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Probabilistic Calibration of Target Safety Dependent Safety Factors for the Design of Steel Concrete Composite Beams

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ABSTRACT

This study presents a reliability-based calibration of partial safety factors for steel–concrete composite beams designed in accordance with Eurocode 4. The research evaluates the reliability performance of composite beams under ultimate limit states and calibrates partial safety factors to achieve specified target reliability levels. Limit state functions were developed for flexural and shear failure modes. Uncertainties in concrete compressive strength, steel yield strength, dead loads, live loads, and model uncertainty were represented using probabilistic models obtained from established literature. Structural reliability analyses were conducted using the First-Order Reliability Method (FORM) implemented in CodeCal software. Reliability indices ranging from 2.0 to 4.3 were investigated, with emphasis on the Eurocode target reliability index of β = 3.8. The influence of importance factors on structural reliability was also examined. The results showed that reliability is highly sensitive to load variability and importance factors, with optimum performance occurring at importance factors between 0.5 and 0.8. Reliability-based calibration produced optimized partial safety factors for both flexural and shear limit states. At β = 3.8, the calibrated flexural safety factors were γM = 0.98, γG = 1.59, and γQ = 1.35, while the calibrated shear safety factors were γM = 1.05, γG = 1.42, and γQ = 1.50. Comparison with Eurocode values indicated that permanent-action factors require upward adjustment, whereas material and variable-action factors can be reduced while maintaining the target reliability level. The study concludes that reliability-based calibration provides a rational basis for optimizing partial safety factors for steel–concrete composite beams. The calibrated factors improve the consistency of safety margins and achieve target reliability levels while promoting structural economy and design efficiency.

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INTRODUCTION

Steel–concrete composite beams are widely used because they combine the compressive strength of concrete with the tensile strength and ductility of steel, resulting in higher stiffness, improved load-carrying capacity, enhanced serviceability performance, and economic material utilization (Johnson, 2018; Oehlers & Bradford, 2015). Structural safety is commonly governed using the Eurocodes' semi-probabilistic limit state design approach, where uncertainties in loads, material properties, geometry, and modelling are accounted for through calibrated partial safety factors derived mainly from European studies (CEN, 2002, 2004).

However, uncertainties vary with environmental conditions, material quality, construction practices, and loading patterns. In many developing regions, these variations may affect the reliability levels implied by Eurocode safety factors, making reliability-based calibration necessary to achieve consistent target safety levels (Holický, 2011; Mamuda et al., 2018). Composite beams are also subject to multiple

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failure modes, including flexural failure, concrete crushing, shear connector failure, longitudinal shear failure, lateral-torsional buckling, and serviceability limit state violations, each influenced by different sources of uncertainty (Abramowicz et al., 2020; Bairán et al., 2021).

Modern reliability methods such as the First Order Reliability Method (FORM) provide efficient tools for estimating failure probabilities and calibrating safety factors to achieve target reliability indices (Ditlevsen & Madsen, 2007; Melchers & Beck, 2018). Despite the extensive use of composite beams and Eurocodes, limited studies have focused on reliability-based calibration of safety factors for steel–concrete composite beams considering multiple failure modes (Nguyen et al., 2022; Scherer et al., 2024). This research addresses that gap through probabilistic reliability analysis and calibration of Eurocode safety factors for composite beams.

The Eurocodes employ partial safety factors that were calibrated primarily using European statistical data and structural conditions (Faber & Sørensen, 2003). When these safety factors are applied in different environments, the resulting reliability levels may deviate from intended target values due to variations in material strength properties, load characteristics, construction quality, environmental conditions, and structural modelling uncertainties (Velarde et al., 2020).

Steel–concrete composite beams are particularly sensitive to uncertainties because they involve interaction between different materials and multiple failure mechanisms. Limited research exists on reliability-based calibration of safety factors for composite beams considering individual failure modes.

The design of steel–concrete composite beams in modern structural engineering is largely governed by the Eurocode framework, which applies partial safety factors to account for uncertainties in loads, material properties, and structural behaviour (CEN, 2004). The direct application of these factors in different regions with varying environmental conditions, material quality, and construction practices may not always guarantee the intended reliability levels (Cheng et al., 2023).

Steel–concrete composite beams are complex structural systems involving interaction between two different materials and multiple potential failure modes, including flexural failure, shear failure, and longitudinal shear failure. Reliability-based methods provide a rational framework for quantifying uncertainties and evaluating structural safety using probabilistic models (Ang & Tang, 2007; Ditlevsen & Madsen, 2007).

