Assessment of Eurocode Provisions for Eccentrically Loaded Concrete-Encased Columns with out-of-code Parameters

By

Caron Kasumba

A dissertation submitted to the University of Zambia in partial fulfilment of the requirements of the degree of Master of Engineering in Structural Engineering

University of Zambia

Lusaka

2023

Copyright Declaration

Declaration

I, Caron Kasumba, declares that this dissertation is entirely my own work as specified in acknowledgements and that neither the dissertation nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Signature: ____________________________ Date: ____________________________

Supervisor's name: Dr. Charles Kahanji

Signature: ____________________________ Date: ____________________________

Certificate of Approval

This dissertation of Caron Kasumba is approved as fulfilling the requirements for the award of the Masters of Engineering in Structural Engineering at the University of Zambia.

Examiner 1: ______________________ Signature: ______________________

Examiner 2: ______________________ Signature: ______________________

Examiner 3: ______________________ Signature: ______________________

Chairperson: ______________________ Signature: ______________________

Dedication

To my wife Changala, my family and my friends, I say thank you for your support and inspiration. Above all may Glory be to God, the giver of life.

Acknowledgements

My sincere appreciation goes to my supervisor Dr.C. Kahanji, for his guidance, support and encouragement during the course of my study at the University of Zambia. My gratitude also goes to Dr.M.N. Mulenga, for his warm help in my research work.

Thanks to my family for their prayers and encouragement.

Abstract

This study aims to comprehensively evaluate the viability of applying the current eccentric compressive design provisions outlined in Eurocode 4 (EC4) for concrete-encased steel composite columns with out-of-code parameters. Specifically, the research undertakes an in-depth analysis of the impact of material and geometric properties on the compressive design provisions prescribed by EC4, particularly under eccentric loading conditions, and checking the viability of applying these provisions specifically for high strength concretes and steels. In addition, this study aims to identify any potential shortcomings in the current design guidelines and to suggest modifications that can enhance their accuracy when applying these provisions beyond code specifications.
Despite no reported failures or complaints associated with the current provisions, it is important to note that there has been limited work to assess these provisions in relation to experimental or detailed non-linear finite element analyses and the current provisions are limited to C60/75 concrete and S460 steel despite recent advancements in high strength concrete and steel. This lack of assessment means that the extent to which the current provisions provide the required levels of safety when extended beyond code specifications remains uncertain.

To address these objectives, the research delves into a comprehensive literature review encompassing both experimental and numerical investigations that delve into the compression behavior of eccentrically loaded concrete encased columns, including both in-code and out-of-code parameters. By critically examining the methodologies employed in these experiments, the research aims to ensure that the collected data is both reliable and consistent.

The evaluation process involves the compilation of experimental and numerical data gathered from the literature. This data is then rigorously assessed against the actual behavior exhibited by concrete-encased steel composite columns. The findings reveal that while the current compressive design provisions within EC4 effectively predict the behavior of concrete-encased steel composite columns with in-code parameters, they exhibit notable inaccuracies when it comes to eccentric loading and out-of-code parameter. In fact, a substantial 46% of the columns examined in the database are found to be under-designed based on these provisions. Consequently, the study proposes refined compressive design provisions that take into account the concept of modification factors.

The suggested modifications incorporate adjustments to model factors to account for columns outside the scope of the code. It is important to recognize that this adjustment may lead to designs that are more conservative even for the columns with out-of-code parameters. However, the resultant design approach offers a 95% probability of producing designs that are suitably conservative. This not only enhances the ductility and energy absorption capacity of the columns but also improves their overall structural performance. Ultimately, the findings from this study offer valuable insights into the intricate behavior of concrete-encased steel composite columns with out-of-code parameters. Moreover, the study provides constructive recommendations aimed at refining the accuracy of the existing design guidelines for extension to use of high strength concretes and steel in these composite columns.

Keywords: Eurocode 4; Concrete-encased columns; eccentric load; Assessment

Table of Contents

List of Figures

List of Tables

Chapter 1: INTRODUCTION

1.1 Background

Concrete encased columns are commonly used in building structures, especially in multi-storey buildings. These columns are constructed by encasing a structural steel member (such as a beam or a column) in concrete (Du et al., 2022). The purpose of the concrete encasement is to enhance the strength and ductility of the steel member by providing confinement and lateral support, thus enabling the column to carry high loads and resist lateral forces such as wind and earthquakes (Xu et al., 2016; X. Zhou et al., 2022). In addition, concrete encasement can provide fire resistance to the steel member, which is essential in ensuring the safety of occupants during a fire (K. Zhou & Han, 2018).

The design and assessment of concrete encased columns is a complex task that requires consideration of several factors, such as material properties, cross-sectional design, load combinations, ductility, stability, and detailing requirements (Lai & Liew, 2020). Concrete encased columns can fail due to various modes of failure, such as flexural failure, shear failure, local buckling, and instability (EN-1994, 2009). Therefore, the design and assessment of these columns must ensure that they are able to resist different types of loading conditions and failure modes.

In Europe, Eurocode 4 (EC4) (EN-1994, 2009) is the design standard that provides guidelines for the design and assessment of concrete structures, including concrete encased columns. EC4 provides a comprehensive framework for the design and assessment of concrete encased columns, taking into account various design parameters such as the required strength, load conditions, and confinement provided by the concrete. The design provisions of EC4 are based on a limit state design approach, which ensures that the structure is able to resist both ultimate and serviceability limit states.

Despite the comprehensive guidelines provided by EC4, the effectiveness of these provisions in ensuring the safe and reliable performance of concrete encased columns has been subject to debate, especially the possibility of extension to eccentrically loaded concrete encased columns with out-of-code parameters. There are several issues and challenges (Hadi & Widiarsa, 2012; Huang et al., 2017; Huang et al., 2018; Anuntasena et al., 2019; An et al., 2014; Shan et al., 2019; Cross et al., 2020; Hadi, 2007; Yu et al., 2019; Ghaddar, 2021) related to the design and assessment of concrete encased columns that need to be addressed in the EC4. Table 1.1 gives a summary of the key issues and challenges that need to be addressed with respect to concrete encased columns stipulated by each of the researchers previously mentioned. One of the key issues that need to be addressed is the assessment of the compressive design provisions for eccentrically loaded concrete encased columns with out-of-code parameters, notably the use of high strength concrete and steel in these composite columns.

Therefore, there is a need to conduct further research on the design and assessment of concrete encased columns, and to assess the effectiveness of the eccentric compressive design provisions of EC4 when applied to columns with out-of-code parameters. The aim of this thesis is to address this gap in literature, and to evaluate the performance of concrete encased columns under this eccentric compression limit state.

Table 1. 1 Summary of the key issues raised with respect to concrete encased columns.

Researchers	Issue	Date
Hadi & Widiarsa (2012)	Behaviour of columns with different cross-sectional shapes	2012
	Studies primarily focused on circular columns, while real-world columns often have square or rectangular sections. The shape of the section impacts the confinement behaviour of FRP-strengthened concrete columns.	
Huang et al. (2017)	Influence of eccentricity on the performance of columns	2017
	Eccentric loading leads to varying mechanical behaviour in columns based on the magnitude of eccentricity. Resultant failure modes include concrete crushing and spalling in the compressive side and cracking in the tensile side.	
Shan et al. (2019)	Confined behaviour of steel tube in concrete-filled steel tube (CFST) columns under eccentric loading	2019
	The contact stress between the steel tube and inner concrete in concrete-filled steel tube (CFST) columns is affected by eccentric ratios. Confinement by the steel tube varies under concentric and eccentric loading conditions.	
An et al. (2014)	Failure modes of eccentrically loaded columns	2014

	Eccentrically loaded columns experience failure modes like concrete crushing and spalling on the compressive side and concrete cracking on the tensile side.	
Huang et al. (2018)	Degradation of stiffness and ultimate resistance in composite columns with initial flexural cracking	2018
	Composite columns subjected to initial flexural cracking due to end moment load with large eccentricity can experience stiffness degradation and reduced ultimate resistance. Current design codes might over-predict the composite column's combined resistance.	
Cross et al. (2020)	Effect of FRP confinement on compressive strength of concrete	2020
	Carbon-fibre-reinforced-polymer (CFRP) wrapping enhances the load-carrying capacity and ductility of columns under eccentric loading conditions. The application of vertical CFRP straps significantly improves columns with large eccentricity.	
Anuntasena et al. (2019)	Underestimation of strength in short concrete-encased steel (CES) columns under different loadings	2019
	Design provisions specified in AISC360-16 may underestimate the strength of short concrete-	

	encased steel (CES) columns subjected to concentric or eccentric loadings. The compression behaviour of CES columns under various load conditions needs further investigation.	
Shan et al. (2019)	Accuracy of constitutive models for FRP-confined concrete under eccentric loading	2019
	The accuracy of constitutive models for FRP-confined concrete under eccentric loading has been questioned. New models have been proposed and verified to improve the accuracy of predicting the behaviour of such columns.	

1.2 Rationale

Concrete-encased columns are essential components of building structures, providing enhanced strength, ductility, and fire resistance (Anuntasena et al., 2020). However, the design and assessment of these columns are complex tasks that require consideration of various factors. The compressive design provisions of EC4 are crucial for ensuring the safe and reliable performance of concrete-encased columns under compressive loading conditions. The use of high strength concrete and steel in concrete encased columns may increase their axial load capacity and increase allowable floor space for tall buildings. However, the effectiveness of these provisions for applications to these extents has been subject to debate, and there are several issues and challenges related to the compressive design provisions of EC4 that need to be addressed (Anuntasena et al., 2019).

This research is essential because it aims to enhance the safety and reliability of concrete-encased columns by evaluating the effectiveness of the compressive design provisions of EC4 under eccentric compressive loading conditions. The findings of this will provide a deeper understanding of the behaviour of concrete-encased columns under compressive loading conditions, contributing to the development of more accurate and reliable design guidelines for these essential building components.

The results of this research will be valuable for engineers and designers involved in the design and assessment of concrete-encased columns, providing them with improved guidelines and tools for ensuring the safety and reliability of these components in building structures and improved load bearing capacity. Furthermore, the findings of this research will contribute to the development of more efficient and cost-effective design approaches for concrete-encased columns, benefiting the construction industry. Overall, this research is crucial for enhancing the safety, reliability, and performance of concrete-encased columns in building structures.

1.3 Problem statement

Despite the comprehensive guidelines provided by Eurocode 4 (EC4) for the design and assessment of concrete encased columns, the effectiveness of the compressive design provisions in ensuring the safe and reliable performance of the columns under compressive loading conditions has been subject to debate. There are several issues and challenges (see Table 1.1) related to the design provisions of concrete encased columns and other composite concrete-steel columns that need to be addressed to enhance the safety and reliability of concrete encased columns (Hadi & Widiarsa, 2012; Huang et al., 2017; Huang et al., 2018; Anuntasena et al., 2019; An et al., 2014; Shan et al., 2019; Cross et al., 2020; Hadi, 2007; Yu et al., 2019; Ghaddar, 2021).

One of the main challenges is the accuracy of the material properties used in the compressive design provisions of EC4 and the application of high strength materials in these columns. The design provisions may not accurately capture the non-linear behaviour of these high strength materials, leading to potentially unsafe designs especially for out of code specifications. Additionally, the effect of different cross-sectional dimensions and reinforcement detailing on the performance of concrete encased columns under eccentric compressive loading conditions has not been fully explored; the compressive strength and performance of the concrete encased columns remain unclear. The challenges and concerns raised by researchers about the performance of concrete encased columns have spurred investigations into their behaviour. Some of these concerns include the accuracy of existing design provisions, the effect of different loading conditions, and the adequacy of the current design guidelines under practical scenarios. These concerns have been a driving force for research endeavours aimed at enhancing the safety and reliability of concrete encased columns.

Furthermore, the adequacy of the eccentric compressive design provisions of EC4 in ensuring the safe and reliable performance of concrete encased columns with out-of-code parameters needs to be evaluated.

Therefore, the objective of this thesis is to evaluate the effectiveness of the eccentric compressive design provisions of EC4 in ensuring the safe and reliable performance of concrete encased columns with out-of-code parameters. This will involve assessing the viability of using out-of-code specifications in the design of concrete encased columns with the current EC4 provisions under the eccentric compression limit state. The findings of this research will contribute to enhancing the safety and reliability of concrete encased columns with use of high strength materials in tall building structures.

1.4 Aim

The aim of this research is to evaluate the viability of using the current eccentric compressive design provisions of Eurocode 4 (EC4) for columns with out-of-code parameters in order to ensure the safe and reliable performance of eccentrically loaded concrete encased columns.

1.5 Specific objectives

- To assess the viability of existing compressive design provisions for eccentrically loaded concrete-encased columns with out-of-code parameters against experimental and non-linear finite element modelling (FEM) results reported in literature.
- To propose modifications to the existing compressive design provisions for eccentrically loaded concrete-encased columns based on the assessment results, so that the modified provisions can be applied on columns with out-of-code parameters.
- To validate the proposed modifications to the existing compressive design provisions for eccentrically loaded out-of-code concrete-encased columns against experimental and FEM results.

1.6 Research questions

- What are the discrepancies and limitations of the existing compressive design provisions for eccentrically loaded concrete-encased columns when applied with high strength concrete and steel?

- How accurately do the existing compressive design provisions predict the behavior of eccentrically loaded out-of-code concrete-encased columns under compressive loads compared to experimental and FEM results reported in the literature?
- What modifications can be made to the existing compressive design provisions for eccentrically loaded concrete-encased columns to address the identified discrepancies and limitations for the provisions to be applied to columns with out-of-code parameters?

1.7 Significance of study

The significance of the study lies in its potential to improve the accuracy and reliability of the design provisions for composite columns with out-of-code parameters under eccentric compressive loads when applied to columns with high strength concrete and steel. By addressing any discrepancies and limitations in the existing design provisions and proposing modifications, the study can help reduce the risk of structural failure and improve the safety and durability of composite structures.

In addition, the study can have a lot of economic benefits by providing more efficient and cost-effective designs for eccentrically loaded concrete-encased columns with out-of-code parameters. By improving the accuracy of the design provisions, the study can reduce the need for costly safety factors and conservatisms in the design process, which can lead to more efficient use of innovative materials and reduced construction costs.
Overall, this study aims to contribute to the advancement of knowledge in the field of eccentrically loaded concrete-encased column design and provide practical and reliable design provisions for the construction industry.

1.8 Scope of the study

The scope of this research will be limited to the compressive design provisions of EC4 for concrete-encased columns under eccentric compressive loading conditions. The research will focus on evaluating the effectiveness of the compressive design provisions of EC4 in ensuring the safe and reliable performance of eccentrically loaded concrete-encased columns with out-of-code parameters under eccentric compressive loads when applied to columns with high strength concrete and steel. The study will also investigate the accuracy of material properties used in the compressive design provisions of EC4, particularly for high-strength concrete and steel. Additionally, the research will explore the effect of different cross-sectional dimensions and reinforcement detailing on the performance of concrete-encased columns under compressive loading conditions.

However, this research will not cover the following:

- The behavior of concrete-encased columns under other loading conditions, such as shear, and torsion.
- The influence of other factors, such as temperature, moisture, and shrinkage, on the performance of concrete-encased columns.
- The development of new or alternative design methods for concrete-encased columns.

1.9 Structure of the dissertation

This dissertation comprises the following chapters:

Chapter 1: Introduction - This chapter provides an overview of the research topic, including the background, rationale, aim, research objectives, scope, and limitations.

Chapter 2: Literature Review - This chapter provides a critical review of the relevant literature on the compressive design provisions of EC4 for concrete-encased columns under compressive loading conditions. The chapter also discusses the existing knowledge gaps, research challenges, and opportunities for further research.

Chapter 3: Methodology - This chapter describes the research methodology used to achieve the research objectives, including analytical procedures and statistical analyses used.

Chapter 4: Results and Discussion - This chapter presents and analyses the results obtained from the assessment. The chapter also discusses the findings in the context of the existing literature and research objectives.

Chapter 5: Conclusions and Recommendations - This chapter summarizes the key findings of the research, draws conclusions, and provides recommendations for future research and practice.

1.10 Chapter Summary

Chapter 1 introduces the research background, rationale, problem statement, aim, objectives, research questions, significance, and scope. It highlights the importance of evaluating EC4's compressive design provisions for concrete encased columns with out of-code parameters to ensure their safe and reliable performance in building structures.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

Concrete-encased columns are widely used in the construction of buildings and bridges due to their excellent structural properties. They offer high load-bearing capacity, durability, and fire resistance, making them an attractive option for various applications (Zeng et al., 2019). The Eurocode provisions for the compression design of concrete-encased columns are widely adopted by engineers and designers in Europe and other parts of the world (Medeiros et al., 2021). However, the effectiveness and accuracy of these provisions for eccentrically loaded columns are not well understood. The behaviour of eccentrically loaded concrete-encased columns is complex and highly influenced by various factors such as the column geometry, concrete strength, steel reinforcement, and loading conditions (Tunc et al., 2022). Therefore, there is a need to evaluate the Eurocode provisions for the compression design of eccentrically loaded concrete-encased columns and assess their effectiveness in predicting the behaviour of such columns. This literature review aims to critically analyse the existing literature on the Eurocode provisions for compression design of eccentrically loaded concrete-encased columns and identify areas for improvement. The study will provide insights into the current state-of-the-art in the design of eccentrically loaded concrete-encased columns and highlight the gaps in the literature that require further research. By doing so, this study will contribute to the development of more accurate and efficient design codes for concrete-encased columns, which will enhance the safety and sustainability of civil engineering structures.

2.2 Eurocodes

The Eurocodes are a set of European standards that provide guidelines for the design of civil engineering structures, including buildings and bridges. They are developed by the European Committee for Standardization (CEN) and are widely adopted in Europe and other parts of the world. Eurocode 4 (EN 1994-1-1) provides guidance for the design of composite steel and concrete structures, which includes concrete-encased columns.

2.3 Compression design of concrete-encased columns

Concrete-encased columns are commonly used in structural engineering due to their high strength, durability, and fire resistance. They consist of a concrete core that is surrounded by steel reinforcement and encased in concrete (Du et al., 2022). The concrete encasing provides additional strength and stiffness to the column, which allows it to withstand high compressive loads(Lai et al., 2019).

The Eurocode provisions for the compression design of concrete-encased columns are based on the theory of confined concrete. Confined concrete refers to the phenomenon where the strength and ductility of concrete are enhanced when it is subjected to external confinement, such as in a concrete-encased column (Ma et al., 2019). The Eurocode provisions (EN-1994, 2009) provide guidelines for the calculation of the axial resistance of the column, which is based on the concrete strength, the steel reinforcement, and the geometry of the column.

2.4 Composite columns and composite compression members

This section reviews the Eurocode 4 provisions for composite columns and composite compression members, which include concrete-encased columns.

2.4.1 General

According to EN1994 -1-1, Clause 6.7 pertains to the design of composite columns and compression members that feature concrete-encased sections, partially encased sections, and concrete-filled rectangular and circular tubes. Figure 2.1.is provided as an illustrative diagram accompanying this clause. It should be noted that this study focuses on fully encased columns (see Figure 2.1 (a)).

It is also stated in this clause that the current EC4 provisions are applicable to both columns and compression members that are constructed with steel grades ranging from S235 to S460, along with normal-weight concrete that has strength classes ranging from C20/25 to C50/60.

Furthermore, the clause is specifically intended for use with isolated columns, as well as columns and composite compression members found in framed structures where the other structural members consist of either composite or steel elements.

These provisions are also valid for steel contribution ratio δ that fulfil the following condition:

$$0.2 \leq \delta \leq 0.9 \tag{2.1}$$

Where δ is defined using clause 6.7.3.3 (1) according to Equation 2.2 below:

$$\delta = \frac{A_a f_{yd}}{N_{pl,Rd}} \tag{2.2}$$

$N_{pl,Rd}$ is the plastic resistance to compression defined in clause 6.7.3.2 (1) for concrete-encased steel sections as,

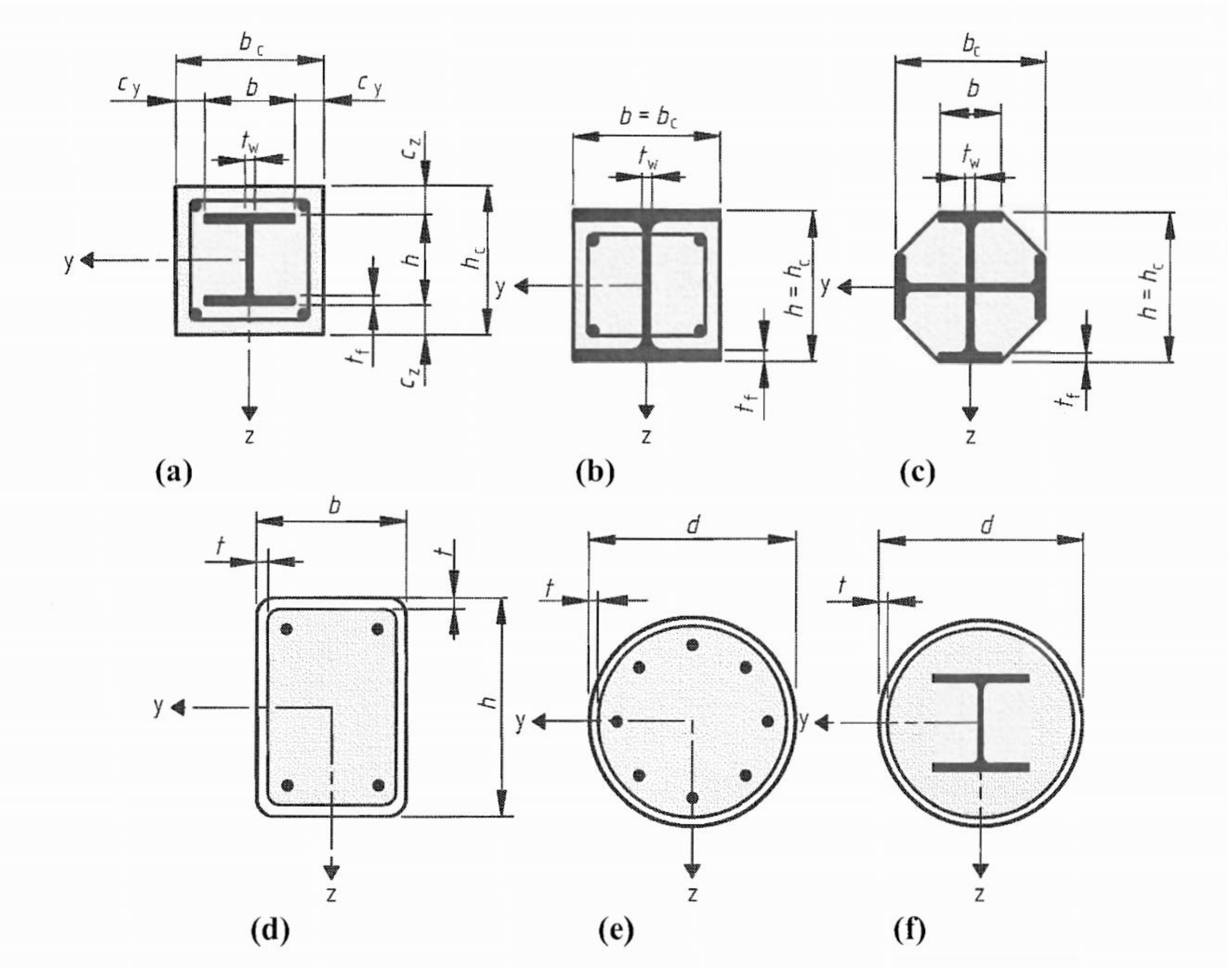


Figure 2. 1 Typical cross-sections of composite columns and notations used in EC4 (EN-1994, 2009)

$$N_{pl,Rd} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd} \quad (2.3)$$

Where:

- A_a is the cross-sectional area of the steel section,
- f_{yd} is the design strength of the steel section,
- A_c is the cross-sectional area of the concrete,
- f_{cd} is the design compressive strength of the confined concrete,
- A_s is the cross-sectional area of the steel reinforcement, and
- f_{sd} is the design strength of the steel reinforcement.

Generally, composite columns or compression members including concrete-encased columns of any cross-section are checked for the following:

- Resistance of the member (Clause 6.7.2 and 6.7.3),
- Resistance to local buckling (Clause 6.7.1 (8) and (9))
- Consideration of loads (Clause 6.7.4.2) and
- Resistance to shear between steel and concrete elements (Clause 6.7.4.3)

In this study, consideration is only made to the provisions of resistance of the member's cross-section and local buckling, and these are discussed in the next section.

