Evaluation of Flexural Strength Reduction Factors of Members in Reinforced Concrete Moment Frames

Naghmeh Haji Mohammad Yazdi[a], Siamak Epackachi[b*], Vahid Sadeghian[c], Ardeshir Deylami[d]

[a] Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran
[b*] Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran,
epackachis@aut.ac.ir
[c] Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada
[d] Department of Civil and Environmental Engineering, Amirkabir University of Technology, Tehran, Iran

ABSTRACT

This paper investigates the accurate estimation of flexural strength reduction factors in beams and columns of reinforced concrete (RC) moment frames. Traditionally, design codes (e.g., ACI 318-19) prescribe constant reduction factors that do not fully reflect the variability introduced by different design parameters and safety levels. This research addresses these shortcomings by incorporating a comprehensive probabilistic analysis. A dataset comprising 6,750 beams and 3,000 columns with various cross-sectional shapes (rectangular, T-shaped, and L-shaped for beams; rectangular and circular for columns) was generated. Key design variables include concrete compressive strength (25–75 MPa), reinforcement yield strength (420 and 520 MPa), reinforcement ratios (ranging approximately from 0.27% to 6%), axial load ratios (0-0.6), and cross-sectional dimensions. To account for uncertainties in material properties, geometric dimensions, and modeling parameters, random sampling via the Latin Hypercube Sampling method (with 1,000 samples per case) was employed. Additionally, updated statistical models for modeling uncertainty were developed using extensive experimental and nonlinear analytical data. Reliability analyses were conducted using the Rockvitz–Fissler method over a broad range of reduction factors to calibrate them against target reliability indices, as prescribed in ASCE 7-22 for risk categories II (e.g., residential buildings) and IV (structures with higher safety requirements). The findings reveal that for many cases—especially in compression-controlled regions—the reduction factors exceed the values currently specified in ACI 318-19. For instance, in gravity-dominated columns, the proposed reduction factor adjustments lead to significant savings in reinforcement weight (up to 40%) and concrete volume (approximately 15% for an eight-story building) while maintaining the desired safety levels. In summary, the updated reduction factors, which vary according to key design parameters, offer a more realistic assessment of structural behavior and hold promise for achieving both economic and safety improvements in reinforced concrete design. The results encourage a reexamination of current design codes and suggest that incorporating variable reduction factors based on probabilistic analysis can enhance the optimization of material usage in concrete structures.

KEYWORDS

Strength reduction factors, Flexural strength, Flexural strength under axial force interaction, Reliability analysis, Modeling uncertainty.

1. Introduction

In structural engineering, design is often based on deterministic methods using nominal dimensions and material properties. However, real-world structural behavior is influenced by numerous uncertainties, particularly in reinforced concrete structures. These uncertainties include variability in material properties (concrete and steel), geometry, modeling, and loading conditions. Design codes like ACI 318 [1] address such uncertainties using resistance reduction factors (ϕ-factors) within limit state or allowable stress design frameworks. Nevertheless, these factors are typically constant across a wide range of design variables and do

* Corresponding Author: Email: epackachis@aut.ac.ir

not fully account for key parameters such as reinforcement ratio, section shape, or axial load levels. Past studies have proposed reliability-based approaches and updated ϕ-factors, but many rely on outdated modeling uncertainty assumptions. Additionally, current code-based ϕ-factors may lead to non-uniform safety levels. This study addresses these gaps by systematically analyzing nearly 10,000 reinforced concrete beam and column sections and proposing an updated statistical model for modeling uncertainty. The goal is to enhance safety uniformity and improve design economy in concrete structures.

2. Methodology

This study presents a comprehensive probabilistic analysis that systematically incorporates uncertainties in material properties, geometry, modeling, and loading conditions. Prior to the stochastic simulations, models were updated using a combination of experimental data and nonlinear sectional analyses. A large database of 6,750 reinforced concrete (RC) beams and 3,000 RC columns with various cross-sectional shapes (rectangular, T, L for beams; rectangular and circular for columns) was systematically generated. Design variables included concrete compressive strength (25–75 MPa), yield strength of steel (420, 520 MPa), reinforcement ratio (0.27%–6%), axial load ratio (0.1–0.6), and cross-sectional dimensions. For each section, 1,000 Latin Hypercube Samples (LHS) [2] were generated, resulting in a total of 9.75 million sectional analyses. Statistical descriptors including mean flexural strength, coefficient of variation (CV), and distribution type were determined. Reliability analyses were then conducted using the Rackwitz–Fiessler [3] method across a range of strength reduction factors (0.50–0.95), considering different live-to-dead load ratios. Optimal reduction factors satisfying target reliability indices were identified. These target reliability indices were adopted from ASCE 7-22 [4] for risk categories II (e.g., residential buildings) and IV (structures with higher safety requirements). Statistical models for material, geometric, and loading uncertainties were primarily sourced from prior research, except for modeling uncertainties which were updated using experimental and numerical data from 260 beams and 406 columns. Special attention was paid to variation in behavior across different cross-sectional shapes, reinforcement ratios, and interaction regions in columns.