This study is justified on theoretical and practical grounds. Theoretically, it advances understanding of reliability-based design of composite structures, develops probabilistic models for key structural parameters, and provides calibrated safety factors aligned with reliability theory. Practically, it enhances safety and economic efficiency of composite beam design, supports adaptation of Eurocode provisions to local conditions, and provides guidance for structural engineers and policymakers.

The scope of the study is limited to simply supported steel–concrete composite beams designed according to Eurocode, considering ultimate limit state failure modes including flexure, shear, and longitudinal shear. Key random variables including loads and material strengths are analysed using reliability analysis based on FORM, and partial safety factors are calibrated using reliability-based computational tools.

The study is subject to certain limitations, including dependence on available statistical data for probabilistic modelling, simplifications inherent in reliability methods such as FORM, and assumptions in structural modelling and load combinations.

THEORETICAL FRAMEWORK AND LIMIT STATES

Principles of Composite Action

The interaction between structural steel profiles and reinforced concrete slabs is achieved through mechanical shear connectors that transfer

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longitudinal shear forces at the steel–concrete interface (Johnson, 2018). Under positive bending, the concrete slab primarily resists compressive stresses while the steel profile carries most of the tensile stresses, creating an efficient structural section with an expanded lever arm (Oehlers & Bradford, 2015).

Ultimate Limit State Formulations

The structural performance of composite beams under extreme load combinations is modeled using limit state equations that separate the safe domain from the failure domain. The performance safety function is mathematically defined as:

$$Z(X) = R(X) - S(X) \quad (1)$$

where failure occurs when $Z(X) \leq 0$. In this study, the two primary ultimate limit states analyzed are the flexural limit state and the vertical shear limit state.

Flexural Failure Limit State

The ultimate plastic moment resistance is computed assuming a fully plastic stress block distribution. The limit state function for flexure is formulated in terms of the moment resistance and the maximum applied bending moment for a simply supported layout:

$$G(X) = \theta \cdot [A_s \cdot f_y \cdot z + 0.85 \cdot f_c \cdot b \cdot h_c \cdot z_c] - (G + Q) \cdot L^2 / 8 \quad (2)$$

where θ represents the structural model uncertainty factor, As is the cross-sectional area of the steel profile, fy is the steel yield strength, z is the lever arm of the steel force, fc is the concrete compressive strength, b is the effective slab width, hc is the depth of the concrete compression zone, zc is the lever arm of the concrete compressive block, G is the dead load component, Q is the variable live load component, and L is the beam span length.

Shear Failure Limit State

Vertical shear resistance is predominantly provided by the web section of the structural steel profile. The performance function for the shear limit state is written as:

$$G(X) = \theta \cdot (A_v \cdot f_y / \sqrt{3}) - (G + Q) \cdot L / 2 \quad (3)$$

where Av represents the plastic shear area of the steel profile web, and the resistance format is established based on the von Mises yield criterion incorporated into Eurocode 3 and Eurocode 4 provisions.

RESEARCH METHODOLOGY AND STOCHASTIC MODELING

A quantitative reliability-based framework was established to execute the calibration process. The software package EasyFit was used for probabilistic distribution fitting, while CodeCal (developed by the Joint Committee on Structural Safety - JCSS) was used to perform First-Order Reliability Method (FORM) evaluations and optimization computations. Uncertainties associated with material properties, load actions, and structural modeling approximations were explicitly modeled as random variables based on extensive historical data and literature references. The adopted stochastic models are outlined in Table 1.

Table 1: Adopted Stochastic Probabilistic Models for Basic Design Variables

Parameter	**Mean Value (μ)**	**Typical Coefficient of Variation (COV)**	**Standard Deviation (σ)**	**Probability Distribution Model**	**Sources**
Concrete compressive strength, f_c	30 N/mm²	0.15	4.50 N/mm²	Lognormal	(JCSS, 2001; Melchers & Beck, 2018)
Steel yield strength, f_y	75 N/mm²	0.08	6.00 N/mm²	Lognormal	(JCSS, 2001; Nowak & Collins, 2013)