The design of concrete-encased columns with doubly symmetrical and uniform cross-sections over the member length is done via a simplified method outlined in clause 6.7.3. Finally, it should also be noted that despite the fact that the influence of local buckling of the steel section on the resistance shall be considered in the design, it may be neglected in the case of a steel section fully encased columns and for partially encased columns provided the following condition hold (Table 6.3 of EC4).

$$\max\left(\frac{b}{t_f}\right) = 44\sqrt{\frac{235}{f_y}} \text{ where } f_y \text{ is in MPa} \quad (2.4)$$

2.4.2 Simplified method of design

2.4.2.1 General and scope

According to the EN 1994, the simplified method referred to here is only applicable to structural members that have a doubly symmetrical and uniform cross-section throughout the member's length. Additionally, the method can only be used with steel sections that have been either rolled, cold-formed, or welded. It is important to note that the simplified method cannot be applied to structural steel components that consist of two or more separate, unconnected sections. Moreover, the relative slenderness parameter $\bar{\lambda}$ defined in section 6.7.3.3 must be less than 0.2 to be suitable for use with this simplified method. According to the standard, there are limitations on the maximum thickness of concrete cover that can be used in calculations for a fully encased steel section as depicted in Figure 2.1a and these limits are:

$$\max c_z = 0.3\,h \qquad \max c_y = 0.4b \tag{2.5}$$

The amount of longitudinal reinforcement used in calculations must not exceed 6% of the concrete area. This ensures that the concrete section retains its structural strength and integrity.

Lastly, the standard mandates that the depth-to-width ratio of the composite cross-section must fall within the range of 0.2 to 5.0. This ensures that the cross-section is designed with a suitable aspect ratio that is conducive to maintaining the structural integrity and stability of the composite member.

2.4.2.2 Resistance of cross-sections

To calculate the plastic resistance to compression $N_{pl,Rd}$ of a composite cross-section, the standard prescribes a method that involves summing the plastic resistances of its components (see Equation 2.3). This means that the plastic resistance of each component within the composite cross-section must be determined first and then added together to determine the overall plastic resistance to compression of the composite member.

For eccentrically loaded columns, the resistance of the cross-section must be computed accounting for combined compression and bending. EC4 allows for the calculation of the interaction curve for a composite member using rectangular stress blocks, as illustrated in Figure 2.2 for a partially encased column. This curve must consider the design shear force V_{Ed} . However, when performing this calculation, the tensile strength of the concrete must be neglected.

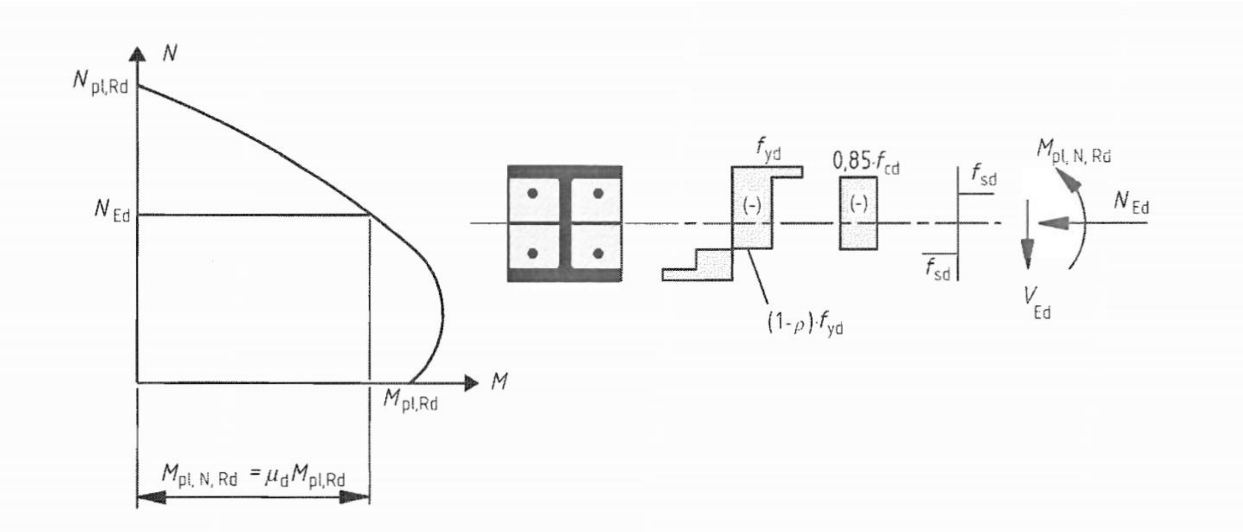


Figure 2. 2 Interaction curve for combined compression and uniaxial bending (EN-1994, 2009)

When determining the interaction curve for a composite member, it is essential to consider the effect of transverse shear forces on the resistance to bending and normal force. This becomes particularly important when the shear force $V_{a,Ed}$ on the steel section exceeds 50% of the design shear resistance $V_{p1,a,Rd}$ of the steel section. In such a scenario, it is crucial to take into account the influence of these transverse shear forces to ensure an accurate and safe interaction curve, in accordance with Clause 6.2.2.2 of EN1994-1-1.

If the shear force $V_{a,Ed}$ on the steel section is greater than 50% of the design shear resistance $V_{p1,a,Rd}$, the impact of transverse shear on the resistance in combined bending and compression should be considered. This can be achieved by reducing the design steel strength $(1-\rho)/f_{yd}$ in the shear area A_v, in line with 6.2.2.4 (2) and Figure 2.2.

Moreover, it is critical to ensure that the shear force $V_{a,Ed}$ does not exceed the resistance to shear of the steel section, which must be calculated according to 6.2.2. Additionally, it is important to verify the resistance to shear $V_{c,Ed}$ of the reinforced concrete part as per EN 1992-1-1, 6.2.

If a more precise analysis is not employed, the design shear force V_{Ed} can be divided into two components: $V_{a,Ed}$, which acts on the structural steel section, and $V_{c,Ed}$, which acts on the reinforced concrete section. This distribution of the shear force can be determined by:

$$V_{ad,Ed} = V_{Ed} \frac{M_{p1,a,Rd}}{M_{p1,Rd}} \tag{2.6}$$

$$V_{c,Ed} = V_{Ed} - V_{a,Ed} \tag{2.7}$$

Where:

- $M_{p1,a,Rd}$ is the plastic resistance moment of the steel sections and
- $M_{p1,Rd}$ is the plastic resistance moment of the composite section.

And for simplification V_{Ed} is assumed to act on the structural steel alone.

Finally, to simplify the analysis, it is possible to use a polygonal diagram (dashed line in Figure 2.3) instead of the complete interaction curve. Figure 2.3 shows an example of the plastic stress distribution for points A to D in a fully encased cross-section as shown in EC4. For concrete-encased and partially concrete-encased sections, the plastic resistance to compression $N_{pm,Rd}$ should be taken as 0.85 multiplied by the concrete effective area A_c and the yield strength f_{ed}.

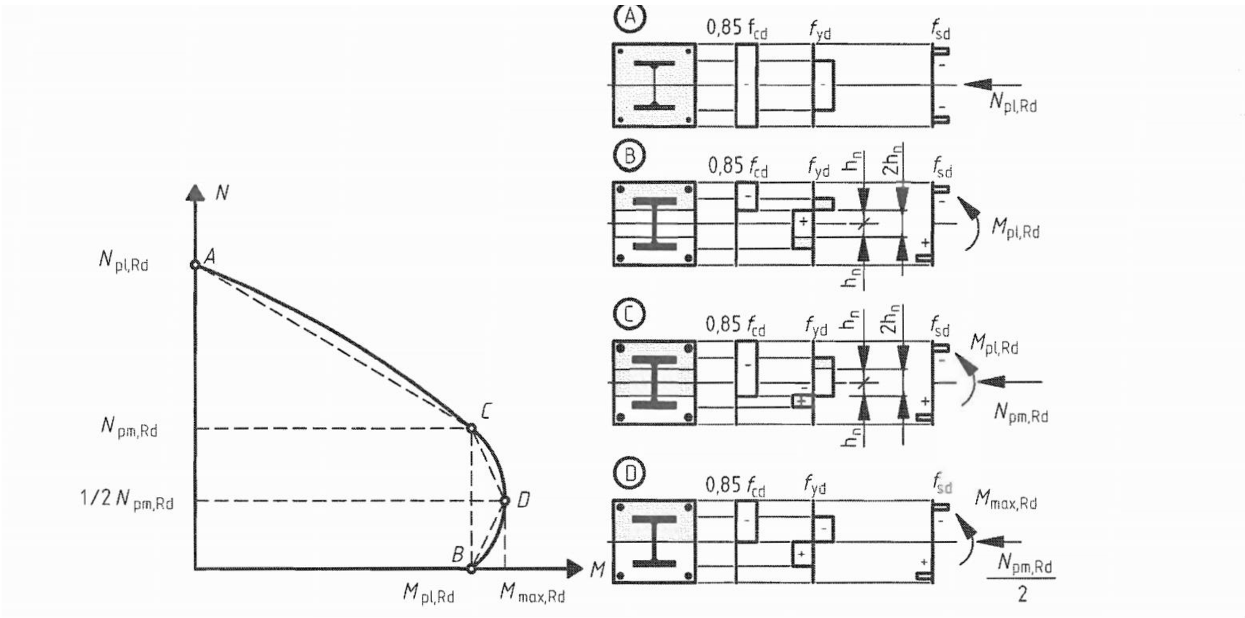


Figure 2. 3 Simplified interaction curve and corresponding stress distribution (EN-1994, 2009)

2.4.2.3 Effective flexural stiffness, steel contribution ratio and relative slenderness

To calculate the resistance of the cross-section accounting for buckling, the effective flexural stiffness, steel contribution and relative slenderness parameters must be computed.

The steel contribution ratio δ is defined as in Equation 2.2 above while the relative slenderness ratio $\bar{\lambda}$ parameter in the plane of bending is given as,

$$\bar{\lambda} = \sqrt{\frac{N_{p1,Rk}}{N_{cr}}} \tag{2.8}$$

Where:

- $N_{p1,Rk}$ is the characteristic value of the plastic resistance to compression and it is noted that instead of the design strengths, the characteristic values are used.
- N_{cr} is the elastic critical normal force for the relevant bucking mode, calculated with the effective flexural stiffness *(EI)_{eff}* determined in Equation 2.9 below,

$$(EI)_{eff} = E_a I_a + E_s I_s + K_e E_{cm} I_c \tag{2.9}$$

Such that:

- K_e is a correction factor that should be taken as 0.6.
- $I_a,\ I_c,\ and\ I_s$ are the second moments of area of the structural steel section, the un-cracked concrete section and the reinforcement for the bending plane being considered.

Lastly, when determining the effective elastic flexural stiffness, the long-term effects should be considered. The modulus of elasticity of concrete E_{cm} should be adjusted according to the following expression:

$$E_{\mathrm{c,eff}} = E_{\mathrm{cm}} \frac{1}{1 + \left(N_{\mathrm{G,Ed}}/N_{\mathrm{Ed}}\right)\varphi_{\mathrm{t}}} \tag{2.10}$$

Where φ_{t} is the creep coefficient according to 5.4.2.2(2); N_{Ed} is the total design normal force; and $N_{\mathrm{G,Ed}}$ is the part of this normal force that is permanent.

Effects of member imperfections verified via second-order linear elastic analysis is accounted for via buckling curves.

2.4.2.4 Resistance of members in axial compression

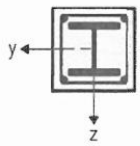
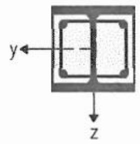
To simplify the analysis for members in axial compression, the design value of the normal force N_{Ed} should meet the following requirement:

$$\frac{N_{\mathrm{Ed}}}{\chi N_{\mathrm{pl,Rd}}} \leq 1{,}0 \tag{2.11}$$

$N_{\mathrm{pl,Rd}}$ is the plastic resistance of the composite section but with f_{yd} computed using the partial factor γ_{M1} given by EN 1993-1-1 clause 6.1 (1); and χ is the reduction factor for the relevant buckling mode, expressed in terms of the relevant relative slenderness $\bar{\lambda}$, is provided in EN 1993-1-1, clause 6.3.1.2.

Table 2.1 provides the buckling curves applicable to composite column cross-sections. The reinforcement ratio, A_s / A_c, is denoted by ρ_s.

Table 2. 1 Buckling curves and member imperfections for concrete-encased columns (Table 6.5 of (EN-1994, 2009))

Cross-section	Limits	Axis of buckling	Buckling curve	Member imperfection
concrete encased section 		y-y	b	$L/200$
		z-z	c	$L/150$
partially concrete encased section 		y-y	b	$L/200$
		z-z	c	$L/150$

2.4.2.5 Resistance of members in axial compression

The interaction curve determined according to clause 6.7.3.2 (2)-(5) of EN1994-1-1 should be used to satisfy the following expression:

$$\frac{M_{\mathrm{Ed}}}{M_{\mathrm{pl,N,Rd}}} = \frac{M_{\mathrm{Ed}}}{\mu_{\mathrm{d}} M_{\mathrm{pl,Rd}}} \leq \alpha_{\mathrm{M}} \qquad (2.12)$$

where:

- M_{Ed} is the greatest of the end moments and the maximum bending moment within the column length, calculated according to clause 6.7.3.4, including imperfections and second order effects if necessary.

- $M_{\mathrm{pl,N,Rd}}$ is the plastic bending resistance considering the normal force N_{Ed}, given by $\mu_{\mathrm{d}} M_{\mathrm{pl,Rd}}$, see Figure 2.2
- $M_{\mathrm{pl,Rd}}$ is the plastic bending resistance, given by point B in Figure 2.3.

The code further states that for steel grades between S235 and S355 inclusive, the coefficient α_{M} should be taken as 0.9 and for steel grades S420 and S460 as 0.8.

To determine the design plastic resistance moment $M_{pl,Rd}$, the valueμ_{d} should be equal to either μ_{dy} or μ_{dz} depending on the plane of bending. Figure 2.4 below provides further guidance on this as illustrated in the Eurocodes. Values of μ_{d} greater than 1.0 should only be used when the moment M_{Ed} is directly related to the action of the normal force, such as when M_{Ed} results from an eccentricity of the normal force V_{Ed}. If this is not the case, an additional verification is required in accordance with clause 6.7.1 (7).

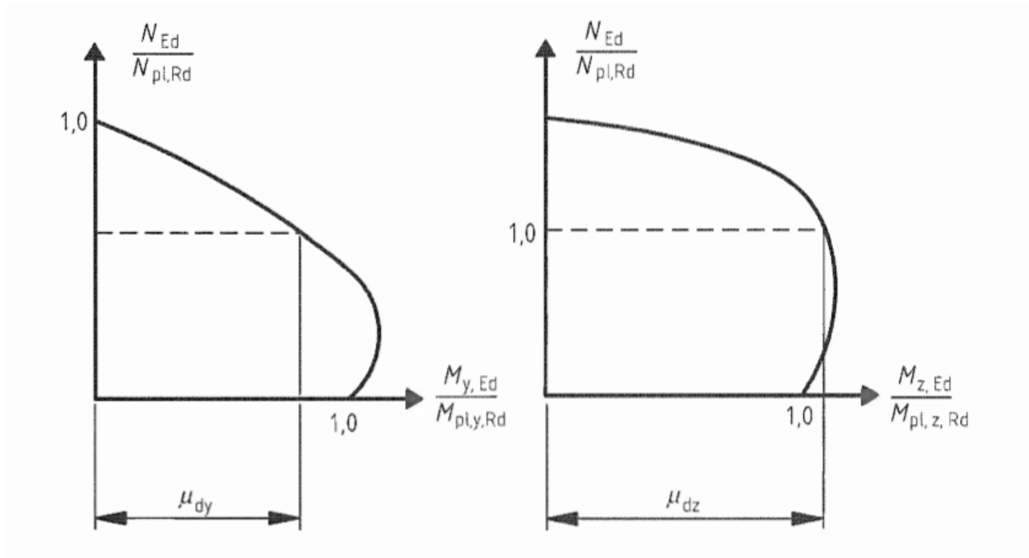


Figure 2. 4 Design for compression and biaxial bending as in (EN-1994, 2009)

2.4.2.6 Combined compression and biaxial bending

For composite columns and compression members with biaxial bending the values μ_{dy} and μ_{dz} in Figure 2.4 may be calculated according to clause 6.7.3.6 separately for each axis. Imperfections should be considered only in the plane in which failure is expected to occur. If it is not evident which plane is the more critical, checks should be made for both planes.

For the stability check within the column length and for the check at the end, the following conditions should be satisfied for combined compression and biaxial bending:

$$\frac{M_{\mathrm{y,Ed}}}{\mu_{\mathrm{dy}} M_{\mathrm{pl,y,Rd}}} \leq \alpha_{\mathrm{M,y}} \frac{M_{\mathrm{z,Ed}}}{\mu_{\mathrm{dz}} M_{\mathrm{pl,z,Rd}}} \tag{2.13}$$

$$\frac{M_{\mathrm{y,Ed}}}{\mu_{\mathrm{dy}} M_{\mathrm{pl,y,Rd}}} + \frac{M_{\mathrm{z,Ed}}}{\mu_{\mathrm{d}z} M_{\mathrm{pl,z,Rd}}} \leq 1{,}0 \tag{2.14}$$

Where:

- $M_{\mathrm{pl,y,Rd}}$ and $M_{\mathrm{pl},z,\mathrm{Rd}}$ are the plastic bending resistances of the relevant plane of bending;
- $M_{\mathrm{y,Ed}}$ and $M_{z,\mathrm{Ed}}$ are the design bending moments including second-order effects and imperfections according to clause 6.7.3.4;
- μ_{dy} and μ_{dz} are defined in clause 6.7.3.6;
- $\alpha_{\mathrm{M}} = \alpha_{\mathrm{M,y}}$ and $\alpha_{\mathrm{M}} = \alpha_{\mathrm{M,z}}$ are given in clause 6.7.3.6(1).

2.5 Previous research on concrete-encased columns

Numerous experimental investigations on concrete-encased steel composite columns have been carried out by various researchers (Al-Shahari et al., 2003; Anuntasena et al., 2019, 2020; Dundar et al., 2008; El-Tawil & Deierlein, 1999; Janss & Anslijn, 1974; Lai & Liew, 2020; S. A. Mirza & Skrabek, 1992; S. Ali Mirza et al., 1996; Morino et al., 1985; SSRC Task Group 20, 1979; Xiang et al., 2020; Xu et al., 2016; K. Zhou & Han, 2018). A comprehensive review of most of research is given by Shanmugam and Lakshmi (2001). These experiments involved concentrically and eccentrically loaded concrete-encased steel composite columns with different slenderness ratios, steel sections, and concrete and steel strengths.

Analytical studies have also been conducted on concentrically and eccentrically loaded concrete-encased steel composite columns by various researchers (Chen & Lin, 2006; Ellobody & Young, 2011; Furlong, 1969; Kato, 1996; Muñoz & Hsu, 1997a, 1997b; Roik & Bergmann, 1990; VIRDI et al., 1973). Recently, Ellobody & Young (2011) developed a nonlinear 3-D finite element model to investigate the behavior of axially concentrically loaded concrete-encased steel composite columns. This model took into account the inelastic material properties of the composite column components, concrete confinement, initial overall geometric imperfection, and the interface between the composite column components. The composite column strengths obtained from the finite element analyses were compared with the design strengths calculated using the American Institute for Steel Construction (ANSI/AISC 360-10, 2010) and Eurocode 4 (EN-1994, 2009) for composite columns. However, to date, no detailed assessment of the Eurocode provisions for concrete-encased columns has been found in the literature that highlights the shortcomings and limitations of the current Eurocode provisions when compared to experimental and complex non-linear finite element predictions.

As previously stated in section 2.2.3.2.1, the current design rules specified in the American Institute for Steel Construction AISC (ANSI/AISC 360-10, 2010), American Concrete Institute(ACI 318, 2019) , and Eurocode 4 (EN-1994, 2009) are applicable to normal strength concrete classes C20/25-C50/60 and steel grades S235-S460. Additionally, the initial geometric imperfections, concrete confinement, and bonding between the concrete-encased steel composite column components are not sufficiently covered by these specifications and previous research. Moreover, the design rules in (ACI 318, 2019; ANSI/AISC 360-10, 2010; EN-1994, 2009) are based on various assumptions and empirical equations, especially for eccentrically loaded concrete-encased steel composite columns, that are only applicable within the limits given by these specifications. This study feels this gap by assessing the current provisions in EC4.

2.6 Chapter Summary

This chapter provided a literature review on the compression design of concrete-encased columns. The chapter began with an introduction to the topic and a brief discussion of the importance of concrete-encased columns in the construction industry. It then provided an overview of Eurocodes, which were a set of European standards for the design of buildings and other civil engineering works. The chapter focused on the compression design of concrete-encased columns and the various design methods that were used, including the key parameters that influenced the design of concrete-encased columns.

In addition, the chapter discussed the design of composite columns and composite compression members, including a general overview of composite construction and the benefits of using composite materials. This was followed by a discussion of the simplified method of design for composite columns.

Moreover, the chapter reviewed previous research on the compression design of concrete-encased columns, including the various studies that had been conducted, the methodologies used, and the findings and conclusions of each study.

Overall, this chapter provided a solid foundation for the research by reviewing the existing literature on the compression design of concrete-encased columns, identifying key design methods and parameters, and summarizing previous research findings.

Chapter 3: METHODOLOGY

3.1 Introduction

This chapter outlines the methodology used in this study to assess the compression design provisions for eccentrically loaded concrete-encased columns in EN1994-1-1. The study involved collecting experimental data from the literature and compiling a database to assess the provisions.

3.2 Database selection criteria

In the process of conducting this comprehensive review of both experimental and numerical studies, clear and transparent selection criteria were established to ensure the relevance, reliability, and validity of the collected data. The following selection criteria had been carefully defined to guide the inclusion or exclusion of specific studies in this assessment:

- *Relevance to the Research Question:* The foremost criterion for inclusion in this review was the direct relevance of the study to the central research question. Studies that addressed specific aspects of eccentrically loaded concrete encased columns were considered for inclusion.
- *Methodology:* This review encompassed both experimental and numerical studies. Studies selected aligned with the research objectives. Experimental studies exhibited a sound experimental design, adequate sample size, and relevant loadings. Numerical studies employed appropriate numerical methods, boundary conditions, and verification/validation procedures.
- *Quality of Research:* The quality of research was of paramount importance. Studies were assessed based on the rigor of their methodology, including data collection and analysis. Validity, reliability, and precision in experimental

measurements, as well as the appropriateness and accuracy of numerical models, were critical factors.

- *Peer-Reviewed Sources:* Priority was given to studies published in peer-reviewed journals, conference proceedings, and renowned research databases. These sources were esteemed for their rigorous review processes, which enhanced the credibility of the studies.
- *Exclusion Criteria:* Studies were excluded if they lacked sufficient detail, contained limited or irrelevant data, or exhibited a high risk of bias. Such exclusions were justified based on these criteria.

3.3 Summary of selected experimental and numerical investigations

3.3.1 General

A comprehensive literature review was conducted to identify existing studies that investigated the compression behavior of eccentrically loaded concrete-encased columns. The review included both experimental and numerical studies published in peer-reviewed journals and conference proceedings. The literature review aimed to collect data from a wide range of sources to ensure that the compiled database (see next section) is representative of the behavior of concrete-encased columns in practical applications. The review also included an analysis of the testing methods used in the experiments to ensure that the collected data is reliable and consistent.

3.3.2 Experimental investigations

The presently valid Eurocode provisions for eccentrically loaded compression concrete-encased steel composite columns were evaluated using partly test results conducted by Morino et al., (1985), SSRC Task Group 20 (1979), and Al-Shahari et al. (2003). The dimensions and material properties of the tested specimens are summarized in Table 3.1 and Table 3.2.

In the study by Al-Shahari et al. (2003), lightweight aggregate concrete-encased steel composite columns with square cross-sections (B×D) of 230 mm×230 mm and lengths of 2000 and 3000 mm were loaded eccentrically along the major axis. The specimens used in verification were denoted as BC1–BC7 and had concrete cube strengths (f_{cu}) ranging from 13.7 to 28.2 MPa and structural steel yield stresses (f_{ys}) ranging from 307 to 337 MPa. The specimens also had longitudinal and transverse reinforcement, as detailed in Table 2.