3. Discussion and Results

For beams, results showed that for Risk Category II buildings (target β = 3.0), a φ-factor of 0.95 is appropriate, suggesting the ACI provision is slightly conservative. For Risk Category IV lower φ-factors are needed, beams with lower tensile reinforcement ratios (<0.5%) displayed higher φ-factors due to increased strain hardening effect and model uncertainty mean. T-shaped and L-shaped beams showed slightly higher φ-factors than rectangular. Columns were categorized into tension-controlled, transition, and compression-controlled regions. Circular sections showed higher φ-factors due to enhanced confinement effects. The lowest φ-factors appeared in compression-controlled sections due to brittle behavior and higher target reliability indexes. Key influencing variables included section shape, axial load ratio, concrete strength, and longitudinal reinforcement ratio. Proposed φ-factors based on these variables are summarized in Tables 1–3, offering more optimized and tailored values than current code φ-factors.

4. Conclusions

The findings reveal that for Risk Category II structures, a flexural resistance reduction factor (φ) of 0.95 can be used for beams instead of the standard 0.90, while in high-risk Category IV structures, a lower φ (e.g., 0.85) is recommended for rectangular beams with high tensile reinforcement. For columns, the results vary depending on section shape and failure mode. Circular columns benefit from higher φ-factors due to better concrete confinement. Generally, variables such as concrete strength, reinforcement ratio, axial load ratio, and section shape significantly influence φ-factors. Compression-controlled sections often exhibited much higher φ-factors than current ACI provisions (0.65–0.75), suggesting for more efficient design without compromising reliability, especially in gravity columns. Updated uncertainty models improved φ-factors, with increases up to 0.20 in compression-controlled columns. Using variable φ-values tailored to section properties can form the basis for updating design codes like ACI 318-19, improving realism and material efficiency. For instance, a φ of 0.85 (instead of 0.65) may be used in certain gravity columns, reducing reinforcement by 10–40% and concrete by 5–20%. However, stricter φ-factors (e.g., 0.85 for beams) are needed in Risk Category IV structures. Future studies should examine the systemic seismic performance impact of these revised φ-factors.

Table 1. Recommended φ-factors for RC beams

f_c' (MPa)	[25-40)		[40-60)		≥70	
ρ_s	≤0.5	>0.5	≤0.5	>0.5	≤0.5	>0.5
II			0.95			

Rectangular	IV	0.95	0.85	0.95	0.85	0.90	0.85
	II	0.95					
T- & L-shaped	IV	0.95	0.90	0.95	0.90	0.95	0.90

Table 2. Recommended φ-factors for RC tension-controlled and transition columns

Shape	Risk Category	Tension-controlled	Transition
Rectangular (Tie transverse reinforcement)	II	0.90	0.90
	IV	0.80	0.80
Circular (Spiral transverse reinforcement)	II	0.95	0.95
	IV	0.95	0.90

5. **References**

[1] ACI, Building code requirements for structural concrete:(ACI 318-19) and commentary (ACI 318R-19), American Concrete Institute, 2019.

[2] M.D. McKay, R.J. Beckman, W.J. Conover, A comparison of three methods for selecting values of input variables in the analysis of output from a computer code, Technometrics, 42(1) (2000) 55-61.

Table 3. Recommended φ-factors for RC compression-controlled columns

f_c' (MPa)		[25-40]					
P/P_n		≤0.15		(0.15-0.40]		>0.4	
ρ		[1-3)	[3-6.5)	[1-3)	[3-6.5)	[1-3)	[3-6.5)
Rectangular (Tie transverse reinforcement)	II	-	0.75	0.80	0.80	0.85	0.80
	IV	-	0.65	0.70	0.70	0.75	0.70
Circular (Spiral transverse reinforcement)	II	-	0.95				
	IV	-	0.85	0.90	0.90	0.95	0.95
f_c' (MPa)		[40-60]					
Rectangular (Tie transverse reinforcement)	II	-	0.75	0.75	0.75	0.80	0.80
	IV	-	0.65	0.70	0.65	0.70	0.70
Circular (Spiral transverse reinforcement)	II	-	0.95				
	IV	-	0.85	0.90	0.90	0.95	0.95
f_c' (MPa)		≥70					
Rectangular (Tie transverse reinforcement)	II	-	-	0.75	0.75	0.80	0.80
	IV	-	-	0.70			
Circular (Spiral transverse reinforcement)	II	-	0.95				
	IV	-	0.90	0.90	0.90	0.95	0.90

[3] R. Rackwitz, B. Flessler, Structural reliability under combined random load sequences, Computers & structures, 9(5) (1978) 489-494.

[4] ASCE, Minimum design loads and associated criteria for buildings and other structures, ASCE/SEI 7-22, American Society of Civil Engineers, 2022.