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Parameter	Mean Value (μ)	Typical Coefficient of Variation (COV)	Standard Deviation (σ)	Probability Distribution Model	Sources
Dead load, G	11.2 kN/m	0.10	1.12 kN/m	Normal	(Nowak & Collins, 2013; Ellingwood, 2019)
Live load, Q	13.5 kN/m	0.20	2.70 kN/m	Gumbel	(JCSS, 2001; Nowak & Collins, 2013)
Model uncertainty factorm θ	1.0	0.05	0.05	Normal	(JCSS, 2001; Melchers & Beck, 2018)

The reliability index β is evaluated by transforming the basic variables into an independent standard normal space U and identifying the shortest distance from the origin to the failure surface g(U) = 0, known as the Most Probable Point (MPP) (Breitung, 1984; Ang & Tang, 2007). CodeCal systematically adjusted partial safety factors to minimize the objective penalty function $Y = \Sigma(\beta\text{calculated} - \beta\text{target})^2$ across various load combinations governed by the load importance factor α, following the JCSS code-calibration approach (Faber & Sørensen, 2003), defined as:

$$\alpha = Gk / (Gk + Qk) \quad (4)$$

where Gk and Qk represent nominal characteristic permanent and variable load effects, respectively. The simulated data were fitted to six distribution models (Normal, Lognormal, Lognormal (3P), Gumbel, Weibull, and Weibull (3P) and a test of goodness of fit was carried out using the Kolmogorov-Smirnov Test. The Probability Density and Cumulative Distribution plots are presented in Figures 1 and 2 respectively.

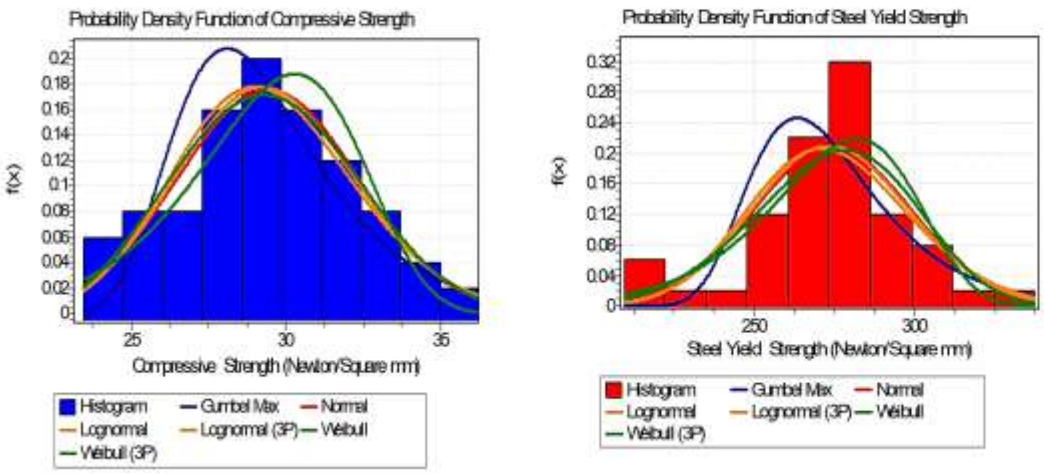

Figure 1: Probability Density Plot for the Compressive Strength of the Concrete and the Yield Strength of the Steel

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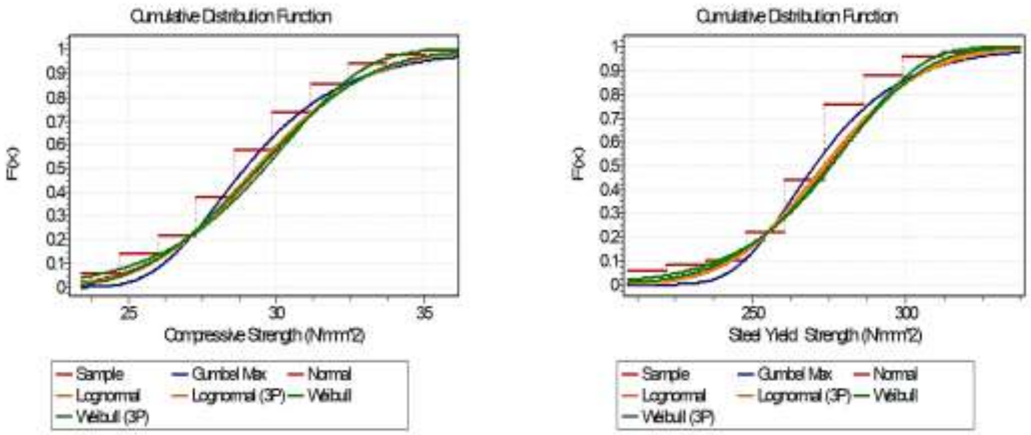