The specimens used in the tests by SSRC Task Group 20 (1979), labelled as BC8–BC12, had rectangular cross-sections of 165.1 mm×177.8 mm and lengths varying from 726 to 2997 mm. The specimens were loaded eccentrically with eccentricity varying from 0.07D to 0.14D along the major axis. The structural steel section used was Universal Beam UB 127×114×29.76, with concrete cylinder strength of 19.3 MPa and steel yield stress of 232 MPa. The details of longitudinal and transverse reinforcement are also presented in Table 3.2. Specimen dimensions and material properties of eccentrically loaded concrete-encased steel composite columns.

Table 3. 1 Specimen dimensions and material properties of eccentrically loaded concrete-encased composite columns

Test	**Dimensions**			**Steel Section**	**e/D**	**Material properties**				**Ref**
	B(mm)	**D(mm)**	**kL(mm)**			**Concrete Strength (Mpa)**		**Fys (Mpa)**	**Fur (Mpa)**	
BC1	230	230	2000	H 100 x 96 x 5 x 8	0.3	20.5	Cube Strength	337	459	(Al-Shahari et al., 2003)
BC2	230	230	2000	H 100 x 96 x 5 x 8	0.3	13.7	Cube Strength	337	459	
BC3	230	230	2000	H 140 x 133 x 5.5 x 8	0.3	20.5	Cube Strength	307	459	
BC4	230	230	2000	H 140 x 133 x 5.5 x 8	0.3	28.2	Cube Strength	307	459	
BC5	230	230	3000	H 140 x 133 x 5.5 x 8	0.3	28.2	Cube Strength	307	459	
BC6	230	230	3000	H 100 x 96 x 5 x 8	0.17	20.5	Cube Strength	337	459	
BC7	230	230	3000	H 100 x 96 x 5 x 8	0.17	13.7	Cube Strength	337	459	
BC8	165.1	177.8	726	UB 127 x 114 x 29.76	0.11	19.3	Cylinder Strength	232	460	(SSRC Task Group 20, 1979)
BC9	165.1	177.8	1156	UB 127 x 114 x 29.76	0.07	19.3	Cylinder Strength	232	460	
BC10	165.1	177.8	2083	UB 127 x 114 x 29.76	0.11	19.3	Cylinder Strength	232	460	
BC11	165.1	177.8	2997	UB 127 x 114 x 29.76	0.07	19.3	Cylinder Strength	232	460	
BC12	165.1	177.8	2997	UB 127 x 114 x 29.76	0.14	19.3	Cylinder Strength	232	460	
BC13	160	160	960	H 100 x 100 x 6 x 8	0.25	21.1	Cube Strength	345	460	(Morino et al., 1985)
BC14	160	160	2400	H 100 x 100 x 6 x 8	0.25	23.4	Cube Strength	345	460	
BC15	160	160	3600	H 100 x 100 x 6 x 8	0.25	23.3	Cube Strength	345	460	

Table 3. 2 Composite section dimensions and reinforcement details

Test	Composite Section (mm)						Reinforcement				Ref
	b1	**b2**	**b3**	**d1**	**d2**	**d3**	**Longitudinal**		**Transverse**		
							No.	**dia**	**No.**	**dia**	
BC1	100	35	30	96	35	32	4	12	140	8	(Al-Shahari et al., 2003)
BC2	100	35	30	96	35	32	4	12	140	8	
BC3	140	35	10	133	35	13.5	4	12	140	8	
BC4	140	35	10	133	35	13.5	4	12	140	8	
BC5	140	35	10	133	35	13.5	4	12	140	8	
BC6	100	35	30	96	35	32	4	12	140	8	
BC7	100	35	30	96	35	32	4	12	140	8	
BC8	114.3	14.4	11	127	14.4	11	4	6	75	4	(SSRC Task Group 20, 1979)
BC9	114.3	14.4	11	127	14.4	11	4	6	75	4	
BC10	114.3	14.4	11	127	14.4	11	4	6	75	4	
BC11	114.3	14.4	11	127	14.4	11	4	6	75	4	
BC12	114.3	14.4	11	127	14.4	11	4	6	75	4	
BC13	100	19	11	100	19	11	4	6	75	4	(Morino et al., 1985)
BC14	100	19	11	100	19	11	4	6	75	4	
BC15	100	19	11	100	19	11	4	6	75	4	

3.3.3 Numerical investigations

Ellobody et al. (2011) developed a nonlinear 3-D finite element model to study the behavior of eccentrically loaded concrete-encased steel composite columns. The columns were pin-ended and subjected to an eccentric load along the major axis, with eccentricities ranging from 0.125 to 0.375 of the overall depth (D) of the column sections. The model considered the inelastic behavior of steel, concrete, longitudinal and transverse reinforcement bars, and the effect of concrete confinement. It also accounted for the bond behavior between the different components of the column. The model was validated using test results, where the concrete strengths ranged from 30 to 110 MPa and steel section yield stresses varied from 275 to 690 MPa. In addition, a parametric study was conducted to investigate the effects of different variables on the behavior and strength of the eccentrically loaded composite columns.

In the study, a total of 54 eccentrically loaded column specimens were analyzed with varying eccentricities, overall cross-section dimensions, structural steel sections, concrete strength and structural steel yield stresses. The columns were divided into 18 groups denoted as G1–G18. Table 3.4 and Table 3.5 summarize the dimensions and material properties of the columns with square and rectangular cross-sections, respectively. The eccentricities along the major axis varied from 0.125D to 0.375D. The first nine groups G1–G9 had square cross-sections (B×D) of 230 mm×230 mm, similar to the tests conducted by Al-Shahari et al. (2003). The remaining groups G10–G18 had rectangular cross-sections of 165.1 mm×177.8 mm, similar to the tests conducted by SSRC Task Group 20 (1979). Groups G1–G3, G4–G6, and G7–G9 had eccentricities along the major axis of 0.125D, 0.25D, and 0.375D, respectively. Similarly, G10–G12, G13–G15, and G16–G18 had the same eccentricities of 0.125D, 0.25D, and 0.375D, respectively. The structural steel sections used in G1–G9 were HEA 140 (H 140×133×5.5×8), while that in G10–G18 was UB 127×114×29.76, consistent with the tests conducted by Al-Shahari et al. (2003) and SSRC Task Group 20 (1979), respectively.

3.4 Compilation of Experimental Database

The experimental data from the reviewed studies were extracted and compiled into a database. The database includes information on the test specimens, loading conditions, and measured compressive strengths of the concrete-encased columns. The data extraction process involved carefully reviewing the published literature to ensure that all relevant data was captured accurately. Data quality control was performed to ensure that the compiled data was consistent and reliable. The quality control process included checks for missing or erroneous data, as well as comparisons between the compiled data and the original experimental data to ensure that there were no discrepancies. Specifically, the database is a compilation of Tables 3.1-3.4 (see Appendix A for the database).

A summary of the database is given below showing the different statistics of each of the input and output parameters.

Table 3. 3 Specimen Dimensions and Material Properties of Eccentrically Loaded Concrete-encased Steel Composite Square Columns in the numerical study of Ellobody & Young (2011) for Group 1 to 9

	Specimen	Section	Length	Steel Section	e/D	Concrete	Steel		Ref
		BxD (mm)	kL (mm)			Fc (Mpa)	Fys (Mpa)	Fur (Mpa)	
G1	S1	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	30	275	430	(Ellobody & Young, 2011)
	S2	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	70	275	430	
	S3	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	110	275	430	
G2	S4	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	30	460	530	
	S5	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	70	460	530	
	S6	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	110	460	530	
G3	S7	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	30	690	760	
	S8	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	70	690	760	
	S9	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	110	690	760	
G4	S10	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	30	275	430	(Ellobody & Young, 2011)
	S11	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	70	275	430	
	S12	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	110	275	430	
G5	S13	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	30	460	530	
	S14	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	70	460	530	
	S15	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	110	460	530	
G6	S16	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	30	690	760	
	S17	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	70	690	760	
	S18	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	110	690	760	
G7	S19	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	30	275	430	(Ellobody & Young, 2011)
	S20	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	70	275	430	
	S21	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	110	275	430	
G8	S22	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	30	460	530	
	S23	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	70	460	530	
	S24	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	110	460	530	
G9	S25	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	30	690	760	
	S26	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	70	690	760	
	S27	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	110	690	760	

Table 3. 4 Specimen Dimensions and Material Properties of Eccentrically Loaded Concrete-encased Steel Composite Square Columns in the numerical study of Ellobody & Young (2011) for Group 10 to 18

Group	Specimen	Section	Length	Steel Section	e/D	Concrete	Steel		Ref
		BxD (mm)	kL (mm)			Fc (Mpa)	Fys (Mpa)	Fur (Mpa)	
G10	S28	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	30	275	430	(Ellobody & Young, 2011)
	S29	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	70	275	430	
	S30	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	110	275	430	
G11	S31	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	30	460	530	
	S32	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	70	460	530	
	S33	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	110	460	530	
G12	S34	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	30	690	760	
	S35	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	70	690	760	
	S36	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	110	690	760	
G13	S37	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	30	275	430	(Ellobody & Young, 2011)
	S38	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	70	275	430	
	S39	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	110	275	430	
G14	S40	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	30	460	530	
	S41	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	70	460	530	
	S42	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	110	460	530	
G15	S43	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	30	690	760	
	S44	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	70	690	760	
	S45	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	110	690	760	
G16	S46	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	30	275	430	(Ellobody & Young, 2011)
	S47	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	70	275	430	
	S48	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	110	275	430	
G17	S49	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	30	460	530	
	S50	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	70	460	530	
	S51	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	110	460	530	
G18	S52	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	30	690	760	
	S53	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	70	690	760	
	S54	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	110	690	760	

3.5 Assessment methodology

3.5.1 Data Analysis

The compiled database was analyzed to evaluate the accuracy and reliability of the compression design provisions in EN1994-1-1 when applied to columns with out-of-code parameters. As can be seen in the tables, some concrete encased columns have compressive strength of concrete greater than 60 MPa and steel yield strength greater than 460MPa. Statistical methods based on regression analysis and sensitivity analysis were used to identify any discrepancies between the experimental data and the provisions. The aim of the data analysis was to identify any areas where the design provisions may be improved or where further research was needed.

3.5.2 Calibration of Compression Design Provisions

Based on the analysis of the experimental database, recommendations for calibrating the compression design provisions in EN1994-1-1 were proposed. The proposed calibration was validated against the compiled database and compared to the current provisions. The aim of the calibration process was to ensure that the design provisions accurately reflected the behavior of concrete-encased columns with out-of-code parameters in practical applications and that they provided a safe and reliable basis for design.

Methodology Overview:

The calibration process aimed to refine and improve the existing compression design provisions specified in EN1994-1-1 so that they can be applicable to columns with out-of-code materials parameters. It involved a systematic approach to adjust the provisions based on empirical data and analysis results. The following steps elucidate the calibration process:

Step 1: Data Analysis and Assessment:

The first stage of calibration commenced with a comprehensive analysis of the experimental database. This analysis aimed to identify any discrepancies between the actual behavior of concrete-encased columns, as reflected in the dataset, and the provisions outlined in EN1994-1-1. The data analysis considered various factors, including column geometry, loading conditions, and more importantly material properties.

Step 2: Proposed Modifications:

Based on the findings from the data analysis, a set of proposed modifications to the compression design provisions was formulated. These modifications were designed to align the provisions more closely with the observed behavior of out-of-code concrete-encased columns in practical applications. The modifications encompassed adjustments to design factors within the provisions.

Step 3: Validation Against Data:

The proposed modifications underwent rigorous validation against the compiled database of experimental results. This validation was a pivotal step to ensure that the calibrated provisions accurately reflected the actual behavior of concrete-encased columns including those with out-of-code parameters. The validation process entailed the following key components:

a. Criteria for Validation:

- Fit to Empirical Data: The primary criterion for validation was the extent to which the modified provisions aligned with the empirical data. The calibrated provisions were expected to provide predictions that closely matched the observed behavior in terms of load-carrying capacity, failure modes, and other relevant metrics.
- Residual Analysis: Residual analysis was conducted to assess how well the calibrated provisions minimized the differences between predicted values and

actual measurements. Smaller residuals indicated a better fit and, consequently, a more effective calibration.

b. Benchmarks for Validation:

- Comparison to Existing Provisions: A critical benchmark for validation was a comparison between the calibrated provisions and the original provisions specified in EN1994-1-1. The effectiveness of the calibration was measured by the degree to which it improved upon the accuracy and reliability of the original provisions.
- Predictive Performance: The calibrated provisions were evaluated for their predictive performance on a range of concrete-encased column configurations not included in the calibration process. These predictions were compared to subsequent experimental results to gauge the provisions' ability to generalize beyond the dataset used for calibration.

Step 4: Sensitivity Analysis:

In parallel with validation, a sensitivity analysis was conducted to assess the impact of the proposed modifications on the provisions' responsiveness to variations in key parameters. This analysis tested the robustness of the calibrated provisions and their ability to adapt to different scenarios.

Step 5: Refinement and Iteration:

Based on the outcomes of validation and sensitivity analysis, the calibrated provisions were further refined if necessary. Iterative adjustments were made to enhance their accuracy and reliability.

3.5.3 Sensitivity Analysis

A sensitivity analysis was conducted to investigate the effect of different parameters, such as column slenderness and eccentricity, on the accuracy and reliability of the compression design provisions in EN1994-1-1. The sensitivity analysis involved varying these parameters within a range of practical values and evaluating the effect on the design provisions. The aim of the sensitivity analysis was to identify any limitations or areas where the design provisions may be improved.

3.5.4 Statistical methods

Descriptive Statistics: Descriptive statistics were employed to provide an initial overview of the dataset. Measures such as the mean, median, standard deviation, and range were calculated to summarize key characteristics of the collected data. These statistics facilitated an initial understanding of the dataset's central tendencies and variabilities.

Regression Analysis: To evaluate the accuracy and reliability of the compression design provisions, regression analysis was conducted. Specifically, multiple linear regression models were utilized due to the multivariate nature of the data. The primary equation for the regression analysis was as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \varepsilon$$

Where:

- Y represents the dependent variable related to column behavior.
- $X_1, X_2, \dots, X_n$ denote the independent variables associated with cross-sectional shapes, eccentricity, confinement methods, and loading conditions.
- $\beta_0, \beta_1, \beta_2, \dots, \beta_n$ signify the regression coefficients.
- ε signifies the error term accounting for unexplained variability.

The inclusion of multiple independent variables allowed for the assessment of their combined influence on the dependent variable, thereby providing insights into the accuracy of design provisions.

3.5.5 Model Evaluation

The goodness of fit of the scatter of the compressive provisions about an expected ideal prediction were assessed using the coefficient of determination (R^2) which typically measures the proportion of variance in the dependent variable explained by the independent variables.

3.6 Limitations and potential sources of error

In the pursuit of a comprehensive evaluation of the compression design provisions within EN1994-1-1, it is vital to acknowledge the inherent limitations and potential sources of error embedded within the methodology and data analysis process. The foundations of this study rest upon the availability and quality of the collected data. Any limitations or gaps in the dataset could influence the thoroughness of the analysis and the ensuing calibration procedure. Moreover, the heterogeneity of data sources, stemming from various experiments and research endeavors, brings an element of variability in experimental setups, materials, and measurement techniques, all of which might introduce variability and influence the precision of the calibration.

The modeling and analysis components of the study, central to its core, entail certain limitations. Simplifying assumptions, intrinsic to the development of regression models and sensitivity analyses, serve as crucial tools for analysis but may not encapsulate the full intricacies of real-world scenarios. The efficacy of these regression models hinges on the quality and relevance of the data they are built upon. If the dataset fails to comprehensively represent the breadth of real-world conditions, the models may fall short in reflecting practical situations accurately. Furthermore, while every effort has been made to validate the calibrated provisions, the validation process itself is dependent on the availability of experimental data. If these data do not span all conceivable column configurations or loading conditions, there may be limitations in assessing the provisions' generalizability.

The sensitivity analysis, integral to understanding the robustness of the calibrated provisions, is not devoid of limitations. The selection of parameter ranges for variation, such as column slenderness and eccentricity, is subject to judgment, and there exists a level of uncertainty in determining the most appropriate ranges for certain parameters. In the realm of materials, concrete and steel properties exhibit variability in practice due to factors like material quality, mixing processes, and fabrication techniques, which are complex to comprehensively account for in the analysis. Moreover, the potential for human error during data collection, measurement, and data entry introduces the risk of inaccuracies within the dataset, which, in turn, may reverberate through the calibration and analysis processes.

In conclusion, an understanding and recognition of these limitations and potential sources of error are pivotal to contextualizing the study's findings. While conscientious efforts have been made to mitigate these limitations and ensure the validity of the methodology, researchers and stakeholders should interpret the results with a degree of circumspection. Particularly in areas where data availability or experimental constraints may introduce uncertainty, a cautious approach is warranted. Furthermore, these identified limitations underscore the need for future research endeavors to refine and expand upon the methodology, ultimately enhancing the accuracy and applicability of compression design provisions in practical structural engineering.

3.7 Chapter Summary

This chapter included a review of experimental literature, a compilation of an experimental database, data analysis, calibration of compression design provisions, and sensitivity analysis. The methodology was designed to ensure that the results of the study were accurate, reliable, and representative of the behavior of concrete-encased columns in practical applications. The methodology also included a validation process to ensure that any proposed changes to the design provisions were consistent with the experimental data.

Chapter 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the results and discussion of the assessment of current compressive design provisions for eccentrically loaded concrete encased columns with out-of-code parameters. The aim of this study is to evaluate the performance of existing design methods against experimental and finite element analysis (FEA) results and then asses the viability of use beyond code specifications. The chapter also proposes modified compressive design provisions to use even for columns outside the scope of code specifications based on the findings of the assessment.

4.2 Assessment Methodology Summary

The assessment methodology adopted for this study is a multi-faceted approach that combines experimental investigations, finite element analysis (FEA), and statistical analysis. To assess the performance of current compressive design provisions, the following key steps were undertaken:

- *Data Compilation:* A comprehensive database of experimental results and FEA outcomes related to composite columns was compiled. This database encompassed a wide range of column configurations, materials, and loading conditions.
- *Analysis of Current Provisions:* The existing compressive design provisions, as specified in relevant standards and guidelines, were thoroughly examined. This

analysis included an assessment of the underlying assumptions, equations, and design factors.

- *Comparison with Empirical Data:* The compiled experimental data were compared against predictions made by the current design provisions. Discrepancies between predicted and observed behavior were identified and analyzed.

- *Finite Element Analysis:* FEA simulations were conducted to complement the experimental data. These simulations provided additional insights into the structural response of composite columns under different conditions.
- *Statistical Analysis:* Statistical methods, including regression analysis and sensitivity analysis, were employed to quantitatively evaluate the accuracy and reliability of the current design provisions.
- *Calibration and Modification:* Based on the assessment results, proposed modifications to the design provisions were formulated. These modifications aimed to enhance the provisions' alignment with empirical data and real-world scenarios.

4.3 Current compressive design provisions to be assessed.

To compute second-order effects in columns using the current EN1994-1-1 method, it is necessary to calculate the resistance of a column under pure axial compression (P_o) using Equation 4.1. However, every point on the axial force-bending moment strength interaction diagram represents a column that experiences an eccentric load lower than the pure axial compression. As such, the interaction diagram considers the impact of the bending moment on the column's axial load-carrying capacity, which is lower than its pure axial compression strength. This feature makes the interaction diagram a useful tool for evaluating the capacity of columns subjected to combined axial load and bending moment, a common situation in structural design.

$$P_o = \chi N_{pl} \tag{4.1}$$

where

$$\chi = \frac{1}{\emptyset + \left[\emptyset^2 - \bar{\lambda}^2\right]^{0.5}} \leq 1 \tag{4.2}$$

with

$$\emptyset = 0.5\left[1 + \alpha\left(\bar{\lambda} - \bar{\lambda}_o\right) + \bar{\lambda}^1\right] \tag{4.3}$$

and

$$\bar{\lambda} = \frac{L_e}{\pi}\left(\frac{A_s f_{ys} + 0.85 A_c f_c + A_r f_{yr}}{E_s I_s + 0.6 E_{cm} I_c + I_r I_r}\right)^{0.5} \tag{4.4}$$

In the context of the code, the effective length of a column is denoted as L_e, while the secant modulus of elasticity of concrete is represented by E_{cm} in units of MPa. For the specific case of concrete-encased steel composite columns being studied, the values of α and $\bar{\lambda}_o$were taken as 0.49 and 0.2, respectively, as stipulated by the code.

4.4 Assessment of existing compressive design provisions against experimental results

To evaluate the accuracy of the compressive design provisions in EN 1994-1-1 under eccentric loading and with out-of-code parameters, a comparison was made with a database of experimental results from literature containing such parameters (Al-Shahari et al., 2003; SSRC Task Group 20, 1979; Morino et al., 1985). The comparison with respect to the test results of Al-Shahari et al. (2003), SRC Task Group 20 (1979) and Morino et al. (1985) are referred to in this study as Series A, B, and C, respectively. To the knowledge of the author, this is the comprehensive overview of all the experimental and numerical studies conducted on eccentrically loaded concrete encased columns. The corresponding experimental results were used to calculate the axial compressive strength values (P_o) using Equations 4.1- 4.4 and the known material and dimensional parameters of the composite concrete-encased cross-section. A partial factor of unity was used for the comparison. In addition, statistical model error (ME) is used for comparison and is defined as,

$$ME = \frac{P_{Test/FEM}}{P_{EN1994-1-1}} \tag{4.5}$$

4.4.1 Series A

Figure 4.1 presents the comparison between the axial compressive strength predictions from EN1994-1-1 and the corresponding experimental results (series A), while Table 4.1 shows the statistical comparison. The results indicate that the compressive design provisions in EN1994-1-1 provide under predictions of compressive strength, with a mean value of ME equal to *0.70* and a coefficient of variation (COV) of *0.16*. This under-prediction can be explained by the research conducted by Al-Shahari et al. (2003) which suggests that the material strength properties and buckling behavior of composite concrete-encased cross-sections are not fully captured by the current design provisions.

4.4.2 Series B

Table 4.1 and Figure 4.2 illustrate the comparison between the axial compressive strength predictions obtained from EN1994-1-1 and the corresponding experimental results (Series B). The mean model error is *0.88*, which suggests that the predicted compressive strength is, on average, *0.88* times lower than the actual compressive strength. The COV of *0.15* indicates that there is a moderate level of variability in the errors.

4.4.3 Series C

Based on Table 4.1 and Figure 4.3, it appears that Series C was also used to compare the predicted axial compressive strength values obtained from EN1994-1-1 with the corresponding experimental results. The mean model error of *0.81* suggests that the predicted compressive strength values are, on average, *0.81* times lower than the actual compressive strength values obtained from the experiments. This indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns.

Additionally, the COV of *0.07* indicates that there is a low level of variability in the errors. This suggests that the model errors are consistent and not influenced by factors that cause significant variability.

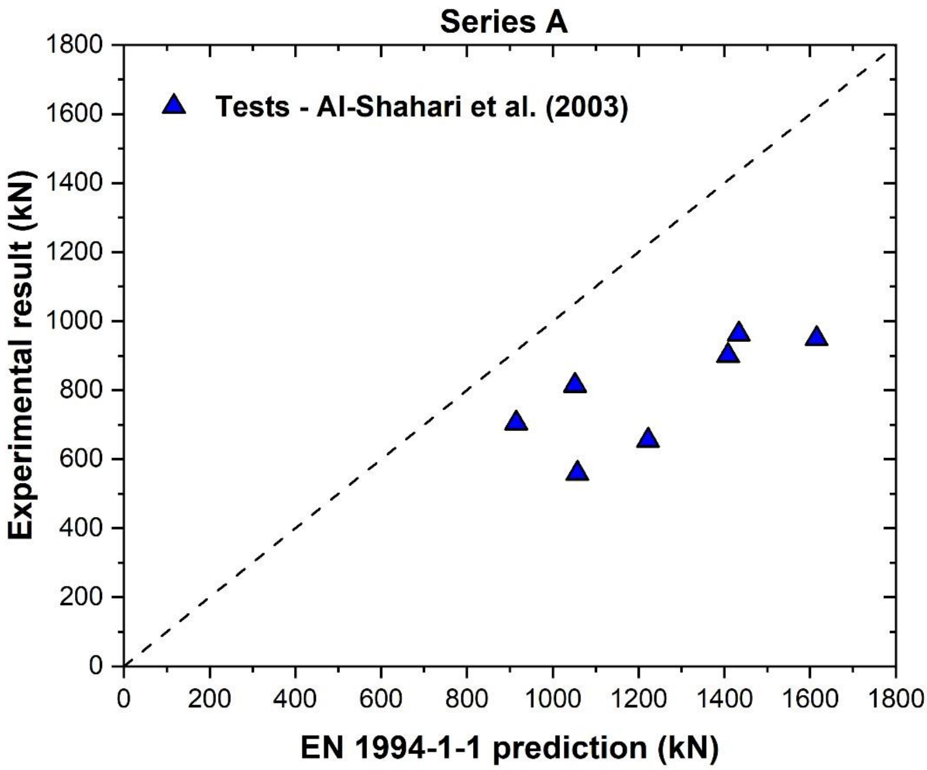


Figure 4. 1 Comparison of CEC sections experimental results (Al-Shahari et al., 2003) (Series A) with predictions from current EN1994-1-1.

