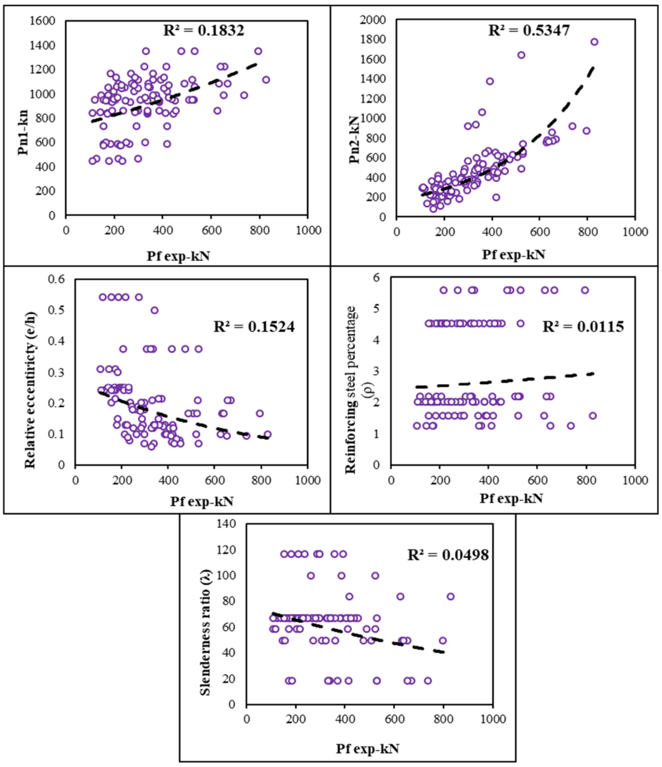

Fig. 8. Relationship between nominal load, relative eccentricity (e/h) slenderness ratio, reinforcement ratio and experimental failure load.

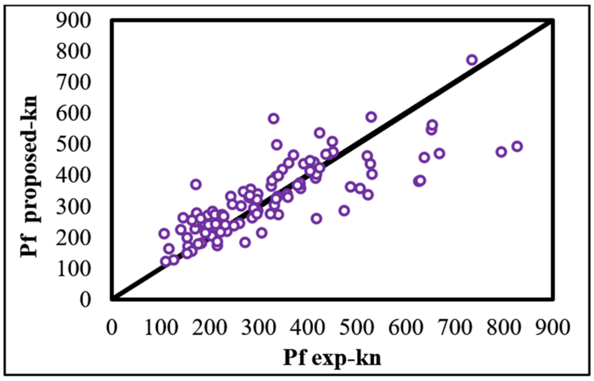

Fig. 9. Validation of proposed failure load model (Model 1) against experimental results.

Figure 9 demonstrates excellent agreement between Model 1 predictions and experimental failure loads. The tight clustering around the 45° line indicates significantly improved accuracy compared to current code methods, with substantial reduction in scatter and bias.

b) Model 2: Slender Column Analysis-Based Approach

This method utilizes relationship given in (8):

$$Pf_{P2} = \frac{0.4 P_n \rho^{0.09} \lambda^{0.07}}{(\frac{e}{h})^{0.53}} \quad (8)$$

where P_n is calculated considering slender column effects.

Performance metrics:

- Mean value: 361.1 kN
- Standard deviation: 230.4 kN
- Coefficient of variation: 63.8%
- Average absolute error: 84.6 kN

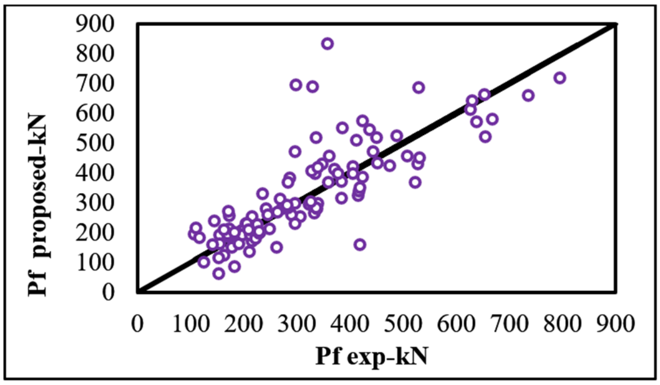

Fig. 10. Validation of proposed failure load model (Model 2) against experimental results.

The scatter plot in Figure 10 shows a reasonable correlation between Model 2 predictions and experimental failure loads. While exhibiting more scatter than Model 1. In spite of scatter, this approach provides improved accuracy compared to current code-based methods for slender column analysis predictions.

V. MODEL VALIDATION AND PERFORMANCE ASSESSMENT

A. Statistical Performance Comparison

1) Lateral Displacement Predictions

TABLE I. STATISTICAL COMPARISON FOR LATERAL DISPLACEMENT PREDICTIONS

Parameter	Code Method	Proposed Model	Improvement
Mean (μ) (mm)	26.30	21.90	16.7%
Standard Deviation (σ) (mm)	16.60	9.70	41.6%
Coefficient of Variation (CV)	63.1%	44.1%	30.1%
Average Absolute Error	12.90	5.40	58.1%
Correlation Coefficient (R^2)	0.612	0.847	38.4%
95% Confidence Interval (mm)	±11.8	±4.2	64.4%

Comprehensive statistical analysis was conducted to evaluate the performance of proposed models against current code provisions. Analysis results are presented in Table I, Table II and Table III:

2) Load Capacity Model Performance

TABLE II. STATISTICAL COMPARISON FOR LATERAL DISPLACEMENT PREDICTIONS

Parameter	Code Method	Proposed Model 1	Improvement
Mean (μ) (mm)	931.40	328.30	-
Standard Deviation (σ) (mm)	211.20	116.80	44.7%
Coefficient of Variation (CV)	22.7%	35.5%	-56.4%
Average Absolute Error	602.50	66.20	89.0%
Correlation Coefficient (R^2)	0.524	0.892	70.2%
95% Confidence Interval (mm)	±184.7	±58.4	68.4%

TABLE III. STATISTICAL COMPARISON FOR LATERAL DISPLACEMENT PREDICTIONS

Parameter	Code Method	Proposed Model 2	Improvement
Mean (μ) (mm)	464.40	361.10	-
Standard Deviation (σ) (mm)	281.50	230.40	18.1%
Coefficient of Variation (CV)	60.6%	63.8%	-5.3%
Average Absolute Error	147.20	84.60	42.5%
Correlation Coefficient (R^2)	0.445	0.763	71.5%
95% Confidence Interval (mm)	±246.1	±78.6	68.1%

B. Model Selection Recommendations

Based on thorough statistical analysis, the recommendations for practical application are as follows:

- For section capacity-based calculation of lateral displacement, Equation (5) performs better with significant improvement in all the statistical criteria and must be utilized as the recommended alternative for serviceability assessment.
- For load capacity evaluation, Model 1 based on (7) is strongly suggested for section capacity-based analysis owing to its much lower absolute error and higher consistency relative to currently available code practices.
- Model 2 based on (8) is another option, providing adequate accuracy for slender column analysis use, but with more scatter than Model 1 and should be used when slender column analysis methods are absolutely required or desired in preference to section capacity.

VI. DISCUSSION

A. Significance of Findings

The enhanced predictive models developed overcome serious limitations of current code provisions by achieving several fundamental advances. The power-law equations achieve good representation of nonlinear effects by simulating complex nonlinear interrelationships between leading design parameters poorly addressed by current methods. The models greatly improve accuracy by reaching substantial reductions in prediction errors, and thus, design reliability for practicing engineers. The models also reduce scatter to the extent that they can have lower coefficients of variation, i.e., are more consistent for different structural arrangements and eliminate most of the uncertainty of current code provisions. Important to the proposal is that the equations remain tractable by maintaining the simplicity required for everyday use in design so that improved accuracy is not obtained at the cost of computation complexity or implementation simplicity.

B. Physical Interpretation of Model Parameters

The exponents in the proposed equations clearly indicate the relative effect of different parameters on slender column behavior. The slenderness ratio (λ) is the most influencing parameter with an exponent of 1.44 in the displacement equation indicating that slenderness has the highest effect on lateral deformations. Relative eccentricity (e/h) exhibits a powerful but secondary influence, as reflected in the moderate exponents of 0.44 for displacement and 0.60 and 0.53 for load capacity, suggestive of its important function in governing column behavior but still in a second-order capacity to slenderness effects. Conversely, however, the reinforcement ratio (ρ) features comparably small exponents in all of the equations, which shows that reinforcement ratio has a comparatively insignificant direct effect on the parameters being investigated, but it still has a role in the overall predictive validity of the models.

C. Limitations and Future Research

While the models proposed have significant improvements, there are several limitations that need to be stated. The models have been developed from specific experimental programs and may be anticipated to require validation for other structural configurations beyond those tested. The models also have been developed in concrete strengths of 26.5-113.32 MPa and may be anticipated to require adjustment for extreme material properties beyond this range. The geometric constraints of the models only apply to the cross-sectional sizes and slenderness ratios described in the experimental database. The next generation of research must focus on expanding the experimental database of structural details, studying the influence of different types of concrete and steel grades, developing models for specific applications such as high-performance concrete structures, and incorporating the proposed models into commercial design packages so that they can be used in general engineering practice.

VII. CONCLUSIONS

This research conducts a detailed evaluation of current slender column design provisions in Saudi Building Code (SBC 304) and proposes enhanced predictive models through rigorous experimental validation. The key findings and contributions are:

A. Current Code Limitations

Statistical analysis revealed critical deficiencies in the SBC 304 design provisions, undermining the reliability of slender column predictions. Lateral displacement predictions show unacceptably large scatter ($CV = 63.1\%$) and substantial errors (12.9 mm average), while load capacity predictions showed even greater inaccuracies, with absolute errors reaching up to 602.5 kN using section capacity methods. These results demonstrate that current code procedures inadequately capture geometric and material nonlinearities, leading to predictions that lack the consistency and accuracy required for safe and efficient structural design.

B. Enhanced Model Performance

The developed models demonstrate transformational improvement in every performance metric. The lateral displacement model based on (5) reduced the average absolute error and coefficient of variation by 58% and 30%, respectively, while the load capacity models achieved even greater improvements, with Model 1 based on (7) delivering an 89% decrease in error and Model 2 based on (8) delivering a 42% decrease in error. These substantial advances mean change rather than incremental gain, significantly increasing the accuracy and reliability of slender column design predictions for engineering application.

C. Recommendations for Practice

Based on extensive verification, the study provides clear guidance for implementation in engineering practice. Equation (5) can be used for the calculation of lateral displacement for enhancing serviceability studies, while (7) is exclusively suggested for load capacity calculation using section capacity analysis due to its greater accuracy and reliability. If analysis of slender columns is desired, (8) can yield acceptable accuracy with significant enhancement compared to the available methods. All proposed equations possess the simplicity required for standard design procedures and offer substantial improvements in accuracy, making them suitable for direct use without the need for advanced computational methods.

ACKNOWLEDGMENT

The authors acknowledge the support provided by the Faculty of Engineering at Umm Al-Qura University, KSA, in facilitating this research.

DATA AVAILABILITY

The dataset supporting the findings of this study is available from the corresponding author upon reasonable request.

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