Figure 2: Cumulative Distribution Plot for the Compressive Strength of the Concrete and the Yield Strength of the Steel

The results of the test of goodness of fit are presented in Table 2

Table 2. Test of Goodness of Fit Results for Simulated Data for Concrete and Steel

Distribution Model	Kolmogorov Smirnov Test of Goodness of Fit			
	Concrete Compressive Strength		Steel Yield Strength	
	Test Statistics	Rank	Test Statistics	Rank
Gumbel Max	0.11	6	2.5	6
Lognormal	0.06	4	0.8	5
Lognormal (3P)	0.05	1	0.6	4
Normal	0.05	3	0.56	3
Weibull	0.07	5	0.53	1
Weibull (3P)	0.05	2	0.55	2

RESULTS AND DISCUSSION

Reliability Index Variations

The structural reliability safety index (β) was evaluated across a wide range of target reliability indices (βt = 2.0, 2.5, 3.0, 3.5, 3.8, 4.0, 4.3) as a function of the action participation ratio or load importance factor (α) varying from 0.0 to 1.0.

Variation of Safety Index with Importance Factor for Flexural Limit State

The flexural reliability results demonstrate a clear, symmetric parabolic pattern. For every target safety tier, the computed reliability index peaks in the central importance factor range (α = 0.5 – 0.6) and experiences drops at the load dominance boundaries (α = 0.0 and α = 1.0) as shown in Figure 3. For the standard ultimate limit state target reference of βt = 3.8 (stipulated by EN 1990 for standard RC2 structural systems), the achieved index varies smoothly between a minimum of 3.54 at full permanent load dominance and a maximum of 4.01 at a balanced action ratio. This confirms that the conventional Eurocode 4 formulation provides uneven safety margins across different structural configurations, leaning toward conservatism in mixed action fields while showing minor safety drops under fully static load conditions.

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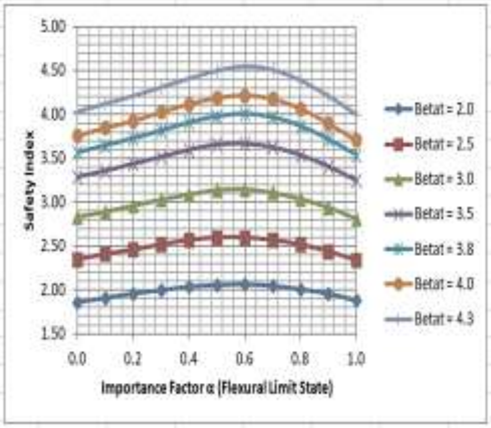

Figure 3. Variation of Safety Index with Importance Factor for Flexural Limit State

Variation of Safety Index with Importance Factor for Shear Limit State

The shear reliability field exhibits a distinct non-monotonic skew compared to flexure. The reliability index increases steadily as the permanent load contribution rises from α = 0.0 to a sharp peak at α = 0.8, followed by a steep drop-off at α = 1.0. At βt = 3.8, the safety indices range between 3.56 at the variable load boundary and 4.21 at α = 0.8, falling to 3.33 under dead load dominance as shown in Figure 4.

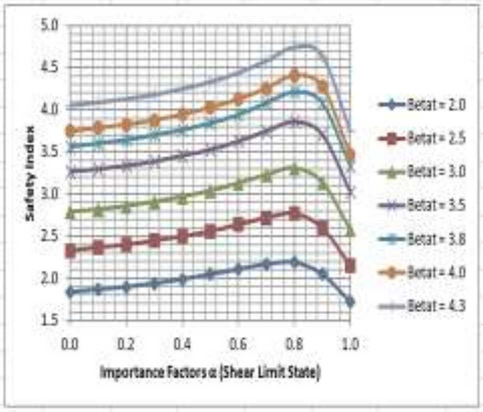

Figure 4. Variation of Safety Index with Importance Factor for Shear Limit State

This indicates high sensitivity to the uncertainty structures of competing actions, highlighting a structural vulnerability when permanent self-weight governs total demand.

Calibration of Partial Safety Factors

Reliability-based optimizations using CodeCal yielded target-dependent partial safety factors. The interaction plots showing calibrated factors against target safety tiers are shown in Table 3 and Table 4.