Table 4. 1 summary of the collected experimental database.

Source	Series	Statistical moment	Model error
(Al-Shahari et al., 2003)	A	Mean	0.70
		COV	0.16
(SSRC Task Group 20, 1979)	B	Mean	0.88
		COV	0.15
(Morino et al., 1985)	C	Mean	0.81
		COV	0.07

Overall, the results suggest that the compressive design provisions in EN1994-1-1 consistently underestimate the compressive strength, with mean errors ranging from *0.70* to *0.88* across different sources of data. The level of variability in the errors varies between moderate and low, depending on the source of data. These results may have implications for the design of steel-concrete composite structures, and further investigation may be necessary to determine if any modifications to the design provisions are needed.

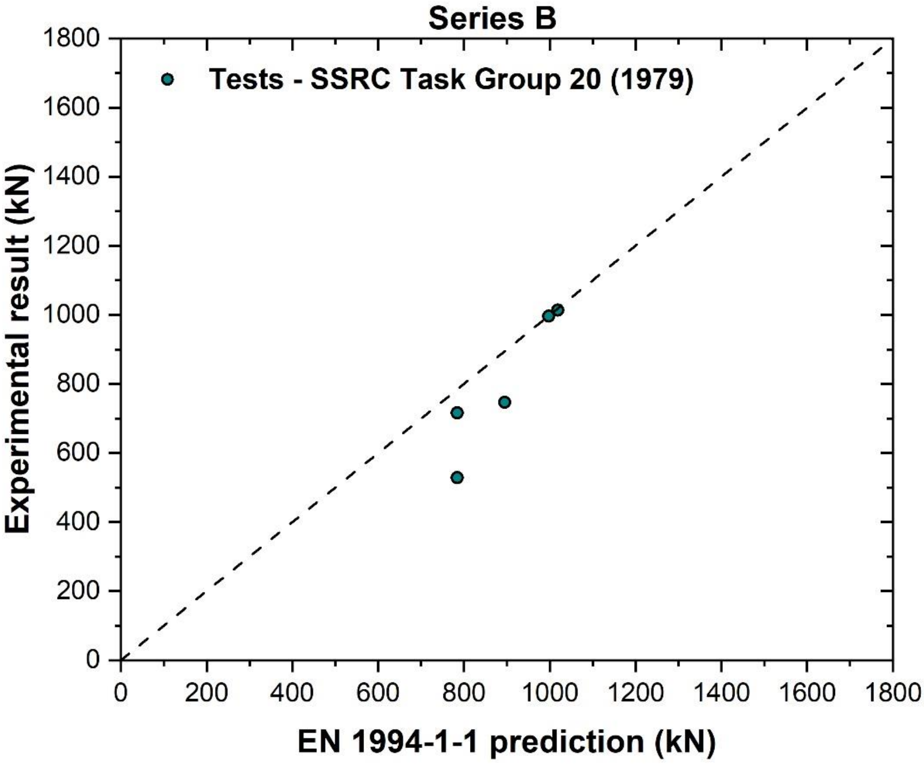


Figure 4. 2 Comparison of CEC sections experimental results (SSRC Task Group 20, 1979) (Series B) with predictions from current EN1994-1-1.

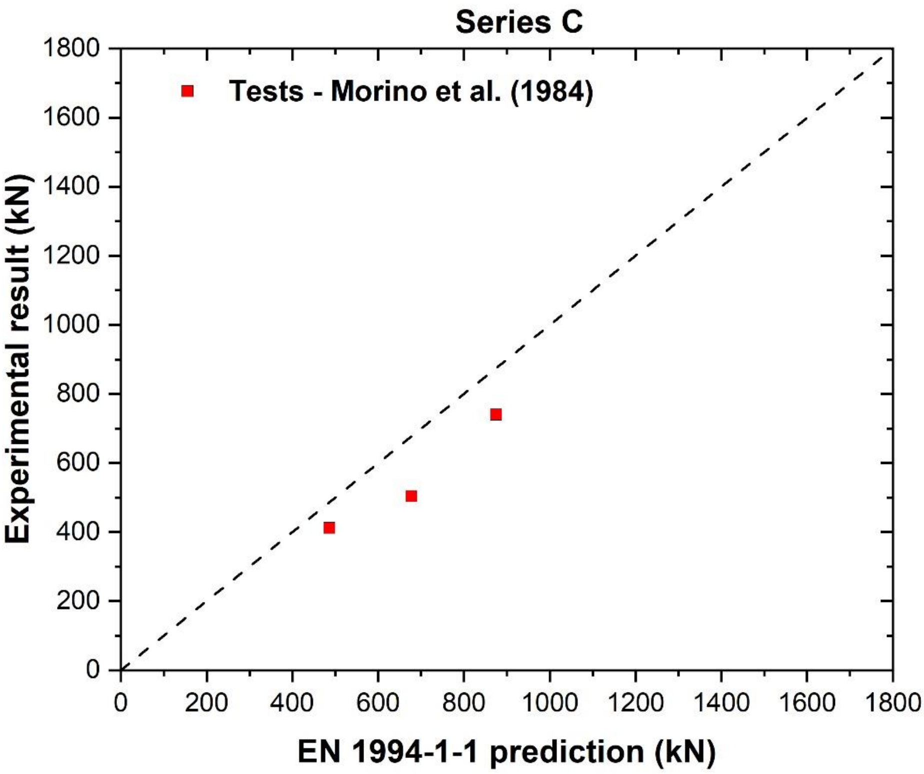


Figure 4. 3 Comparison of CEC sections experimental results (Morino et al., 1985) (Series C) with predictions from current EN1994-1-1.

4.5 Assessment of existing compressive design provisions against FEM results

To further evaluate the accuracy of the compressive design provisions in EN 1994-1-1 under eccentric loading, a comparison was made with a database of FEM results from the literature, in addition to the comparison with test results. The axial compressive strength values (P_o) were calculated from Equation 2.3 using the known material and dimensional parameters of the composite concrete-encased columns, and the corresponding FEM results. Like before, a partial factor of unity and the ME was utilized for the comparison.

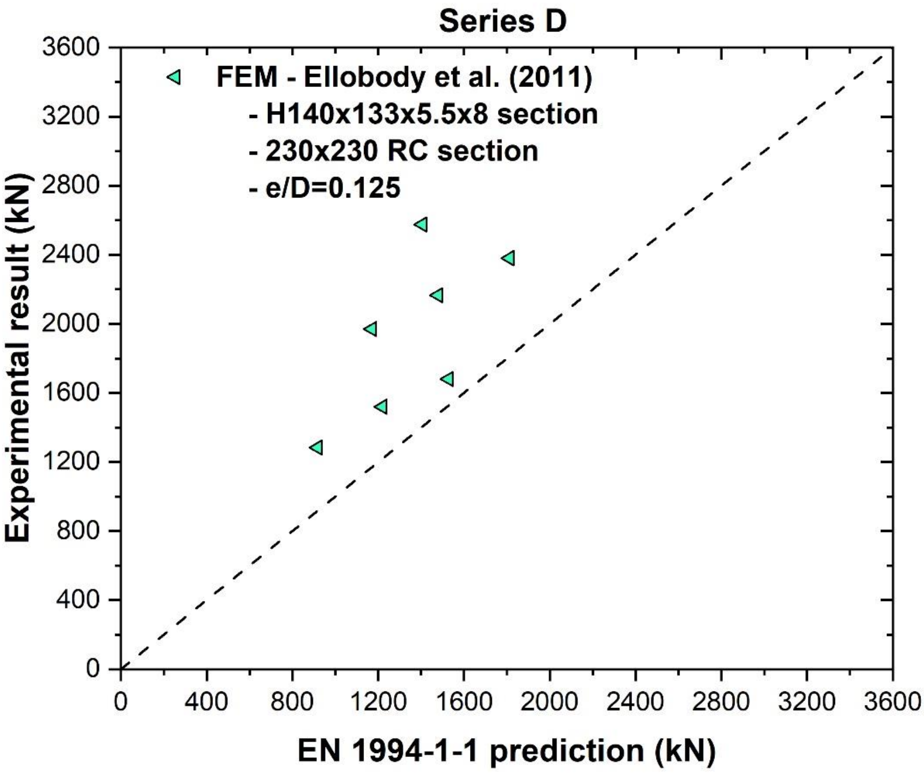


Figure 4. 4 Comparison of CEC sections FEM results (Ellobody et al., 2011) (Series D) with predictions from current EN1994-1-1.

Table 4.2 and Figures 4.4-4.9 shows the six different series of data (D, E, F, G, H, and I) with different series of FEM models. Each series is compared based on two statistical moments of the model error, that is, the mean and coefficient of variation (COV) of the model error.

The model errors represent the difference between the predicted compressive strength using the compressive design provisions in EN1994-1-1 and the actual compressive strength measured in the experiments.

4.5.1 Series D

The mean model error of *1.46* suggests that the predicted compressive strength is, on average, *1.46* times lower than the actual compressive strength (Figure 4.4). This indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns for this source of data. Additionally, the moderate COV of *0.16* indicates that there is some variability in the errors. This suggests that the underestimation may be influenced by factors that cause significant variability.

4.5.2 Series E

The mean model error of *1.05* suggests that the predicted compressive strength is, on average, *1.05* times lower than the actual compressive strength (Figure 4.5). This again indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns. The moderate COV of *0.10* suggests that there is some variability in the errors, but not to the same extent as in Series D.

Table 4. 2 Summary of collected FEM database

Source	Series	Statistical moment	Model error
	D	Mean	1.46

		COV	0.16
	E	Mean	1.05
		COV	0.10
	F	Mean	0.79
		COV	0.05
	G	Mean	1.50
		COV	0.10
	H	Mean	1.18
		COV	0.07
	I	Mean	0.96
		COV	0.06

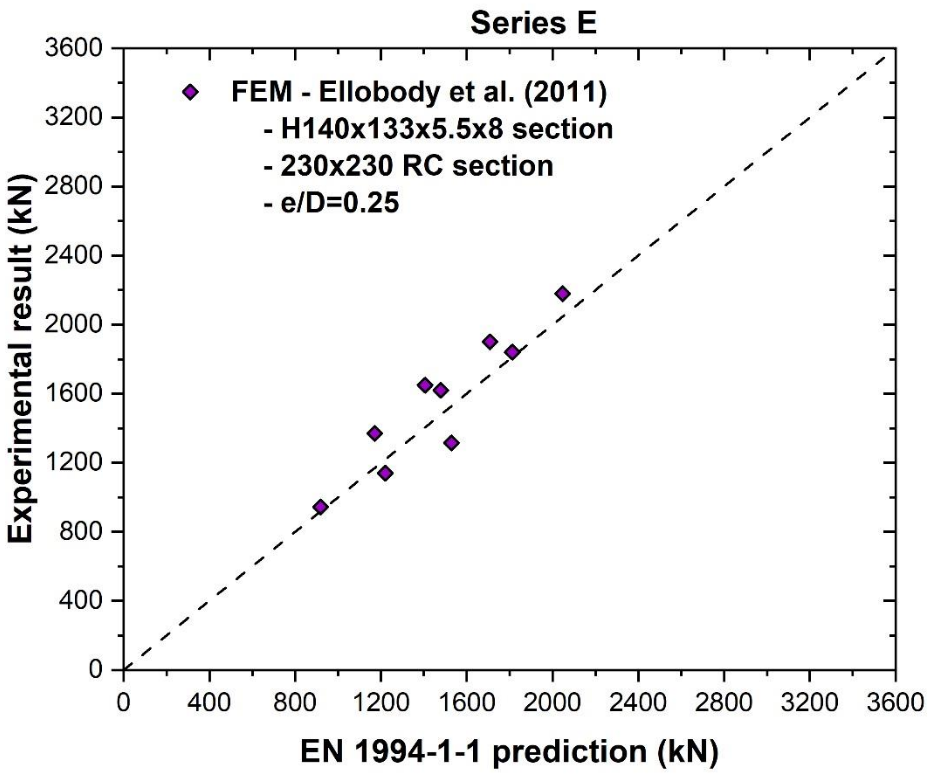


Figure 4. 5 Comparison of CEC sections FEM results (Ellobody et al., 2011) (Series E) with predictions from current EN1994-1-1.

4.5.3 Series F

The mean model error of *0.79* suggests that the predicted compressive strength is, on average, *0.79* times lower than the actual compressive strength (Figure 4.6). This indicates that EN1994-1-1 consistently underestimates the axial compressive strength of composite columns for this source of data. The low COV of *0.05* suggests that the underestimation is relatively consistent across different FEM setups, reinforcing the need for further investigation into the design provisions.

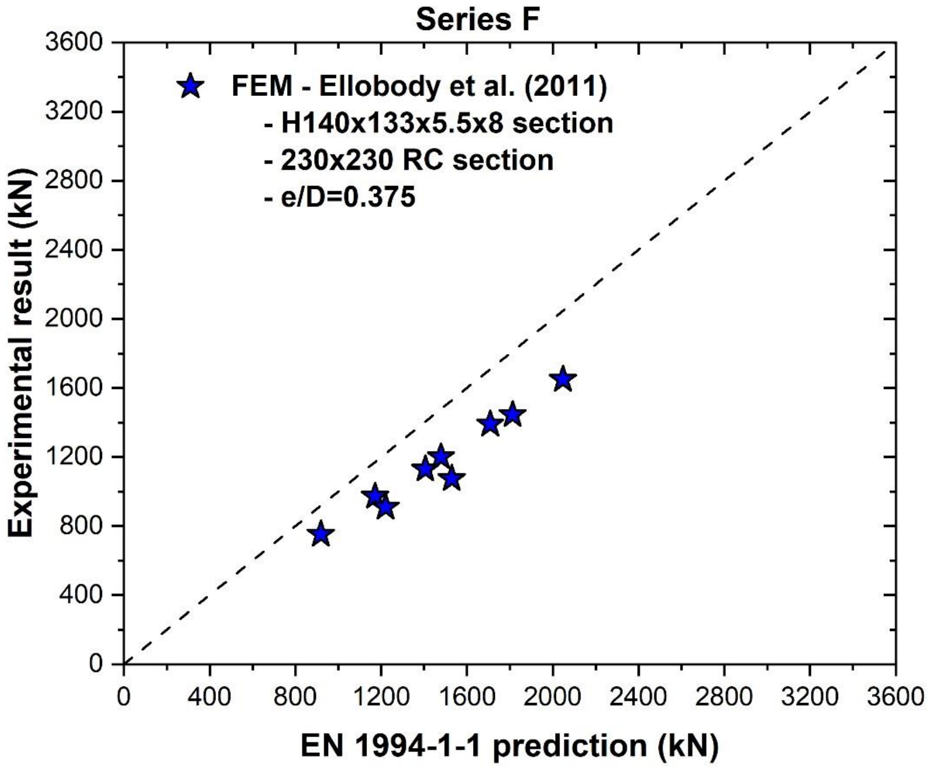


Figure 4. 6 Comparison of CEC sections FEM results (Ellobody et al., 2011) (Series F) with predictions from current EN1994-1-1.

4.5.4 Series G

The mean model error of *1.50* suggests that the predicted compressive strength is, on average, *1.50* times lower than the actual compressive strength (Figure 4.7). This again indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns for this source of data. The moderate COV of *0.10* suggests that there is some variability in the errors, but not to the same extent as in Series D.

4.5.5 Series H

The mean model error of *1.18* suggests that the predicted compressive strength is, on average, *1.18* times lower than the actual compressive strength (Figure 4.8). This indicates that EN1994-1-1 consistently underestimates the axial compressive strength of composite columns for this source of data. The low COV of *0.07* suggests that the underestimation is relatively consistent across different experimental setups, reinforcing the need for further investigation into the design provisions.

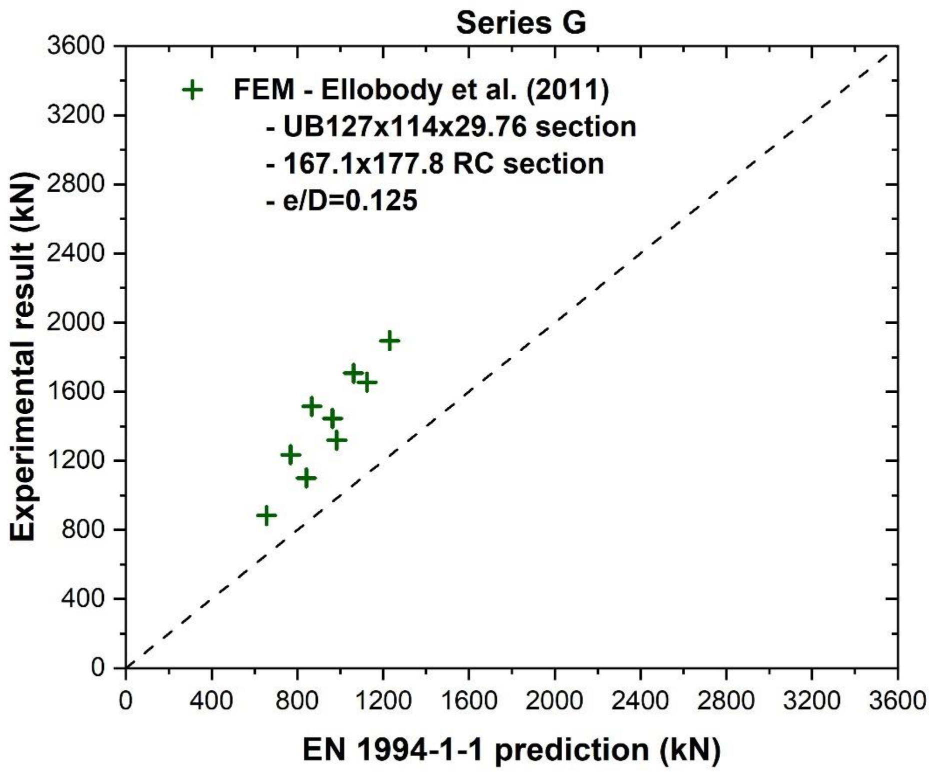


Figure 4. 7 Comparison of CEC sections FEM results (Ellobody et al., 2011) (Series G) with predictions from current EN1994-1-1.

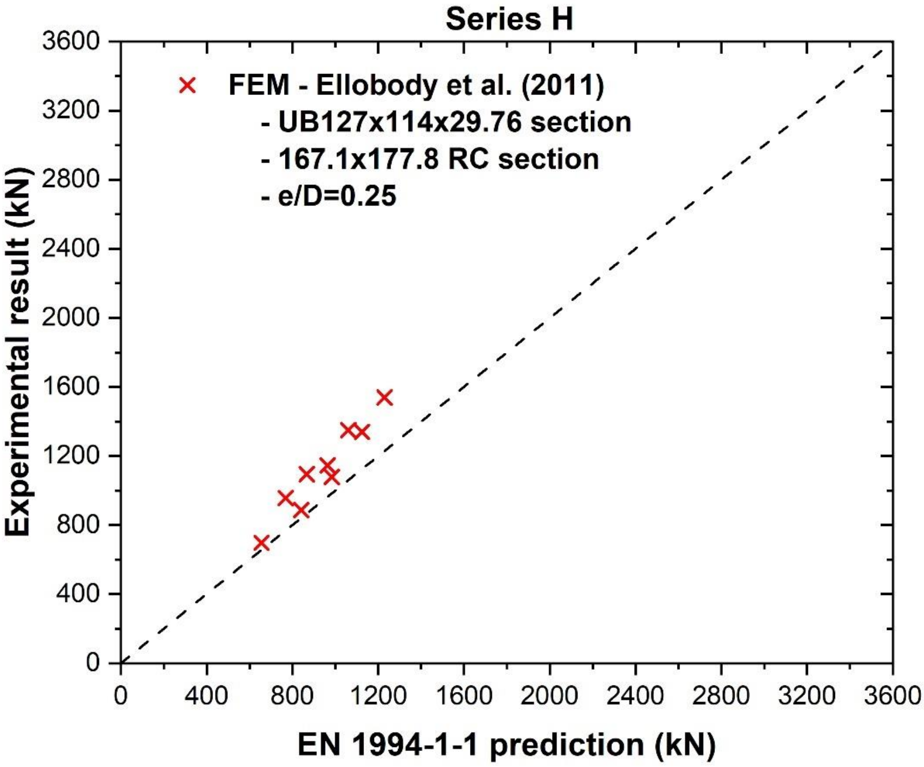


Figure 4. 8 Comparison of CEC sections FEM results (Ellobody et al., 2011) (SeriesH) with predictions from current EN1994-1-1.

4.5.6 Series I

The mean model error of *0.96* suggests that the predicted compressive strength is, on average, *0.96* times lower than the actual compressive strength (Figure 4.9). This indicates that EN1994-1-1 consistently underestimates the axial compressive strength of composite columns for this source of data. The low COV of *0.06* suggests that the underestimation is relatively consistent across different experimental setups, reinforcing the need for further investigation into the design provisions.

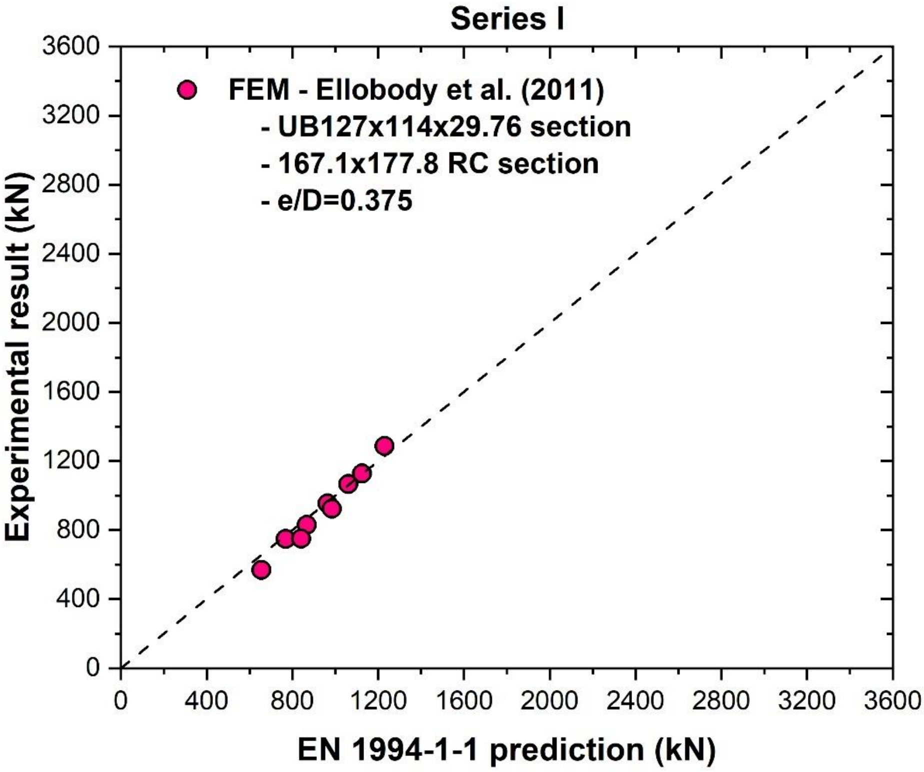


Figure 4. 9 Comparison of CEC sections FEM results (Ellobody et al., 2011) (Series I) with predictions from current EN1994-1-1.

Overall, the results suggest that the compressive design provisions in EN1994-1-1 consistently underestimate the compressive strength across different sources of data, with mean errors ranging from *0.79* to *1.50*. The level of variability in the errors varies between low and moderate, depending on the source of data. These findings provide further evidence that the design provisions may need to be modified to improve the accuracy of the predicted compressive strength.

4.6 Assessment of existing compressive design provisions against entire database

Figure 4.10 shows the comparison between the experimental and FEM results of the entire database and EN1994-1-1 compressive strength predictions, revealing that the current provisions are inadequate for accurate compressive strength predictions for eccentrically loaded CEC columns with out-of-code parameters. Based on the entire database (Table 4.3), the mean model error is *1.1*, which suggests that the predicted compressive strength is, on average, *1.1* times higher or lower than the actual compressive strength. However, the high coefficient of variation (COV) of *0.32* indicates that there is a significant level of variability in the errors. This suggests that the predictions may not always be reliable, and caution should be exercised when using them for designing CEC with high strength concrete and steel materials. New provisions to address these issues are presented in the following section.

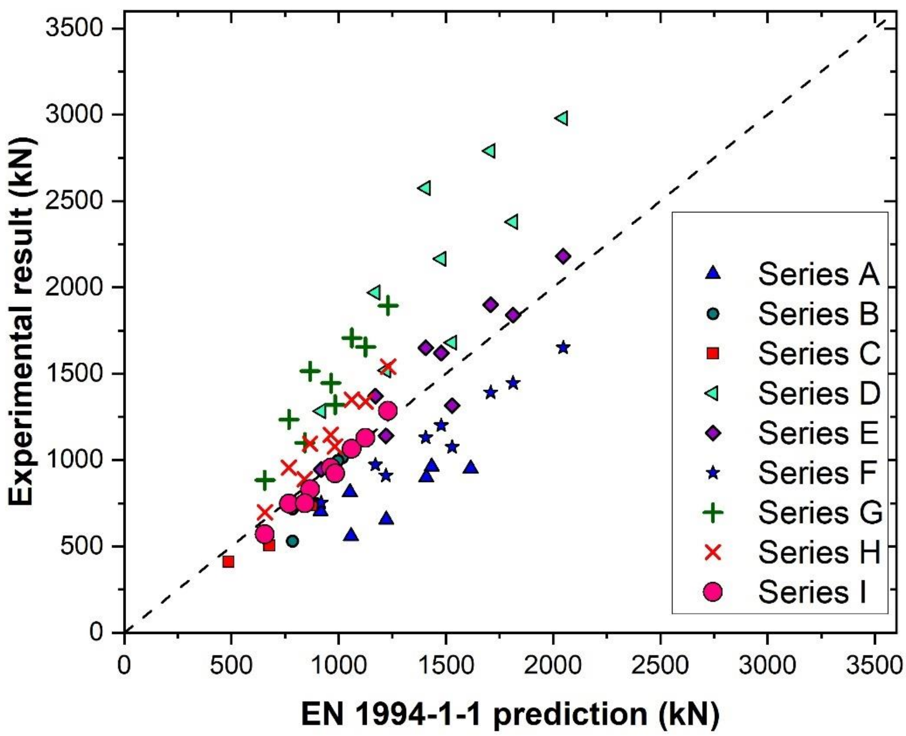


Figure 4. 10 Comparison of CEC sections for results of entire database (Series A to I) with predictions from current EN1994-1-1.

4.7 Proposed compressive design provisions.

The current Eurocode provisions under predict the experimental results for about *46%* of the experimental and FEM database. This means that the current Eurocode provisions would lead to under-designs with a probability of exceedance of *46%* if used for the design of CEC with out-of-code parameters. Eurocode 0 stipulates that the basis of design for the Eurocodes should be *5%*. This section will modify the current equations of EN1994-1-1 for compressive design with a multiplicative modification factor K_{mod} such that only *5%* of the data points will be below the line. This modification factor will be assessed by statistically analyzing the probability distribution of model error for the entire database and calculating the *5%* fractile from this distribution.

4.7.1 Assessment of model factor

Model factor also called the model assessed in detail in this section to find a modification factor K_{mod} that should be multiplied by the current Eurocode provisions such that *95%* of the data points in Figure 4.10 is above the perfect prediction line (the dotted line). This represents a *5%* fractile of the probability distribution of the ME, typically assumed to be lognormally distributed (Jcss, 2001). Table 4.3 shows that the ME has a mean value of *1.1* and COV of *0.32* (see also Figure 4.11 for box plot representation of ME).

Table 4. 3 Statistical moments of model error for the entire database inclusion of all experimental and FEM results

Database	Series	Statistical moment	ME
All experimental and FEM results	A to I	Mean	1.1
		COV	0.32

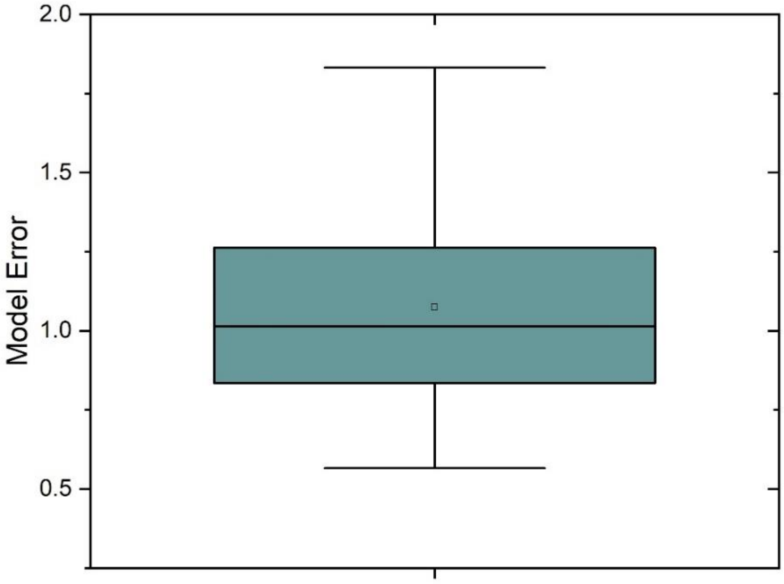


Figure 4. 11 Box plot scatter representation of ME of the EN1994-1-1 compressive design provisions for the entire database.

Assessment of ME involves conducting Pearson correlation analysis and sensitivity analysis to find out the influence of each of the parameters in the EN1994-1-1 equation on the derived ME.

Pearson correlation analysis was conducted, and this revealed (see Table 4.4 for the correlation matrix) that none of the parameters were strongly correlated (with $|r| > 0.5$). However, it was revealed that the elastic modulus of concrete ($|r| = 0.41$), the cross-section area of the steel section ($|r| = 0.40$), and the compressive strength of concrete ($|r| = 0.35$), had relatively higher correlation coefficients with the MEs compared to other variables.

Table 4. 4 Pearson Correlation Matrix

A_a	f_{ys}	A_c	f_c	A_r	f_{ur}	I_s	E_{cm}	I_c	I_r	L_e	ME
1.00	0.14	-0.50	**0.26**	-0.51	0.19	0.24	**0.36**	-0.48	-0.45	0.20	0.44
0.15	1.00	0.05	**0.08**	0.04	0.98	-0.35	**0.11**	0.06	0.07	0.29	0.68
-0.50	0.05	1.00	**0.04**	1.00	0.01	-0.10	**-0.01**	1.00	1.00	0.09	-0.49
0.26	**0.08**	**0.04**	**1.00**	**0.03**	**0.09**	**0.02**	**0.98**	**0.05**	**0.05**	**0.14**	**0.07**
-0.51	0.04	1.00	**0.03**	1.00	0.01	-0.10	**-0.03**	1.00	1.00	0.09	-0.49
0.19	0.98	0.01	**0.09**	0.01	1.00	-0.22	**0.12**	0.02	0.03	0.22	0.64
0.24	-0.35	-0.10	**0.02**	-0.10	-0.22	1.00	**0.00**	-0.11	-0.12	-0.49	-0.42
0.36	**0.11**	**-0.01**	**0.98**	**-0.03**	**0.12**	**0.00**	**1.00**	**-0.01**	**0.01**	**0.17**	**0.11**
-0.48	0.06	1.00	**0.05**	1.00	0.02	-0.11	**-0.01**	1.00	1.00	0.11	-0.47
-0.45	0.07	1.00	**0.05**	1.00	0.03	-0.12	**0.01**	1.00	1.00	0.12	-0.47
0.20	0.29	0.09	**0.14**	0.09	0.22	-0.49	**0.17**	0.11	0.12	1.00	0.58
0.44	0.68	-0.49	**0.07**	-0.49	0.64	-0.42	**0.11**	-0.47	-0.47	0.58	1.00
-0.44	-0.67	0.44	**-0.09**	0.45	-0.61	0.47	**-0.14**	0.43	0.42	-0.66	-0.99
0.40	0.10	-0.19	**0.35**	-0.19	0.08	-0.28	**0.41**	-0.17	-0.15	0.28	0.33

Sensitivity analysis of the ME with these three variables was conducted and Figures 4.12 - 4.14 show the effect of each of these variables on the model factor.

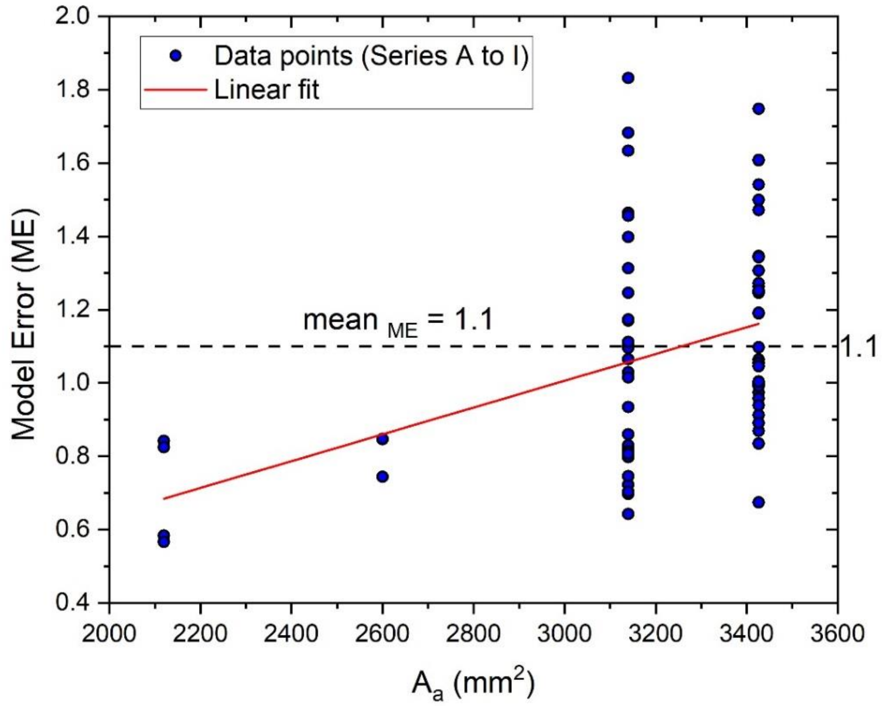


Figure 4. 12 Effect of steel section cross-section area on the model error

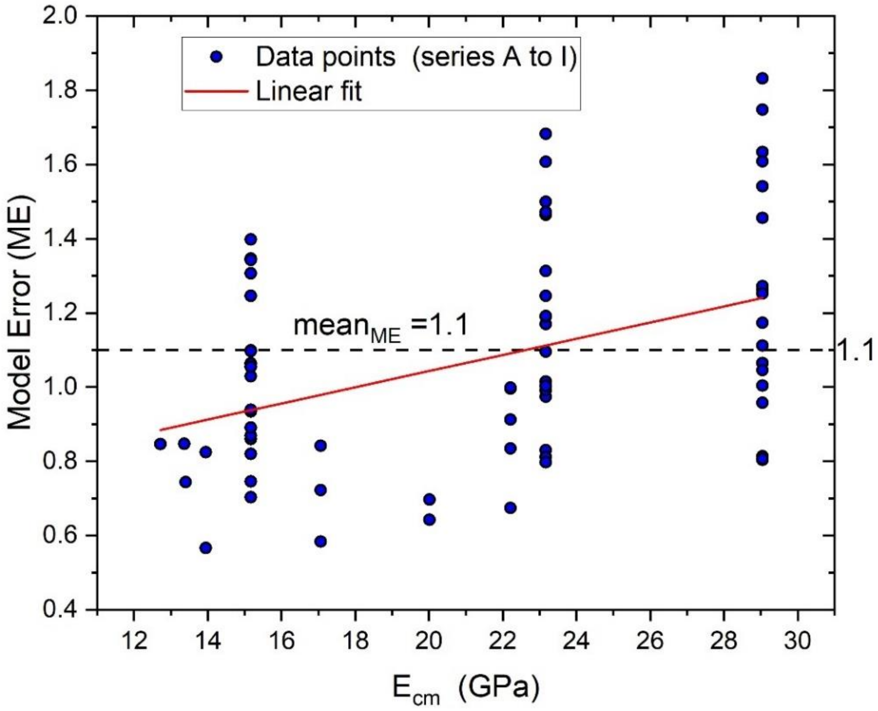


Figure 4. 13 Effect of elastic modulus of concrete on the model error

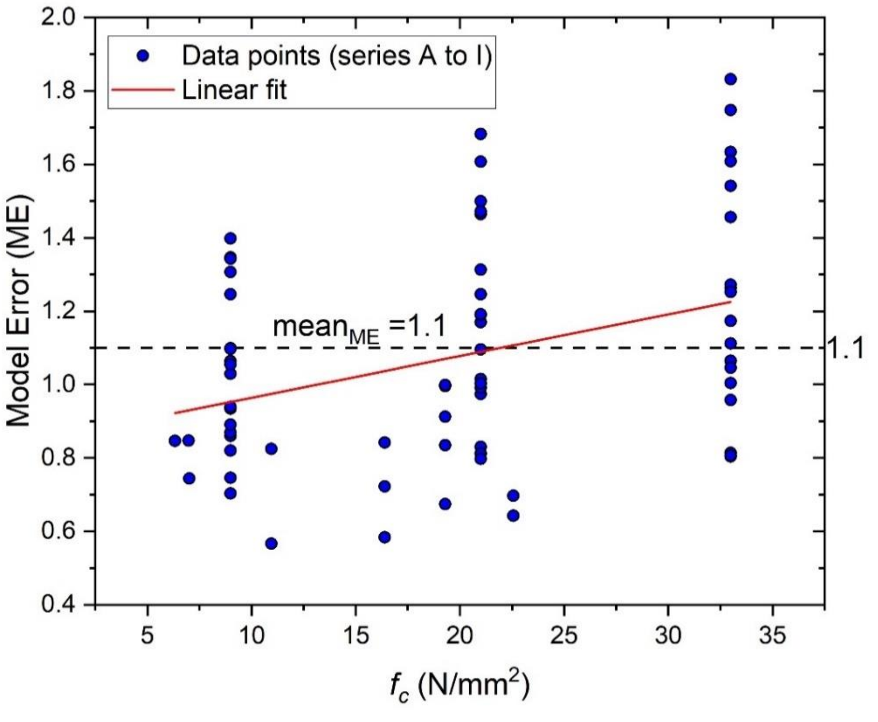


Figure 4. 14 Effect of concrete compressive strength on the model error

Figure 4.14 shows a histogram and fit lognormal distribution of the ME with tables showing the descriptive statistics of the ME, quantiles of ME and T goodness-fit test. It can be seen from the goodness of fit test that the Lognormal distribution cannot be rejected or this data set. From Figure 4.16, the multiplicative modification factor K_{mod} was calculated as the *95%* fractile. This gave a value of $K_{mod}=0.6$. This value is implemented to modify the Eurocode provisions for compression design as shown in Section 4.5.

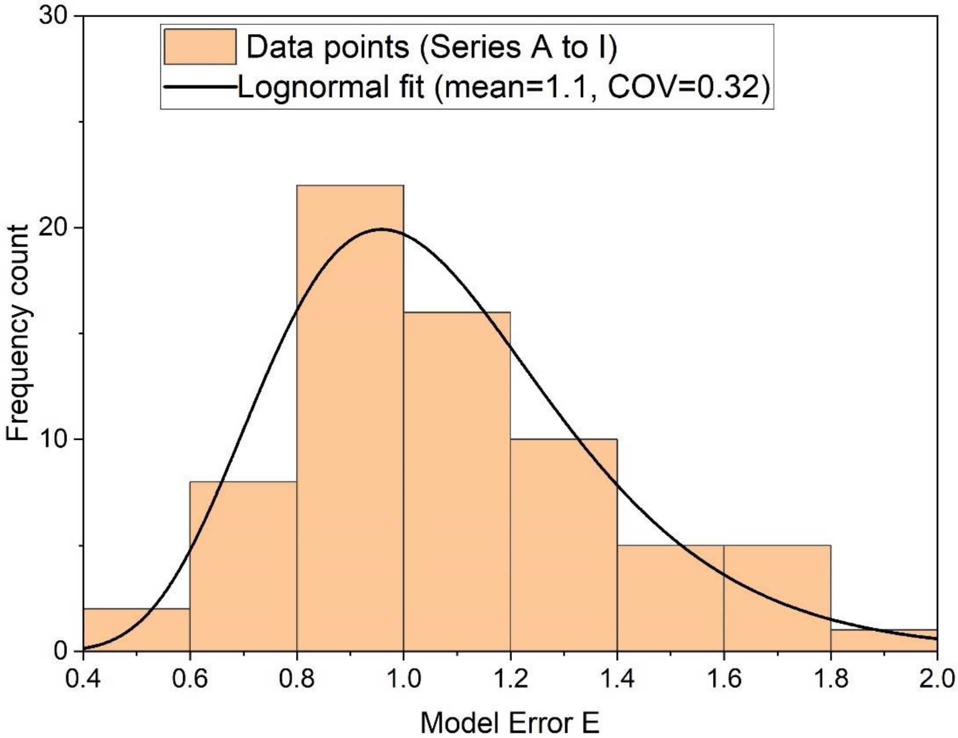


Figure 4. 15 Histogram and lognormal probability fit of ME

Table 4. 5 Descriptive statistics of the Model error

	N	Missing	Mean	Standard Deviation	SE of mean	Lower 95% CI of Mean	Upper 95% CI of Mean	Variance	Skewness	Coefficient of Variation

P	69	0	1.07552	0.30146	0.03629	1.0031	1.14794	0.09088	0.58853	0.2803

Table 4. 6 Quantiles of ME

	Minimum	1st Quartile (Q1)	Median	3rd Quartile (Q3)	Maximum	Interquartile Range (Q3 - Q1)	Range (Maximum - Minimum)	Median Absolute Deviation	Robust Coefficient of Variation
P	0.56613	0.83449	1.01487	1.26309	1.8317	0.4286	1.26557	0.20129	0.29406

Table 4. 7 Goodness-of-fit tests of ME

	Distribution	Goodness of Fit tests	Statistics	P-value	Decision at level(5%)
P	Lognormal	K-S test	0.07	0.97207	Can't reject Lognormal

From the above distribution, the *5%* fractile is found to be at $K_{mod} = 0.6$, as shown in Figure 4.16

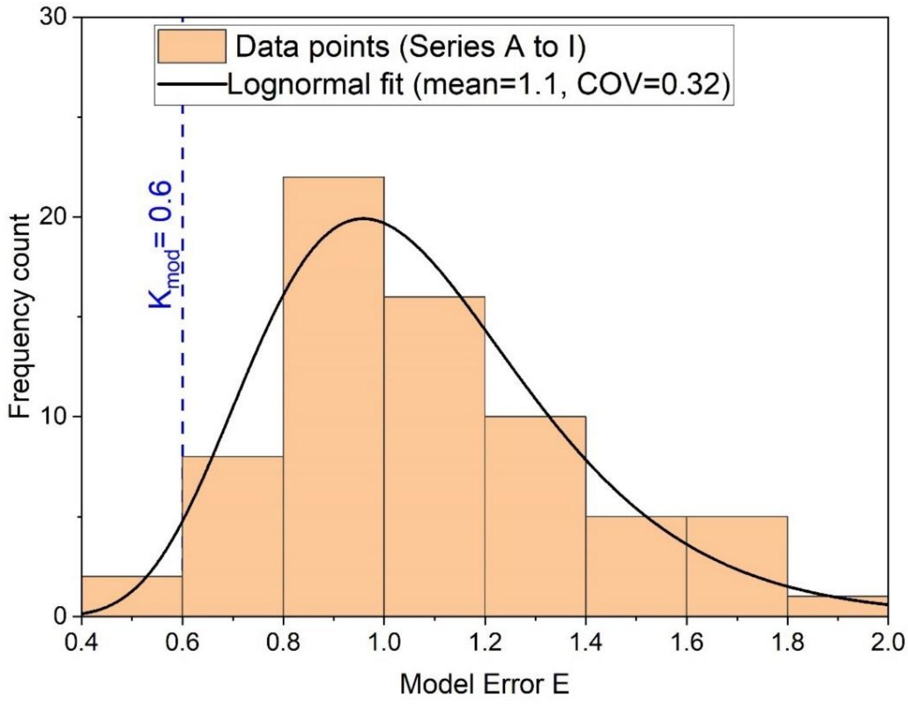


Figure 4. 16 Calculation of K_{mod} from the frequency distribution of ME

4.7.2 Modified EN-1994-1-1 compressive provisions

The proposed EN-1994-1-1 compressive design provisions are presented in this section.

Similar to the current Eurocode 4 method, in the proposed modified EN1994-1-1 method, calculating the resistance of a column under pure axial compression (P_o) using Equation 4.6 is also a necessary step for computing second-order effects in columns. However, every point on the axial force-bending moment strength interaction diagram represents a column that experiences an eccentric load lower than the pure axial compression. This means that the interaction diagram considers the impact of bending moment on the column's axial load-carrying capacity, which is lower than its pure axial compression strength, but this time modified with a multiplicative factor $K_{mod} = 0.6$ as given in see Equations 4.6-4.9

$$P_o = K_{mod}\chi N_{pl} \tag{4.6}$$

where

$$\chi = \frac{1}{\emptyset + \left[\emptyset^2 - \bar{\lambda}^2\right]^{0.5}} \leq 1 \tag{4.7}$$

with

$$\emptyset = 0.5\left[1 + \alpha\left(\bar{\lambda} - \bar{\lambda}_o\right) + \bar{\lambda}^1\right] \tag{4.8}$$

and

$$\bar{\lambda} = \frac{L_e}{\pi}\left(\frac{A_s f_{ys} + 0.85A_c f_c + A_r f_{yr}}{E_s I_s + 0.6E_{cm}I_c + I_r I_r}\right)^{0.5} \tag{4.9}$$

4.7.3 Assessment of proposed EN-1994-1-1 compressive provisions

Figure 4.17 shows the comparison of the proposed EN1994-1-1 compressive design provisions with the entire database considered in section 4.5. The proposed design provisions have led to most of the data points lying above the perfect prediction line. Despite being conservative across the entire database, this led to overly conservative designs for columns under series D. Careful analysis of series D shows that the columns that are overly designed have a very low concrete strength of less than 9 MPa. It was observed that the higher the compressive strength the better the prediction. This implies that the modified equation should be restricted to concrete strength classes above C25/30 but more accurate for high strength concretes.