Table 3: Calibrated Partial Safety Factors for Flexural Limit State

Target Safety Index (βt)	Material Resistance Factor (γM)	Permanent Load Factor (γG)	Variable Load Factor (γQ)	Implied Change over Eurocode (%)
2.0	0.69	1.70	1.34	Material: −37.3% | Dead: +25.9% | Live: −10.7%
2.5	0.69	1.83	1.47	Material: −37.3% | Dead: +35.6% | Live: −2.0%
3.0	0.77	1.77	1.45	Material: −30.0% | Dead: +31.1% | Live: −3.3%
3.5	0.94	1.57	1.32	Material: −14.5% | Dead: +16.3% | Live: −12.0%

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3.8 (Eurocode Target)	0.98	1.59	1.35	Material: −10.9% | Dead: +17.8% | Live: −10.0%
4.0	1.04	1.53	1.32	Material: −5.5% | Dead: +13.3% | Live: −12.0%
4.3 (High Consequence)	1.09	1.53	1.34	Material: −0.9% | Dead: +13.3% | Live: −10.7%

Table 4: Calibrated Partial Safety Factors for Shear Limit State

Target Safety Index (βt)	Material Resistance Factor (γM)	Permanent Load Factor (γG)	Variable Load Factor (γQ)	Implied Change over Eurocode (%)
2.0	0.56	2.05	1.48	Material: −49.1% | Dead: +51.9% | Live: −1.3%
2.5	0.66	1.86	1.52	Material: −40.0% | Dead: +37.8% | Live: +1.3%
3.0	0.85	1.56	1.42	Material: −22.7% | Dead: +15.6% | Live: −5.3%
3.5	0.97	1.47	1.45	Material: −11.8% | Dead: +8.9% | Live: −3.3%
3.8 (Eurocode Target)	1.05	1.42	1.50	Material: −4.5% | Dead: +5.2% | Live: 0.0%
4.0	1.08	1.39	1.53	Material: −1.8% | Dead: +3.0% | Live: +2.0%
4.3 (High Consequence)	1.16	1.38	1.60	Material: +5.5% | Dead: +2.2% | Live: +6.7%

Critical Analysis and Comparative Synthesis

The optimization results reveal a clear shift in how safety margins are allocated across design variables. At the code reference target of β = 3.8, the flexural safety factors (γM = 0.98, γG = 1.59, γQ = 1.35) and shear factors (γM = 1.05, γG = 1.42, γQ = 1.50) show significant deviations from standard Eurocode baseline values (γM = 1.10, γG = 1.35, γQ = 1.50) as shown in Figures 5 and 6 respectively.