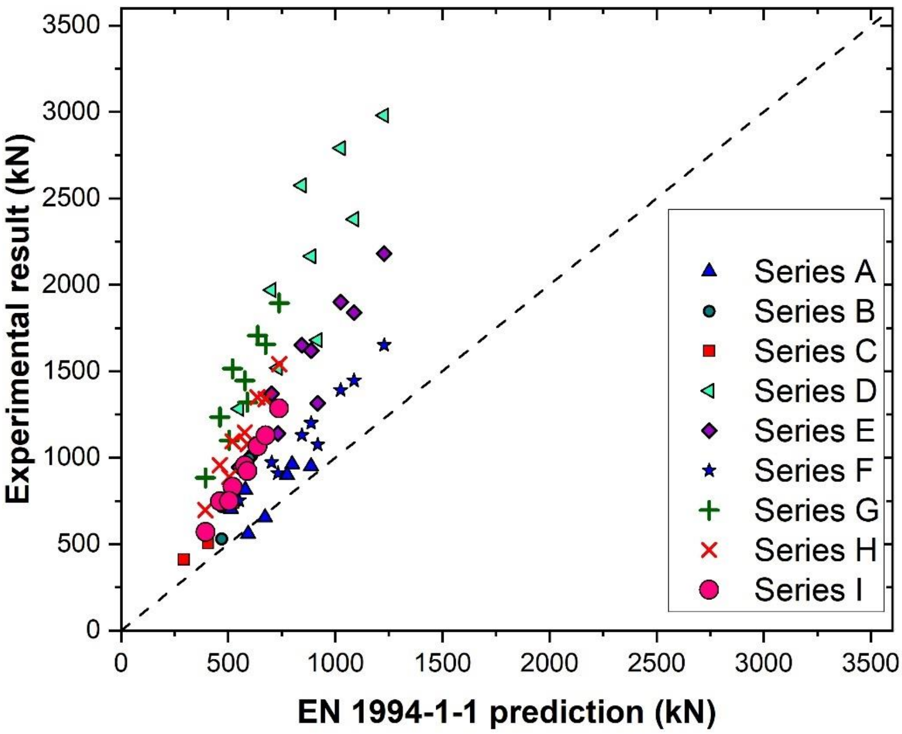


Figure 4. 17 Comparison of CEC sections for results of entire database (Series A to I) with predictions from modified proposed EN1994-1-1.

Furthermore, a sensitivity analysis of the ME of the modified EN1994-1-1 compressive design provision with these three variables was conducted and Figures 4.18 - 4.20 below show the effect of each of these variables on the model factor. Like before a positive correlation can be observed between ME and the basic variables, that is the steel cross-section area, the elastic modulus of concrete and the compressive strength of concrete. However, the mean value of the ME is seen to increase from *1.1* to *1.8.* The frequency distribution of the ME of the modified EN1994-1-1 provisions is shown in Figure 4.21 with Tables 4.8, 4.9 and 4.10 showing the descriptive statistics, the quantiles and the goodness-of-fit results of the ME. Lognormal distribution was selected as the best fit.

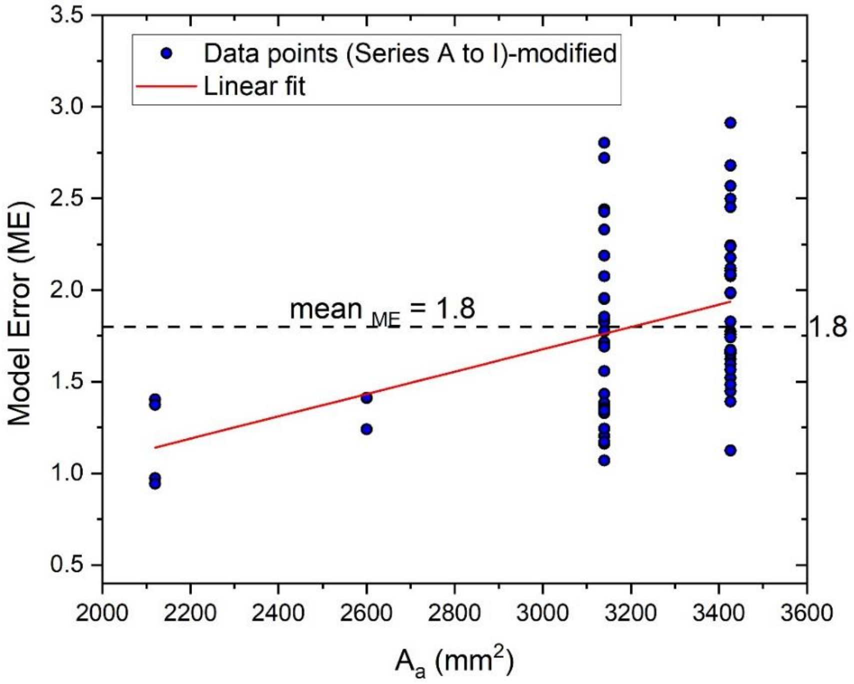


Figure 4. 18 Effect of steel section cross-section area on the model error of the proposed provisions

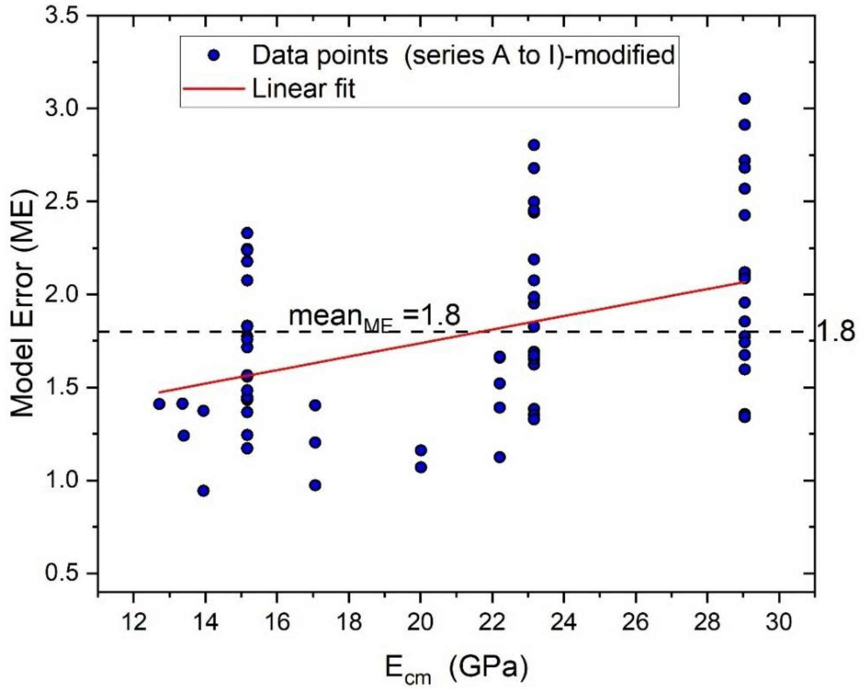


Figure 4. 19 Effect of elastic modulus of concrete on the model error of the proposed provisions

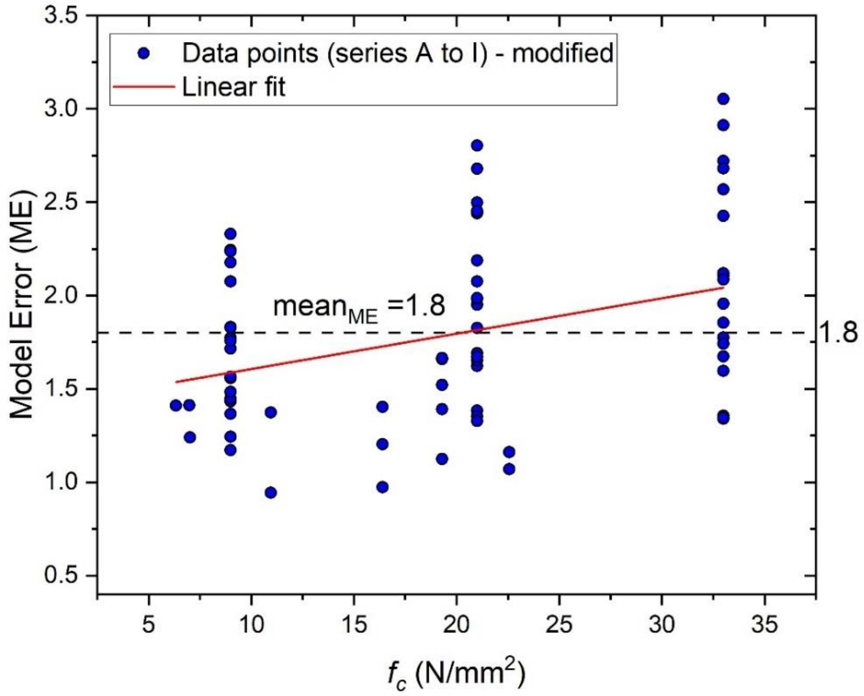


Figure 4. 20 Effect of concrete compressive strength on the model error of the proposed provisions

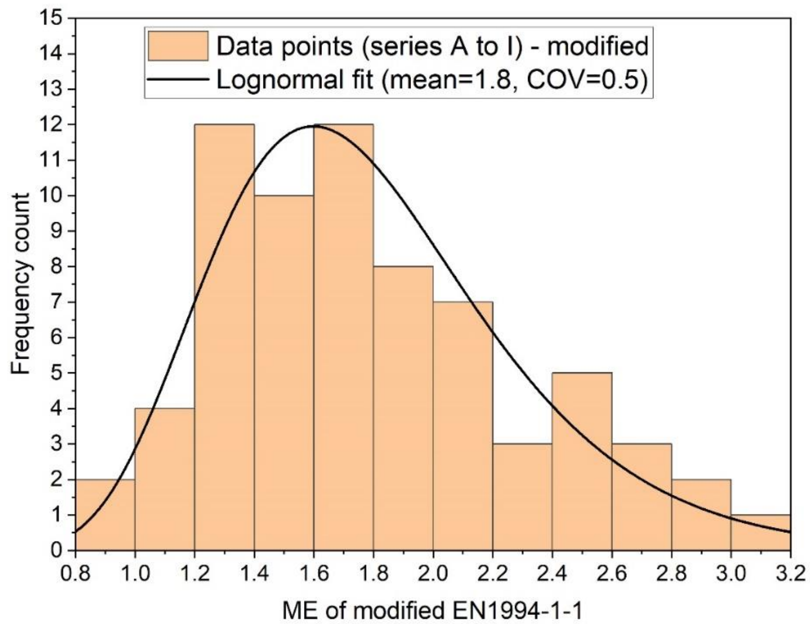


Figure 4. 21 Frequency distribution of the ME of the modified EN-1994-1-1 provisions

Table 4. 8 descriptive statistics of modified ME

	N	Missing	Mean	Standard Deviation	SE of mean	Lower 95% CI of Mean	Upper 95% CI of Mean
P	69	0	1.79253	0.50244	0.06049	1.67183	1.91323

Table 4. 9 Quantiles of modified ME

	Minimum	1st Quartile (Q1)	Median	3rd Quartile (Q3)	Maximum	Interquartile Range (Q3 - Q1)	Range (Maximum - Minimum)	Median Absolute Deviation	Robust Coefficient of Variation
P	0.94355	1.39081	1.69145	2.10515	3.05283	0.71434	2.10928	0.33548	0.29406

Table 4. 10 Goodness-of-fit test of modified ME

	Distribution	Goodness of Fit tests	Statistics	P-value	Decision at level (5%)
P	Lognormal	K-S test	0.07	0.97207	Can't reject Lognormal

4.8 Chapter Summary

This Chapter has presented a detailed assessment of current and proposed design provisions for CEC with out-of-code parameters under eccentric compressive loads. The chapter began with an introduction (section 4.1) that provided an overview of the topic and outlines the objectives of the study and then delved into a summary of the assessment methodology (Section 4.2) then delved into Section 4.3 which described the current compressive design provisions that will be assessed in the study. This included a discussion of the relevant European and British design standards, as well as specific design equations and factors that are used to calculate the required column size and reinforcement.

The next few sections (4.4-4.6) presented the results of the assessment of the existing design provisions. Section 4.4 evaluated the existing provisions against experimental results from a range of tests on composite columns. Section 4.5 assessed the provisions against results from finite element simulations of composite columns. Finally, section 4.6 presented an assessment of the provisions against an entire database of experimental results, which provides a more comprehensive picture of their performance across different types of columns and loading conditions.

Section 4.7 presented the proposed compressive design provisions that are developed based on the results of the assessment. This section was further divided into three parts. Subsection 4.7.1 assessed the model factor that is used in the design equations to account for uncertainties in the design process. Subsection 4.7.2 presented the modified EN-1994-1-1 compressive provisions that are proposed based on the assessment results. Finally, subsection 4.7.3 provided an assessment of the proposed provisions against the same experimental database used in section 4.6.

Overall, this chapter provided a comprehensive and detailed analysis of current and proposed design provisions for composite steel and concrete columns. The results and insights presented in the chapter are likely to be of interest to engineers, researchers, and other professionals involved in the design and construction of composite structures.

Chapter 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study aimed to assess the existing compressive design provisions for concrete-encased steel composite columns with out-of-code parameters and propose potential modifications based on experimental and FEM results. The following conclusions can be drawn:

- The existing compressive design provisions in EN-1994-1-1 accurately predict the behaviour of concrete-encased steel composite columns with out-of-code parameters under axial compression but show significant inaccuracies in predicting their behaviour under eccentric loading.
- The experimental and FEM results show that the current design provisions produce overly under conservative predictions for the axial load-carrying capacity of the columns with out-of-code parameters under eccentric loading, resulting in a significant reduction in the column's ductility and energy absorption capacity.
- The proposed compressive design provisions, which incorporate modified model factors and reduced effective length, demonstrate improved accuracy in predicting the behaviour of concrete-encased steel composite columns under eccentric loading and with out-of-code parameters. These proposed provisions can result in an increase in the columns' ductility and energy absorption capacity, thereby enhancing their overall structural performance.

5.2 Recommendations for Future Research

Based on the study's findings, the following recommendations are proposed:

- The current design provisions for concrete-encased steel composite columns under eccentric loading should be revised to incorporate modified model factors for application with high strength concretes and steels. The proposed provisions can result in more accurate predictions of the columns' behaviour and improved overall structural performance.
- Further experimental and numerical studies should be conducted to validate and refine the proposed eccentric compressive design provisions.
- The proposed compressive design provisions should be considered for inclusion in future updates to the EN-1994-1-1 code for concrete-encased steel composite columns with out-of-code parameters.

5.3 Chapter Summary

Chapter 5 presents the conclusions and recommendations based on the study's evaluation of existing compressive design provisions for concrete-encased steel composite columns with out-of-code parameters. The conclusions highlight the inaccuracies in the current provisions under eccentric loading conditions and propose modifications to enhance the columns' structural performance. Additionally, recommendations for future research emphasize the need for validation and refinement of the proposed provisions, as well as their potential incorporation into future updates of relevant design codes.

REFERENCES

ACI 318. (2019). “Building Code Requirements for Structural Concrete and Commentary.” *ACI Structural Journal*.

Al-Shahari, A. M., Hunaiti, Y. M., & Ghazaleh, B. A. (2003). Behaviour of lightweight aggregate concrete-encased composite columns. *Steel and Composite Structures*. https://doi.org/10.12989/scs.2003.3.2.097

ANSI/AISC 360-10. (2010). ANSI/AISC 360-10. Specification for Structural Steel Buildings. *American Institute of Steel Construction*.

Anuntasena, W., Lenwari, A., & Thepchatri, T. (2019). Finite element modelling of concrete-encased steel columns subjected to eccentric loadings. *Engineering Journal*. https://doi.org/10.4186/ej.2019.23.6.299

Anuntasena, W., Lenwari, A., & Thepchatri, T. (2020). Axial compression behaviour of concrete-encased cellular steel columns. *Journal of Constructional Steel Research*. https://doi.org/10.1016/j.jcsr.2020.106220

Chen, C. C., & Lin, N. J. (2006). Analytical model for predicting axial capacity and behaviour of concrete-encased steel composite stub columns. *Journal of Constructional Steel Research*. https://doi.org/10.1016/j.jcsr.2005.04.021

Du, Y., Zhou, H., & Liew, J. Y. R. (2022). Experimental study on behaviours of ultra-high strength concrete-encased steel columns under static load. *Jianzhu Jiegou Xuebao/Journal of Building Structures*. https://doi.org/10.14006/j.jzjgxb.2019.0776

Dundar, C., Tokgoz, S., Tanrikulu, A. K., & Baran, T. (2008). Behaviour of reinforced and concrete-encased composite columns subjected to biaxial bending and axial load. *Building and Environment*. https://doi.org/10.1016/j.buildenv.2007.02.010

El-Tawil, S., & Deierlein, G. G. (1999). Strength and Ductility of Concrete-encased Composite Columns. *Journal of Structural Engineering*. https://doi.org/10.1061/(asce)0733-9445(1999)125:9(1009)

Ellobody, E., & Young, B. (2011). Numerical simulation of concrete-encased steel composite columns. *Journal of Constructional Steel Research*. https://doi.org/10.1016/j.jcsr.2010.08.003

Ellobody, E., Young, B., & Lam, D. (2011). Eccentrically loaded concrete-encased steel composite columns. *Thin-Walled Structures*. https://doi.org/10.1016/j.tws.2010.08.006

EN-1994. (2009). Eurocode 4. *Design of Composite Steel and Concrete Structures - Part 1-1: General Rules and Rules for Buildings Eurocode*.

Furlong, R. W. (1969). Closure to "Design of Steel-Encased Concrete Beam-Columns." *Journal of the Structural Division*. https://doi.org/10.1061/jsdeag.0002254

Janss, J., & Anslijn, R. (1974). Le Calcul des Charges Ultimes des Colonnes Métalliques Enrobés de Béton. *Rapport CRIF, MT*.

Jcss. (2001). Probabilistic Model Code - Part 1. *Structural Safety*.

Kato, B. (1996). Column Curves of Steel-Concrete Composite Members. *Journal of Constructional Steel Research*. https://doi.org/10.1016/S0143-974X(96)00030-2

Lai, B., & Liew, J. Y. R. (2020). Design and testing of concrete-encased steel composite beam-columns with C90 concrete and S690 steel section. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2020.110995

Lai, B., Richard Liew, J. Y., & Wang, T. (2019). Buckling behaviour of high strength concrete-encased steel composite columns. *Journal of Constructional Steel Research*. https://doi.org/10.1016/j.jcsr.2018.11.023

Ma, D. Y., Han, L. H., & Zhao, X. L. (2019). Seismic performance of the concrete-encased CFST column to RC beam joint: Experiment. *Journal of Constructional Steel Research*. https://doi.org/10.1016/j.jcsr.2018.11.030

Medeiros, W. A., Parsekian, G. A., & Moreno, A. L. (2021). Critical analysis of the use of international codes and standards to design Brazilian structural masonry in fire situation. *International Journal of Masonry Research and Innovation*. https://doi.org/10.1504/IJMRI.2021.116202

Mirza, S. A., & Skrabek, B. W. (1992). Statistical Analysis of Slender Composite Beam-Column Strength. *Journal of Structural Engineering*. https://doi.org/10.1061/(asce)0733-9445(1992)118:5(1312)

Mirza, S. Ali, Hyttinen, V., & Hyttinen, E. (1996). Physical Tests and Analyses of Composite Steel-Concrete Beam-Columns. *Journal of Structural Engineering*. https://doi.org/10.1061/(asce)0733-9445(1996)122:11(1317)

Morino, S., Matsui, C., & Watanabe, H. (1985). *Strength of biaxially loaded SRC columns*.

Muñoz, P. R., & Hsu, C.-T. T. (1997a). Behaviour of Biaxially Loaded Concrete-Encased Composite Columns. *Journal of Structural Engineering*. https://doi.org/10.1061/(asce)0733-9445(1997)123:9(1163)

Muñoz, P. R., & Hsu, C.-T. T. (1997b). Biaxially Loaded Concrete-Encased Composite Columns: Design Equation. *Journal of Structural Engineering*. https://doi.org/10.1061/(asce)0733-9445(1997)123:12(1576)

Roik, K., & Bergmann, R. (1990). Design method for composite columns with unsymmetrical cross-sections. *Journal of Constructional Steel Research*. https://doi.org/10.1016/0143-974X(90)90046-J

Shanmugam, N. E., & Lakshmi, B. (2001). State of the art report on steel-concrete composite columns. *Journal of Constructional Steel Research*. https://doi.org/10.1016/S0143-974X(01)00021-9

SSRC Task Group 20. (1979). A specification for the design of steel–concrete composite columns. *AISC Engineering Journal Fourth Quarter*, 1101–1115.

Tunc, G., Othman, M. M., & Mertol, H. C. (2022). Finite Element Analysis of Frames with Reinforced Concrete-encased Steel Composite Columns. *Buildings*. https://doi.org/10.3390/buildings12030375

VIRDI, K., PILKINGTON, J., DOWLING, P., & CROFT, D. (1973). DISCUSSION. THE ULTIMATE STRENGTH OF COMPOSITE COLUMNS IN BIAXIAL BENDING. *Proceedings of the Institution of Civil Engineers*. https://doi.org/10.1680/iicep.1973.4708

Xiang, S., Zeng, L., Liu, Y., Mo, J., Ma, L., Zhang, J., & Chen, J. (2020). Experimental study on the dynamic behaviour of T-shaped steel reinforced concrete columns under impact loading. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2020.110307

Xu, W., Han, L. H., & Li, W. (2016). Seismic performance of concrete-encased column base for hexagonal concrete-filled steel tube: Experimental study. *Journal of Constructional Steel Research*. https://doi.org/10.1016/j.jcsr.2016.02.003

Zeng, L., Ren, W., Zou, Z., Chen, Y., Xie, W., & Li, X. (2019). Experimental study on seismic behaviour of frame structures composed of concrete-encased columns with L-shaped steel section and steel beams. *Earthquake and Structures*. https://doi.org/10.12989/eas.2019.16.1.097

Zhou, K., & Han, L. H. (2018). Experimental performance of concrete-encased CFST columns subjected to full-range fire including heating and cooling. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2018.03.042

Zhou, X., Xu, T., Liu, J., Wang, X., & Chen, Y. F. (2022). Seismic performance of concrete-encased column connections for concrete filled thin-walled steel tube piers. *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2022.114803

Appendix A: Compiled database

Table A.1 Compiled database

Ar	fur	Es	Is	Ecm	Ic	Er	Ir	Le	lamda	phi	xsi	Npl	Ptest	Po-EC4	Po-Modified	Series
mm²	N/mm²	N/ mm²	mm⁴	N/ mm²	mm⁴	N/ mm²	mm⁴	mm	-	-	-	kN	kN	kN	kN	
452.45	459.00	200000.00	3492000.00	17061.85	226809094.10	200000.00	2899739.23	2000.00	0.43	0.65	0.88	1269.55	654.00	1120.62	672.37	Series A
452.45	459.00	200000.00	3492000.00	13947.92	226809094.10	200000.00	2899739.23	2000.00	0.42	0.64	0.89	1114.41	559.00	987.41	592.44	
452.45	459.00	200000.00	10330000.00	17061.85	219971094.10	200000.00	2899739.23	2000.00	0.39	0.62	0.90	1477.06	962.00	1331.51	798.91	
452.45	459.00	200000.00	10330000.00	20011.22	219971094.10	200000.00	2899739.23	2000.00	0.40	0.63	0.90	1649.18	949.00	1477.39	886.44	
452.45	459.00	200000.00	10330000.00	20011.22	219971094.10	200000.00	2899739.23	3000.00	0.60	0.78	0.78	1649.18	900.00	1291.12	774.67	
452.45	459.00	200000.00	3492000.00	17061.85	226809094.10	200000.00	2899739.23	3000.00	0.64	0.81	0.76	1269.55	813.00	965.74	579.45	
452.45	459.00	200000.00	3492000.00	13947.92	226809094.10	200000.00	2899739.23	3000.00	0.63	0.81	0.77	1114.41	704.00	854.04	512.42	
113.11	460.00	200000.00	9660000.00	22210.79	67044275.90	200000.00	628054.38	726.00	0.15	0.50	1.00	1018.78	1014.00	1018.78	611.27	Series B
113.11	460.00	200000.00	9660000.00	22210.79	67044275.90	200000.00	628054.38	1156.00	0.24	0.54	0.98	1018.78	996.00	997.32	598.39	
113.11	460.00	200000.00	9660000.00	22210.79	67044275.90	200000.00	628054.38	2083.00	0.43	0.65	0.88	1018.78	747.00	895.16	537.10	
113.11	460.00	200000.00	9660000.00	22210.79	67044275.90	200000.00	628054.38	2997.00	0.63	0.80	0.77	1018.78	716.00	784.42	470.65	
113.11	460.00	200000.00	9660000.00	22210.79	67044275.90	200000.00	628054.38	2997.00	0.63	0.80	0.77	1018.78	529.00	784.42	470.65	
113.11	460.00	200000.00	4495000.00	12720.00	49697189.08	200000.00	421144.25	960.00	0.27	0.55	0.96	907.34	740.00	874.58	524.75	Series C
113.11	460.00	200000.00	4495000.00	13395.34	49697189.08	200000.00	421144.25	2400.00	0.68	0.85	0.74	916.29	504.00	677.11	406.27	
113.11	460.00	200000.00	4495000.00	13366.69	49697189.08	200000.00	421144.25	3600.00	1.02	1.22	0.53	915.90	412.00	486.45	291.87	
452.45	430.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.60	0.78	0.78	1171.51	1284.00	918.39	551.03	Series D
452.45	430.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.61	0.79	0.78	1506.81	1970.00	1170.90	702.54	
452.45	430.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.64	0.81	0.76	1842.10	2575.00	1405.80	843.48	
452.45	530.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.72	0.89	0.71	1715.99	1520.00	1220.11	732.07	
452.45	530.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.71	0.87	0.72	2051.28	2165.00	1478.64	887.18	
452.45	530.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.71	0.88	0.72	2386.57	2790.00	1708.49	1025.09	
452.45	760.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.85	1.03	0.63	2434.48	1680.00	1528.84	917.30	
452.45	760.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.81	0.98	0.65	2769.77	2380.00	1813.04	1087.82	
452.45	760.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.80	0.97	0.66	3105.06	2980.00	2046.92	1228.15	
452.45	430.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.60	0.78	0.78	1171.51	945.00	918.39	551.03	Series E
452.45	430.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.61	0.79	0.78	1506.81	1370.00	1170.90	702.54	

452.45	430.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.64	0.81	0.76	1842.10	1650.00	1405.80	843.48	
452.45	530.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.72	0.89	0.71	1715.99	1140.00	1220.11	732.07	
452.45	530.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.71	0.87	0.72	2051.28	1620.00	1478.64	887.18	
452.45	530.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.71	0.88	0.72	2386.57	1900.00	1708.49	1025.09	
452.45	760.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.85	1.03	0.63	2434.48	1315.00	1528.84	917.30	
452.45	760.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.81	0.98	0.65	2769.77	1840.00	1813.04	1087.82	
452.45	760.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.80	0.97	0.66	3105.06	2180.00	2046.92	1228.15	
452.45	430.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.60	0.78	0.78	1171.51	753.00	918.39	551.03	
452.45	430.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.61	0.79	0.78	1506.81	972.00	1170.90	702.54	
452.45	430.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.64	0.81	0.76	1842.10	1130.00	1405.80	843.48	
452.45	530.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.72	0.89	0.71	1715.99	910.00	1220.11	732.07	
452.45	530.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.71	0.87	0.72	2051.28	1200.00	1478.64	887.18	Series F
452.45	530.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.71	0.88	0.72	2386.57	1390.00	1708.49	1025.09	
452.45	760.00	200000.00	4495000.00	15167.24	225432824.50	200000.00	3273008.83	3000.00	0.85	1.03	0.63	2434.48	1075.00	1528.84	917.30	
452.45	760.00	200000.00	4495000.00	23168.34	225432824.50	200000.00	3273008.83	3000.00	0.81	0.98	0.65	2769.77	1445.00	1813.04	1087.82	
452.45	760.00	200000.00	4495000.00	29043.05	225432824.50	200000.00	3273008.83	3000.00	0.80	0.97	0.66	3105.06	1650.00	2046.92	1228.15	
113.11	430.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	0.80	0.97	0.66	993.26	883.00	656.06	393.64	
113.11	430.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	0.81	0.98	0.66	1168.81	1235.00	768.25	460.95	
113.11	430.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	0.83	1.00	0.64	1344.35	1515.00	866.92	520.15	
113.11	530.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	1.00	1.19	0.54	1554.27	1100.00	841.96	505.18	Series G
113.11	530.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	0.97	1.16	0.56	1729.81	1445.00	963.63	578.18	
113.11	530.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	0.97	1.16	0.56	1905.36	1707.00	1061.38	636.83	
113.11	760.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	1.20	1.46	0.43	2262.13	1320.00	983.41	590.04	
113.11	760.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	1.14	1.39	0.46	2437.68	1655.00	1124.90	674.94	

113.11	760.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	1.13	1.36	0.47	2613.22	1895.00	1229.96	737.98	
113.11	430.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	0.80	0.97	0.66	993.26	698.00	656.06	393.64	
113.11	430.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	0.81	0.98	0.66	1168.81	957.00	768.25	460.95	
113.11	430.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	0.83	1.00	0.64	1344.35	1095.00	866.92	520.15	
113.11	530.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	1.00	1.19	0.54	1554.27	888.00	841.96	505.18	
113.11	530.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	0.97	1.16	0.56	1729.81	1146.00	963.63	578.18	Series H
113.11	530.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	0.97	1.16	0.56	1905.36	1350.00	1061.38	636.83	
113.11	760.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	1.20	1.46	0.43	2262.13	1079.00	983.41	590.04	
113.11	760.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	1.14	1.39	0.46	2437.68	1340.00	1124.90	674.94	
113.11	760.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	1.13	1.36	0.47	2613.22	1540.00	1229.96	737.98	
113.11	430.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	0.80	0.97	0.66	993.26	570.00	656.06	393.64	
113.11	430.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	0.81	0.98	0.66	1168.81	748.00	768.25	460.95	
113.11	430.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	0.83	1.00	0.64	1344.35	830.00	866.92	520.15	
113.11	530.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	1.00	1.19	0.54	1554.27	750.00	841.96	505.18	
113.11	530.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	0.97	1.16	0.56	1729.81	955.00	963.63	578.18	Series I
113.11	530.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	0.97	1.16	0.56	1905.36	1066.00	1061.38	636.83	
113.11	760.00	200000.00	4495000.00	15167.24	72209275.90	200000.00	628054.38	3000.00	1.20	1.46	0.43	2262.13	923.00	983.41	590.04	
113.11	760.00	200000.00	4495000.00	23168.34	72209275.90	200000.00	628054.38	3000.00	1.14	1.39	0.46	2437.68	1128.00	1124.90	674.94	
113.11	760.00	200000.00	4495000.00	29043.05	72209275.90	200000.00	628054.38	3000.00	1.13	1.36	0.47	2613.22	1286.00	1229.96	737.98	

Appendix B: Ethical Clearance Approval Letter

THE UNIVERSITY OF ZAMBIA
DIRECTORATE OF RESEARCH AND GRADUATE STUDIES

Great East Road Campus | P.O. Box 32379 | Lusaka10101 | Tel: +260-211-290 258/291 777
Fax: (+260)-211-290 258/253 952 | **E-mail**: director.drgs@unza.zm | **Website**: www.unza.zm

APPROVAL OF STUDY

IORG No. 0005376
NASRECREC IRB No. 00006465

22nd December, 2023

REF NO. NASREC-2023- NOV – 008

Mr. Caron Kasumba
The University of Zambia,
P.O. Box 32379,
LUSAKA.

Dear Mr. Kasumba

RE: "ASSESSMENT OF EUROCODE PROVISION FOR ECCENTRICITY LOADED CONCRETE ENCASED COLUMNS WITH OUT-OF-CODE PARAMETERS."

Reference is made to your protocol dated as captioned above. NASREC resolved to approve this study and your participation as Principal Investigator for a period of one year.

REVIEW TYPE	ORDINARY REVIEW	APPROVAL NO. NASREC-2023 - NOV - 008
Approval and Expiry Date	Approval Date: 22nd December, 2024	Expiry Date: 21st December, 2024
Protocol Version and Date	Version - Nil.	21st December, 2024
Information Sheet, Consent Forms and Dates	• English.	To be provided
Consent form ID and Date	Version - Nil	To be provided
Recruitment Materials	Nil	Nil
Other Study Documents	Questionnaire.	

Specific conditions will apply to this approval. As Principal Investigator it is your responsibility to ensure that the contents of this letter are adhered to. If these are not adhered to, the approval may be suspended. Should the study be suspended, study sponsors and other regulatory authorities will be informed.

CONDITIONS OF APPROVAL

- No participant may be involved in any study procedure prior to the study approval or after the expiration date.
- All unanticipated or Serious Adverse Events (SAEs) must be reported to NASREC within 5 days.
- All protocol modifications must be approved by NASREC prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address.
- All protocol deviations must be reported to NASREC within 5 working days.
- All recruitment materials must be approved by NASREC prior to being used.
- Principal investigators are responsible for initiating Continuing Review proceedings. NASREC will only approve a study for a period of 12 months.
- It is the responsibility of the PI to renew his/her ethics approval through a renewal application to NASREC.
- Where the PI desires to extend the study after expiry of the study period, documents for study extension must be received by NASREC at least 30 days before the expiry date. This is for the purpose of facilitating the review process. Documents received within 30 days after expiry will be labelled "late submissions" and will incur a penalty fee of K500.00. No study shall be renewed whose documents are submitted for renewal 30 days after expiry of the certificate.
- Every 6 (six) months a progress report form supplied by The University of Zambia Natural and Applied Sciences Research Ethics Committee as an IRB must be filled in and submitted to us. There is a penalty of K500.00 for failure to submit the report.
- When closing a project, the PI is responsible for notifying, in writing or using the Research Ethics and Management Online (REMO),both NASREC
- and the National Health Research Authority (NHRA) when ethics certification is no longer required for a project.
- In order to close an approved study, a Closing Report must be submitted in writing or through the REMO system. A Closing Report should be filed when data collection has ended and the study team will no longer be using human participants or animals or secondary data or have any direct or indirect contact with the research participants or animals for the study.
- Filing a closing report (rather than just letting your approval lapse) is important as it assists NASREC in efficiently tracking and reporting on projects. Note that some funding agencies and sponsors require a notice of closure from the IRB which had approved the study and can only be generated after the Closing Report has been filed.

- A reprint of this letter shall be done at a fee.

- All protocol modifications must be approved by NASREC by way of an application for an amendment prior to implementation unless they are intended to reduce risk (but must still be reported for approval). Modifications will include any change of investigator/s or site address or methodology and methods. Many modifications entail minimal risk adjustments to a protocol and/or consent form and can be made on an Expedited basis (via the IRB Chair). Some examples are: format changes, correcting spelling errors, adding key personnel, minor changes to questionnaires, recruiting and changes, and so forth. Other, more substantive changes, especially those that may alter the risk-benefit ratio, may require Full Board review. In all cases, except where noted above regarding subject safety, any changes to any protocol document or procedure must first be approved by NASREC before they can be implemented.

Should you have any questions regarding anything indicated in this letter, please do not hesitate to get in touch with us at the above indicated address.

On behalf of NASREC, we would like to wish you all the success as you carry out your study.

Yours faithfully,

Dr. Mususu Kaonda

VICE-CHAIRPERSON
THE UNIVERSITY OF ZAMBIA NATURAL AND APPLIED SCIENCES RESEARCH ETHICS COMMITTEE - IRB

cc: Director, Directorate of Research and Graduate Studies
Assistant Director (Research), Directorate of Research and Graduate Studies
Assistant Registrar (Research), Directorate of Research and Graduate Studies

Appendix C: Publication Proof (Published Paper)

Structures

Assessment of Eurocode compressive design provisions for concrete-cased columns with out-of-code parameters

--Manuscript Draft--

Manuscript Number:	
Article Type:	Research Paper
Keywords:	Concrete-encased columns; Compressive load capacity; Experimental and Numerical data; Eurocode 4; Modification Factor.
Corresponding Author:	Caron Kasumba University of Zambia ZAMBIA
First Author:	Caron Kasumba
Order of Authors:	Caron Kasumba
	Charles Kahanji, PhD, MEng, BEng
Abstract:	Concrete-encased column (CEC) sections are widely preferred structural systems for tall building construction and the use of high strength steel and concrete is expected to increase the load capacity leading to slender sections and more usable area. However, provisions for the design of CEC section with high strength steel and concrete are still lacking and moreover, the Eurocode 4 (EC4) for restricts steel strength below S460 and concrete strength below C60/75. The main aim of this study is to assess the applicability of EC4 compressive design provisions to concrete-encased steel composite columns, particularly those with parameters exceeding the current code boundaries. Existing experimental and numerical studies of CEC columns including those with out-of-code parameters were assembled from the literature and the collected data was used for assessment. Findings show a discrepancy in safety predictions for out-of-code parameters, with a notable portion of columns being under-designed. The study proposes modified design provisions incorporating a constant modification factor, which while conservative, ensures a higher confidence level in structural safety for high-strength materials. The research contributes to safer design practices for composite columns with advanced materials.
Suggested Reviewers:	Lenganji Simwanda, PhD Postdoctoral Research Fellow, University of South Africa simwals@unisa.ac.za
	Amika Akuta Usongo, PhD candidate PhD, Stellenbosch University 22409432@sun.ac.za
Opposed Reviewers:	

Assessment of Eurocode compressive design provisions for concrete-cased columns with out-of-code parameters

Caron Kasumba[a*], Charles Kahanji[a]

Department of Civil & Environmental Engineering, University of Zambia, Lusaka, Zambia

[*]caronkas@gmail.com

Abstract

Concrete-encased column (CEC) sections are widely preferred structural systems for tall building construction and the use of high strength steel and concrete is expected to increase the load capacity leading to slender sections and more usable area. However, provisions for the design of CEC section with high strength steel and concrete are still lacking and moreover, the Eurocode 4 (EC4) for restricts steel strength below S460 and concrete strength below C60/75. The main aim of this study is to assess the applicability of EC4 compressive design provisions to concrete-encased steel composite columns, particularly those with parameters exceeding the current code boundaries. Existing experimental and numerical studies of CEC columns including those with out-of-code parameters were assembled from the literature and the collected data was used for assessment. Findings show a discrepancy in safety predictions for out-of-code parameters, with a notable portion of columns being under-designed. The study proposes modified design provisions incorporating a constant modification factor, which while conservative, ensures a higher confidence level in structural safety for high-strength materials. The research contributes to safer design practices for composite columns with advanced materials.

Keywords

Concrete-encased columns; Compressive load capacity; Experimental and Numerical data; Eurocode 4; Modification Factor.

1. Introduction

Concrete-encased columns are commonly used in building structures, especially in multi-storey buildings. These columns are constructed by encasing a structural steel member (such as a beam or a column) in concrete [1]. The purpose of the concrete encasement is to enhance the strength and ductility of the steel member by providing confinement and lateral support, thus enabling the column to carry high loads and resist lateral forces such as wind and earthquakes [2][3]. In addition, concrete encasement can provide fire resistance to the steel member, which is essential in ensuring the safety of occupants during a fire [4].

The design and assessment of concrete-encased columns is a complex task that requires consideration of several factors, such as material properties, cross-sectional design, load combinations, ductility, stability, and detailing requirements [5]. Concrete-encased columns can fail due to various modes of failure, such as flexural failure, shear failure, local buckling, and instability [6]. Therefore, the design and assessment of these columns must ensure that they are able to resist different types of loading conditions and failure modes.

In Europe, Eurocode 4 (EC4) [6] is the design standard that provides guidelines for the design and assessment of concrete structures, including concrete-encased columns. EC4 provides a comprehensive framework for the design and assessment of concrete encased columns, taking into account various design parameters such as the required strength, load conditions, and confinement provided by the concrete. The design provisions of EC4 are based on a limit state design approach, which ensures that the structure is able to resist both ultimate and serviceability limit states.

Concrete encased columns, due to their prevalence in multi-storey buildings, have been the subject of various studies and research efforts. A significant body of literature has examined different aspects of these columns, ranging from their structural behaviour under different loading conditions to their performance in fire scenarios. Studies by Lai et al. [7][8] have highlighted the critical role of material properties such as concrete strength and steel quality in the overall performance of these columns. Furthermore, research by Chen et al. [9] has delved into the impact of cross-sectional design on the ductility and stability of concrete encased columns, emphasizing the importance of considering these factors in design.

The failure modes of concrete encased columns, including flexural failure, shear failure, and local buckling, have been extensively investigated. For instance, Ellobody and Young [10] presented a comprehensive analysis of the failure mechanisms in these columns, suggesting that an integrated approach to design and assessment is necessary to account for these varied failure modes. This aligns with the principles of the EC4, which advocates for a holistic view in structural design.

However, there are concerns regarding the applicability of EC4's design provisions to concrete encased columns with out-of-code parameters, such as those using high-strength materials. The use of such materials has become more prevalent, yet the Eurocode's guidelines may not fully encapsulate the behaviour of columns constructed with these advanced materials. Studies by Lai et al. [11] and Ellobody et al. [12] have indicated potential discrepancies in the performance predictions of EC4 when applied to columns with high-strength concrete or steel.

This gap in the literature and the evolving nature of construction materials necessitate a detailed investigation into the effectiveness of EC4's compressive design provisions, particularly for eccentrically loaded columns with out-of-code parameters. The objective of this study is to critically assess these provisions and evaluate the performance of concrete encased columns under eccentric compression limit states, using high-strength materials. This research aims to provide insights into whether the current Eurocode 4 adequately addresses the behaviour of these columns and to suggest potential modifications or enhancements to the code, ensuring safer and more reliable design practices for contemporary building structures.

2. Database

2.1 General

A literature review was conducted to identify existing studies [13]–[15] that investigated the compression behaviour of eccentrically loaded concrete-encased columns with high strength steel and concrete. The review included both experimental and numerical studies published in peer-reviewed journals and conference proceedings. The literature review aimed to collect data from a wide range of sources to ensure that the compiled database is representative of the behaviour of concrete-encased columns in practical applications. The review also included an analysis of the testing methods used in the experiments to ensure that the collected data is reliable and consistent.

2.2 Overview of experimental studies

The presently valid Eurocode provisions for eccentrically loaded compression concrete-encased steel composite columns were evaluated using partly test results conducted by Morino et al. [13], SSRC Task Group 20 [14], and Al-shahari et al. [15]. The dimensions and material properties of the tested specimens are summarized in Table 1 and

Table 2.

In the study by Al-shahari et al. [15], lightweight aggregate concrete-encased steel composite columns with square cross-sections (B×D) of 230 mm×230 mm and lengths of 2000 and 3000 mm were loaded eccentrically along the major axis. The specimens used in verification were denoted as BC1–BC7 and had concrete cube strengths (f_{cu}) ranging from 13.7 to 28.2 MPa and structural steel yield stresses (f_{ys}) ranging from 307 to 337 MPa. The specimens also had longitudinal and transverse reinforcement, as detailed in

Table 2.

The specimens used in the tests SSRC Task Group 20 [14], labelled as BC8–BC12, had rectangular cross-sections of 165.1 mm×177.8 mm and lengths varying from 726 to 2997 mm. The specimens were loaded eccentrically with eccentricity varying from 0.07D to 0.14D along the major axis. The structural steel section used was Universal Beam UB 127×114×29.76, with concrete cylinder strength of 19.3 MPa and steel yield stress of 232 MPa. The details of longitudinal and transverse reinforcement are also presented in

Table 2.

Table 1 Specimen dimensions and material properties of eccentrically loaded concrete-encased composite columns

Test	Dimensions			Steel Section	e/D	Material properties		
	B(mm)	D(mm)	kL(mm)			Concrete Strength (Mpa)		Fys (Mpa)
BC1	230	230	2000	H 100 x 96 x 5 x 8	0.3	20.5	Cube Strength	337
BC2	230	230	2000	H 100 x 96 x 5 x 8	0.3	13.7	Cube Strength	337
BC3	230	230	2000	H 140 x 133 x 5.5 x 8	0.3	20.5	Cube Strength	307
BC4	230	230	2000	H 140 x 133 x 5.5 x 8	0.3	28.2	Cube Strength	307
BC5	230	230	3000	H 140 x 133 x 5.5 x 8	0.3	28.2	Cube Strength	307
BC6	230	230	3000	H 100 x 96 x 5 x 8	0.17	20.5	Cube Strength	337
BC7	230	230	3000	H 100 x 96 x 5 x 8	0.17	13.7	Cube Strength	337
BC8	165.1	177.8	726	UB 127 x 114 x 29.76	0.11	19.3	Cylinder Strength	232
BC9	165.1	177.8	1156	UB 127 x 114 x 29.76	0.07	19.3	Cylinder Strength	232
BC10	165.1	177.8	2083	UB 127 x 114 x 29.76	0.11	19.3	Cylinder Strength	232
BC11	165.1	177.8	2997	UB 127 x 114 x 29.76	0.07	19.3	Cylinder Strength	232
BC12	165.1	177.8	2997	UB 127 x 114 x 29.76	0.14	19.3	Cylinder Strength	232
BC13	160	160	960	H 100 x 100 x 6 x 8	0.25	21.1	Cube Strength	345
BC14	160	160	2400	H 100 x 100 x 6 x 8	0.25	23.4	Cube Strength	345
BC15	160	160	3600	H 100 x 100 x 6 x 8	0.25	23.3	Cube Strength	345

Table 2 Composite section dimensions and reinforcement details

Test	Composite Section (mm)						Reinforcement		
	b1	b2	b3	d1	d2	d3	Longitudinal		T
							No.	dia	No.
BC1	100	35	30	96	35	32	4	12	140
BC2	100	35	30	96	35	32	4	12	140
BC3	140	35	10	133	35	13.5	4	12	140
BC4	140	35	10	133	35	13.5	4	12	140
BC5	140	35	10	133	35	13.5	4	12	140
BC6	100	35	30	96	35	32	4	12	140
BC7	100	35	30	96	35	32	4	12	140
BC8	114.3	14.4	11	127	14.4	11	4	6	75
BC9	114.3	14.4	11	127	14.4	11	4	6	75
BC10	114.3	14.4	11	127	14.4	11	4	6	75
BC11	114.3	14.4	11	127	14.4	11	4	6	75
BC12	114.3	14.4	11	127	14.4	11	4	6	75
BC13	100	19	11	100	19	11	4	6	75
BC14	100	19	11	100	19	11	4	6	75
BC15	100	19	11	100	19	11	4	6	75

2.3 Overview of numerical studies

Ellobody et al. [10] developed a nonlinear 3-D finite element model to study the behavior of eccentrically loaded concrete-encased steel composite columns. The columns were pin-ended and subjected to an eccentric load along the major axis, with eccentricities ranging from 0.125 to 0.375 of the overall depth (D) of the column sections. The model considered the inelastic behavior of steel, concrete, longitudinal and transverse reinforcement bars, and the effect of concrete confinement. It also accounted for the bond behavior between the different components of the column. The model was validated using test results, where the concrete strengths ranged from 30 to 110 MPa and steel section yield stresses varied from 275 to 690 MPa. In addition, a parametric study was conducted to investigate the effects of different variables on the behavior and strength of the eccentrically loaded composite columns.

In the study, a total of 54 eccentrically loaded column specimens were analyzed with varying eccentricities, overall cross-section dimensions, structural steel sections, concrete strength and structural steel yield stresses. The columns were divided into 18 groups denoted as G1–G18. Table 3 and Table 4 summarize the dimensions and material properties of the columns with square and rectangular cross-sections, respectively. The eccentricities along the major axis varied from 0.125D to 0.375D. The first nine groups G1–G9 had square cross-sections (B×D) of 230 mm×230 mm, similar to the tests conducted by Al-shahari et al. [15] . The remaining groups G10–G18 had rectangular cross-sections of 165.1 mm×177.8 mm, similar to the tests conducted by SSRC Task Group 20 [14]. Groups G1–G3, G4–G6, and G7–G9 had eccentricities along the major axis of 0.125D, 0.25D, and 0.375D, respectively. Similarly, G10–G12, G13–G15, and G16–G18 had the same eccentricities of 0.125D, 0.25D, and 0.375D, respectively. The structural steel sections used in G1–G9 were HEA 140 (H 140×133×5.5×8), while that in G10–G18 was UB 127×114×29.76, consistent with the tests conducted by Al-shahari et al. [15] and SSRC Task Group 20 [14], respectively.

2.4 Database overview

The experimental and numerical data from the reviewed studies were extracted and compiled into a database. The database includes information on the test specimens, loading conditions, and measured compressive strengths of the concrete-encased columns. The data extraction process involved carefully reviewing the published literature to ensure that all relevant data was captured accurately. Data quality control was performed to ensure that the compiled data was consistent and reliable. The quality control process included checks for missing or erroneous data, as well as comparisons between the compiled data and the original experimental data to ensure that there were no discrepancies. Specifically, the database is a compilation of Tables 1-4.