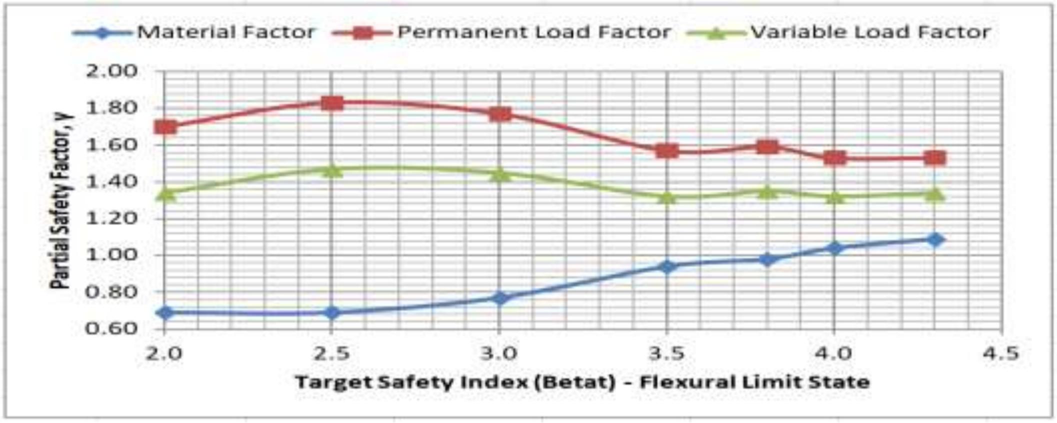

Figure 5. Calibrated Safety Factor for the Flexural Limit State

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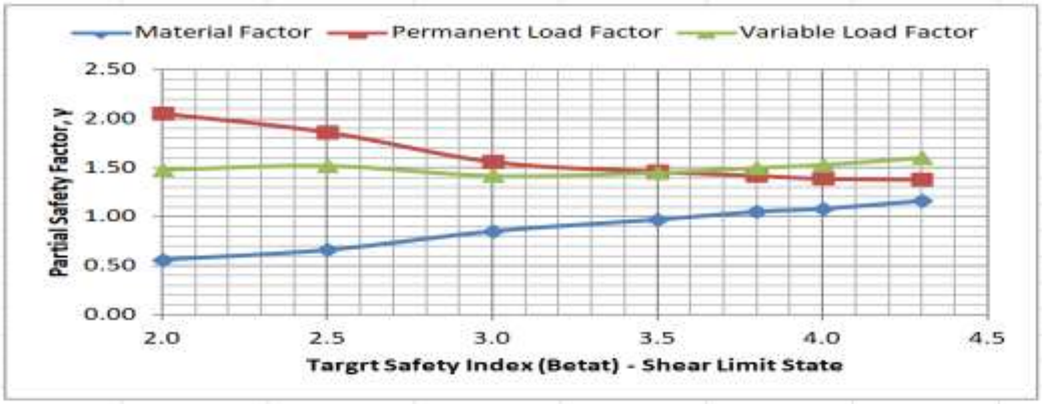

Figure 6. Calibrated Safety Factor for the Shear Limit State

Crucially, the permanent action factor γG requires upward adjustment in both limit states—rising by 17.8% in flexure and 5.2% in shear. This indicates that traditional structural design formats underrepresent dead load uncertainties within specific component configurations, confirming structural trends highlighted by Formichi et al. (2025) and Poutanen (2021), and consistent with the consequence-based recalibration approach reported by Velarde et al. (2020). This redistribution behavior demonstrates that standard deterministic code combinations are not universally optimal for composite members, where material interaction and load composition create unique sensitivity profiles, a pattern also observed by Nguyen et al. (2022) and Scherer et al. (2024) for Eurocode 4-based composite beams and by Cheng et al. (2023) and Bairán et al. (2021) for reinforced and fibre-reinforced concrete members. These findings are broadly consistent with the reliability-based assessment principles established by Holický (2011) for existing structures.

CONCLUSIONS

Based on the analysis, the following conclusions are drawn:

1. Probabilistic modeling demonstrates that variable load parameters introduce significantly higher statistical uncertainty (COV = 0.20) into the structural system compared to material properties under industrial production control.
2. First-Order Reliability Method (FORM) evaluations reveal that standard Eurocode partial factors fail to generate perfectly uniform safety profiles across varying action configurations, with distinct reliability drops under high dead load conditions.
3. Code calibration shows that the current Eurocode 4 format misallocates safety margins for composite beams. It underestimates permanent action risk while overestimating material resistance parameters.
4. Adjusting partial factors to match target reliability demands (e.g., γG = 1.59 and γM = 0.98 for flexure at β = 3.8) balances safety margins and provides a more consistent, rational design format.

Further Study

Based on the findings, the following recommendations should be included in future work:

1. Code Revision Integration: Incorporate component-specific optimization provisions in future updates of the Eurocode framework to reduce reliability scatter across varying load ratios.
2. Regional Database Development: Establish comprehensive regional probabilistic databases to capture variations in local material manufacturing and regional loading conditions.

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3. Limit State Expansion: Extend the reliability-based calibration framework to serviceability, fatigue, and progressive collapse limit states.
4. Advanced Computational Verification: Employ higher-order methods, such as the Second-Order Reliability Method (SORM) and Monte Carlo Simulation, to validate FORM approximations for highly nonlinear cross-sectional layouts.

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Author contributions

JMK, (Conceptualization: Supporting; Formal analysis: Lead; Investigation: Lead; Methodology: Lead; Resources: Lead; Software: Lead; Writing–original draft: Lead; Writing–review & editing: Supporting).

DAL, (Conceptualization: Lead; Investigation: Supporting; Methodology: Supporting; Project administration: Lead; Supervision: Lead; Validation: Lead; Writing–review & editing: Lead).

UNW, (Formal analysis: Supporting; Investigation: Supporting; Methodology: Supporting; Project administration: Equal; Software: Equal; Supervision: Supporting; Writing-review & editing: Supporting).

Declarations

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Consent for Publication: All authors have declared and agreed to publish this research article.

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