Table 3 Specimen Dimensions and Material Properties of Eccentrically Loaded Concrete-encased Steel Composite Square Columns in the numerical study of Ellobody & Young [12] for Group 1 to 9

	Specimen	Section	Length	Steel Section	e/D	Concrete	S
		BxD (mm)	kL (mm)			Fc (Mpa)	Fys (Mpa)
G1	S1	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	30	275
	S2	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	70	275
	S3	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	110	275
G2	S4	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	30	460
	S5	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	70	460
	S6	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	110	460
G3	S7	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	30	690
	S8	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	70	690
	S9	230x230	3000	H 140 x 133 x 5.5 x 8	0.125	110	690
G4	S10	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	30	275
	S11	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	70	275
	S12	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	110	275
G5	S13	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	30	460
	S14	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	70	460
	S15	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	110	460
G6	S16	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	30	690
	S17	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	70	690
	S18	230x230	3000	H 140 x 133 x 5.5 x 8	0.25	110	690
G7	S19	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	30	275
	S20	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	70	275
	S21	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	110	275
G8	S22	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	30	460
	S23	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	70	460
	S24	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	110	460
G9	S25	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	30	690
	S26	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	70	690
	S27	230x230	3000	H 140 x 133 x 5.5 x 8	0.375	110	690

Table 4 Specimen Dimensions and Material Properties of Eccentrically Loaded Concrete-encased Steel Composite Square Columns in the numerical study of Ellobody & Young (2011) for Group 10 to 18

Group	Specimen	Section	Length	Steel Section	e/D	Concrete	Stee	
		BxD (mm)	kL (mm)			Fc (Mpa)	Fys (Mpa)	F
G10	S28	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	30	275	
	S29	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	70	275	
	S30	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	110	275	
G11	S31	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	30	460	
	S32	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	70	460	
	S33	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	110	460	
G12	S34	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	30	690	
	S35	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	70	690	
	S36	165.1x177.8	3000	UB 127 x 114 x 29.76	0.125	110	690	
G13	S37	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	30	275	
	S38	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	70	275	
	S39	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	110	275	
G14	S40	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	30	460	
	S41	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	70	460	
	S42	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	110	460	
G15	S43	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	30	690	
	S44	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	70	690	
	S45	165.1x177.8	3000	UB 127 x 114 x 29.76	0.25	110	690	
G16	S46	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	30	275	
	S47	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	70	275	
	S48	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	110	275	
G17	S49	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	30	460	
	S50	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	70	460	
	S51	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	110	460	
G18	S52	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	30	690	
	S53	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	70	690	
	S54	165.1x177.8	3000	UB 127 x 114 x 29.76	0.375	110	690	

3. Compressive design of CEC columns to Eurocode 4

3.1 Existing compressive design provisions

To compute second-order effects in columns using the current EN1994-1-1 [6] method, it is necessary to calculate the resistance of a column under pure axial compression (P_o) using Equation 1. However, every point on the axial force-bending moment strength interaction diagram represents a column that experiences an eccentric load lower than the pure axial compression. As such, the interaction diagram considers the impact of the bending moment on the column's axial load-carrying capacity, which is lower than its pure axial compression strength. This feature makes the interaction diagram a useful tool for evaluating the capacity of columns subjected to combined axial load and bending moment, a common situation in structural design.

$$P_o = \chi N_{pl} \tag{1}$$

where

$$\chi = \frac{1}{\emptyset + \left[\emptyset^2 - \bar{\lambda}^2\right]^{0.5}} \leq 1 \tag{2}$$

with

$$\emptyset = 0.5\left[1 + \alpha\left(\bar{\lambda} - \bar{\lambda}_o\right) + \bar{\lambda}^1\right] \tag{3}$$

and

$$\bar{\lambda} = \frac{L_e}{\pi}\left(\frac{A_s f_{ys} + 0.85 A_c f_c + A_r f_{yr}}{E_s I_s + 0.6 E_{cm} I_c + I_r I_r}\right)^{0.5} \tag{4}$$

In the context of the code, the effective length of a column is denoted as L_e, while the secant modulus of elasticity of concrete is represented by E_{cm} in units of MPa. For the specific case of concrete-encased steel composite columns being studied, the values of α and $\bar{\lambda}_o$were taken as 0.49 and 0.2, respectively, as stipulated by the code.

3.2 Assessment of existing compressive design provisions

3.2.1 Assessment against Experimental results

To evaluate the accuracy of the compressive design provisions in EN 1994-1-1 under eccentric loading and with out-of-code parameters, a comparison was made with a database of experimental results from literature containing such parameters ([13]–[15]). The comparison with respect to the test results of Morino et al. [13], SSRC Task Group 20 [14], and Al-shahari et al. [15] are referred to in this study as Series A, B, and C, respectively. To the knowledge of the author, this is the comprehensive overview of all the experimental and numerical studies conducted on eccentrically loaded concrete encased columns.

The corresponding experimental results were used to calculate the axial compressive strength values (P_u) using Equations 1-4 and the known material and dimensional parameters of the composite concrete-encased cross-section. A partial factor of unity was used for the comparison. In addition, statistical model error (ME) is used for comparison and is defined as,

$$ME = \frac{P_{Test/FEM}}{P_{EN1994-1-1}} \quad (5)$$

Series A

Figure 1 presents the comparison between the axial compressive strength predictions from EN1994-1-1 and the corresponding experimental results (series A), while Table 5 shows the statistical comparison. The results indicate that the compressive design provisions in EN1994-1-1 provide under predictions of compressive strength, with a mean value of ME equal to *0.70* and a coefficient of variation (COV) of *0.16*. This under-prediction can be explained by the research conducted by Al-Shahari et al. (2003) which suggests that the material strength properties and buckling behavior of composite concrete-encased cross-sections are not fully captured by the current design provisions.

Series B

Table 5 and Figure 2 illustrate the comparison between the axial compressive strength predictions obtained from EN1994-1-1 and the corresponding experimental results (Series B). The mean model error is *0.88*, which suggests that the predicted compressive strength is, on average, *0.88* times lower than the actual compressive strength. The COV of *0.15* indicates that there is a moderate level of variability in the errors.

Series C

Based on Table 5 and Figure 3, it appears that Series C was also used to compare the predicted axial compressive strength values obtained from EN1994-1-1 with the corresponding experimental results. The mean model error of *0.81* suggests that the predicted compressive strength values are, on average, *0.81* times lower than the actual compressive strength values obtained from the experiments. This indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns.

Additionally, the COV of *0.07* indicates that there is a low level of variability in the errors. This suggests that the model errors are consistent and not influenced by factors that cause significant variability.

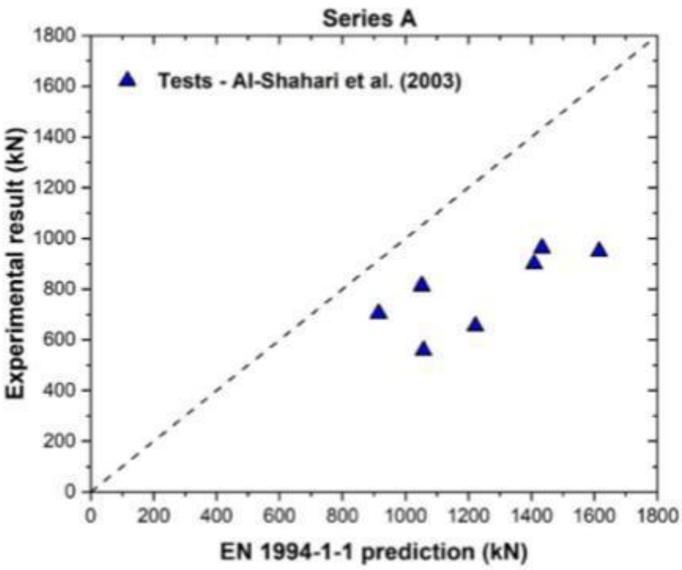


Figure 1 Comparison of CEC sections experimental results *[15] (Series A) with predictions from current EN1994-1-1.*

Table 5 summary of the collected experimental database.

Source	Series	Statistical moment	Model error
[15]	A	Mean	0.70
		COV	0.16
[14]	B	Mean	0.88
		COV	0.15
[13]	C	Mean	0.81
		COV	0.07

Overall, the results suggest that the compressive design provisions in EN1994-1-1 consistently underestimate the compressive strength, with mean errors ranging from *0.70* to *0.88* across different sources of data. The level of variability in the errors varies between moderate and low, depending on the source of data. These results may have implications for the design of steel-concrete composite structures, and further investigation may be necessary to determine if any modifications to the design provisions are needed.

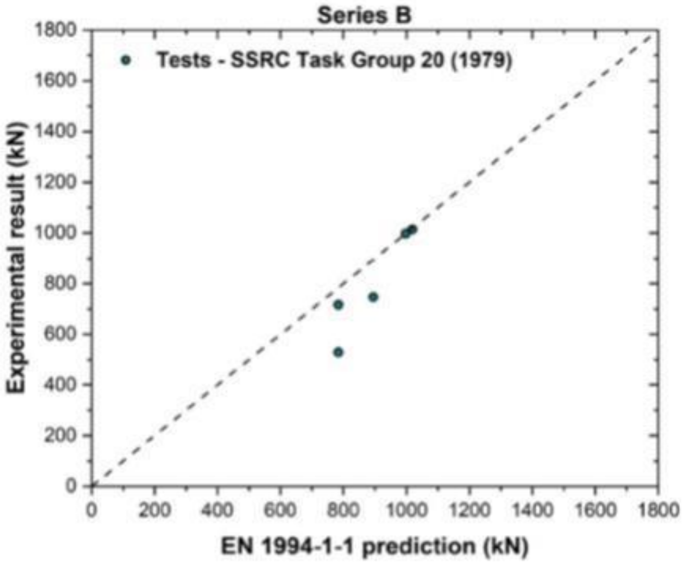


Figure 2 Comparison of CEC sections experimental results *[14]* (Series *B) with predictions from current EN1994-1-1.*

13

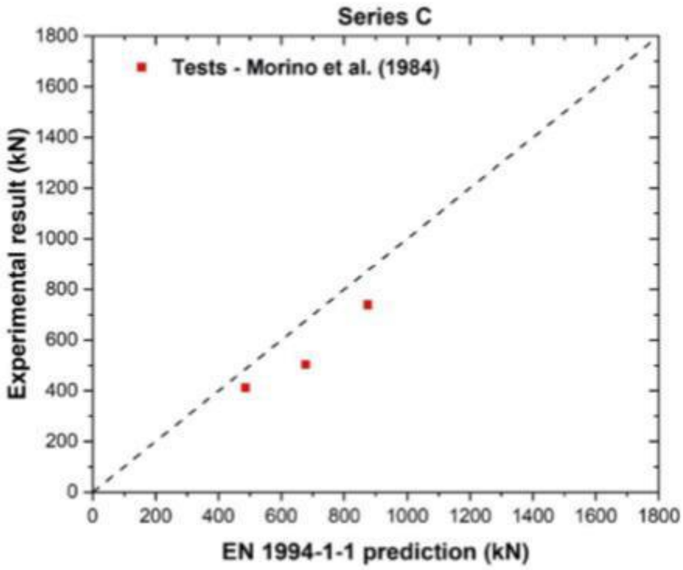


Figure 3 Comparison of CEC sections experimental results [13] (Series C) with predictions from current EN1994-1-1.

3.2.2 Assessment against FEM results

To further evaluate the accuracy of the compressive design provisions in EN 1994-1-1 under eccentric loading, a comparison was made with a database of FEM results from the literature, in addition to the comparison with test results. The axial compressive strength values (P_o) were calculated from Equation 3 using the known material and dimensional parameters of the composite concrete-encased columns, and the corresponding FEM results. Like before, a partial factor of unity and the ME was utilized for the comparison.

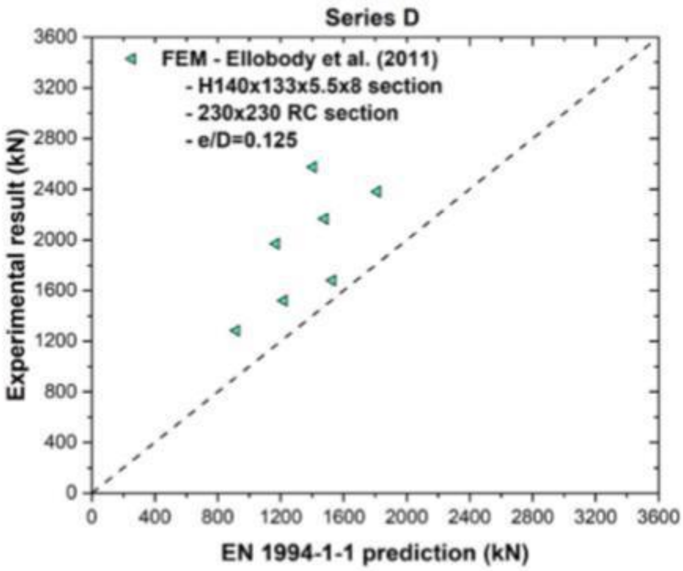


Figure 4 Comparison of CEC sections FEM results [10] (Series D) with predictions from current EN1994-1-1.

Table 6 and Figures 4-9 shows the six different series of data (D, E, F, G, H, and I) with different series of FEM models. Each series is compared based on two statistical moments of the model error, that is, the mean and coefficient of variation (COV) of the model error.

The model errors represent the difference between the predicted compressive strength using the compressive design provisions in EN1994-1-1 and the actual compressive strength measured in the experiments.

Series D

The mean model error of *1.46* suggests that the predicted compressive strength is, on average, *1.46* times lower than the actual compressive strength (Figure 4). This indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns for this source of data. Additionally, the moderate COV of *0.16* indicates that there is some variability in the errors. This suggests that the underestimation may be influenced by factors that cause significant variability.

Series E

The mean model error of *1.05* suggests that the predicted compressive strength is, on average, *1.05* times lower than the actual compressive strength (Figure 5). This again indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns. The moderate COV of *0.10* suggests that there is some variability in the errors, but not to the same extent as in Series D.

Table 6 Summary of collected FEM database

Source	Series	Statistical moment	Model error
	D	Mean	1.46
		COV	0.16
	E	Mean	1.05
		COV	0.10
	F	Mean	0.79
		COV	0.05
	G	Mean	1.50
		COV	0.10
	H	Mean	1.18
		COV	0.07
	I	Mean	0.96
		COV	0.06

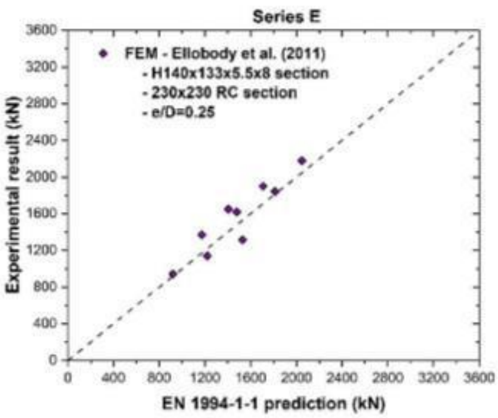


Figure 5 Comparison of CEC sections FEM results [10] (Series E) with predictions from current EN1994-1-1.

Series F

The mean model error of *0.79* suggests that the predicted compressive strength is, on average, *0.79* times lower than the actual compressive strength (Figure 6). This indicates that EN1994-1-1 consistently underestimates the axial compressive strength of composite columns for this source of data. The low COV of *0.05* suggests that the underestimation is relatively consistent across different FEM setups, reinforcing the need for further investigation into the design provisions.

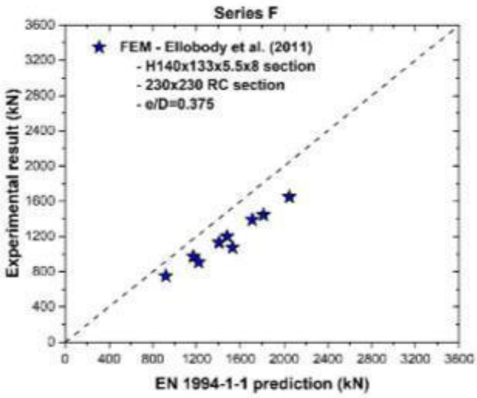


Figure 6 Comparison of CEC sections *FEM results [10] (Series F) with predictions from current EN1994-1-1.*

Series G

The mean model error of *1.50* suggests that the predicted compressive strength is, on average, *1.50* times lower than the actual compressive strength (Figure 7). This again indicates that EN1994-1-1 underestimates the axial compressive strength of composite columns for this source of data. The moderate COV of *0.10* suggests that there is some variability in the errors, but not to the same extent as in Series D.

Series H

The mean model error of *1.18* suggests that the predicted compressive strength is, on average, *1.18* times lower than the actual compressive strength (Figure 8). This indicates that EN1994-1-1 consistently underestimates the axial compressive strength of composite columns for this source of data. The low COV of *0.07* suggests that the underestimation is relatively consistent across different experimental setups, reinforcing the need for further investigation into the design provisions.

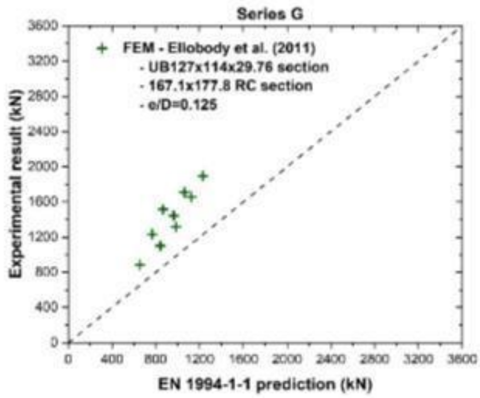


Figure 7 Comparison of *CEC sections FEM results [10] (Series G) with predictions from current EN1994-1-1.*

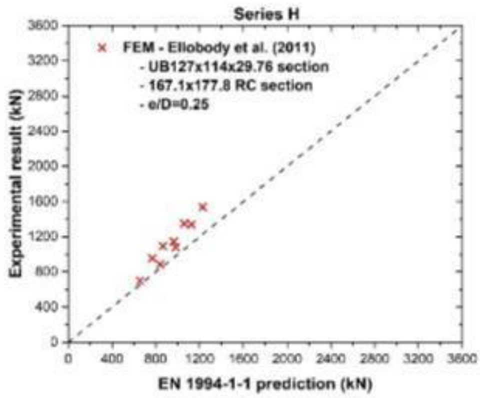


Figure 8 Comparison of CEC sections FEM results [10] (SeriesH) with predictions from current EN1994-1-1.

Series I

The mean model error of *0.96* suggests that the predicted compressive strength is, on average, *0.96* times lower than the actual compressive strength (Figure 9). This indicates that EN1994-1-1 consistently underestimates the axial compressive strength of composite columns for this source of data. The low COV of *0.06* suggests that the underestimation is relatively consistent across different experimental setups, reinforcing the need for further investigation into the design provisions.

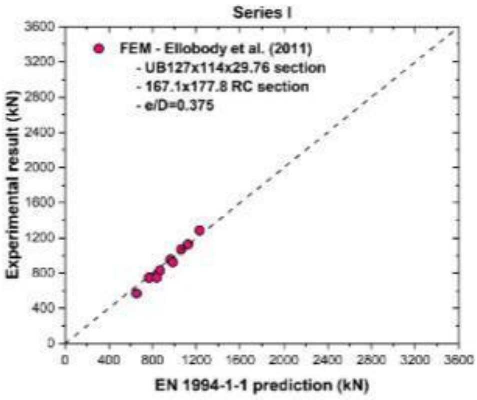


Figure 9 Comparison of CEC sections FEM results [10] (Series I) with predictions from current EN1994-1-1.

Overall, the results suggest that the compressive design provisions in EN1994-1-1 consistently underestimate the compressive strength across different sources of data, with mean errors ranging from *0.79* to *1.50*. The level of variability in the errors varies between low and moderate, depending on the source of data. These findings provide further evidence that the design provisions may need to be modified to improve the accuracy of the predicted compressive strength.

3.2.3 Against entire database

Figure 10 shows the comparison between the experimental and FEM results of the entire database and EN1994-1-1 compressive strength predictions, revealing that the current provisions are inadequate for accurate compressive strength predictions for eccentrically loaded CEC columns with out-of-code parameters. Based on the entire database (Table 7), the mean model error is *1.1*, which suggests that the predicted compressive strength is, on average, *1.1* times higher or lower than the actual compressive strength. However, the high coefficient of variation (COV) of *0.32* indicates that there is a significant level of variability in the errors. This suggests that the predictions may not always be reliable, and caution should be exercised when using them for designing CEC with high strength concrete and steel materials. New provisions to address these issues are presented in the following section.

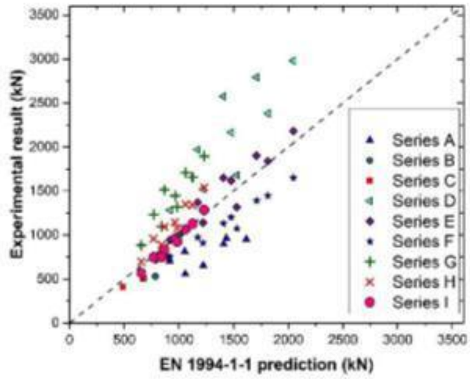


Figure 10 Comparison of CEC sections for results of entire database (Series A to I) with predictions from current EN1994-1-1.

4. Proposed compressive design provisions

4.1 Modified compressive design provisions

The current Eurocode provisions under predict the experimental results for about *46%* of the experimental and FEM database. This means that the current Eurocode provisions would lead to under-designs with a probability of exceedance of *46%* if used for the design of CEC with out-of-code parameters. Eurocode 0 stipulates that the basis of design for the Eurocodes should be *5%*. This section will modify the current equations of EN1994-1-1 for compressive design with a multiplicative modification factor K_{mod} such that only *5%* of the datapoints will be below the line. This modification factor will be assessed by statistically analyzing the probability distribution of model error for the entire database and calculating the *5%* fractile from this distribution.

1.1.1 Assessment of model factor

Model factor also called the model assessed in detail in this section to find a modification factor K_{mod} that should be multiplied by the current Eurocode provisions such that *95%* of the data points in Figure 10 is above the perfect prediction line (the dotted line). This represents a *5%* fractile of the probability distribution of the ME, typically assumed to be lognormally distributed [16]. Table 7 shows that the ME has a mean value of *1.1* and COV of *0.32* (see also Figure 11 for box plot representation of ME).

20

Table 7 Statistical moments of model error for the entire database inclusion of all experimental and FEM results

Database	Series	Statistical moment	ME
All experimental and FEM results	A to I	Mean	1.1
		COV	0.32

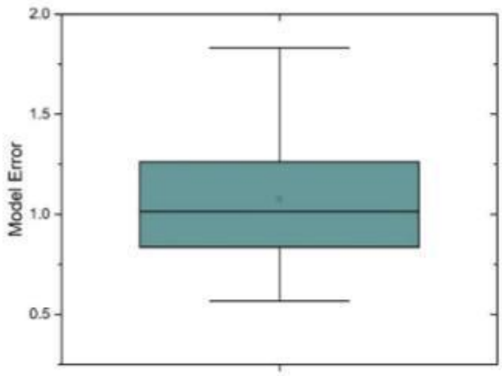


Figure 11 Box plot scatter representation of ME of the EN1994-1-1 compressive design provisions for the entire database.

Assessment of ME involves conducting Pearson correlation analysis and sensitivity analysis to find out the influence of each of the parameters in the EN1994-1-1 equation on the derived ME.

Pearson correlation analysis was conducted, and this revealed (see Table 8 for the correlation matrix) that none of the parameters were strongly correlated (with $|r| > 0.5$). However, it was revealed that the elastic modulus of concrete ($|r| = 0.41$), the cross-section area of the steel section ($|r| = 0.40$), and the compressive strength of concrete ($|r| = 0.35$), had relatively higher correlation coefficients with the MEs compared to other variables.

Table 8 Pearson Correlation Matrix

A_s	f_{ys}	A_c	f_c	A_r	f_{ur}	I_s	E_{cm}	I_c	I_r	L_e	*ME*
1.00	0.14	-0.50	**0.26**	-0.51	0.19	0.24	**0.36**	-0.48	-0.45	0.20	0.44
0.15	1.00	0.05	**0.08**	0.04	0.98	-0.35	**0.11**	0.06	0.07	0.29	0.68
-0.50	0.05	1.00	**0.04**	1.00	0.01	-0.10	**-0.01**	1.00	1.00	0.09	-0.49
0.26	**0.08**	**0.04**	**1.00**	**0.03**	**0.09**	**0.02**	**0.98**	**0.05**	**0.05**	**0.14**	**0.07**
-0.51	0.04	1.00	**0.03**	1.00	0.01	-0.10	**-0.03**	1.00	1.00	0.09	-0.49
0.19	0.98	0.01	**0.09**	0.01	1.00	-0.22	**0.12**	0.02	0.03	0.22	0.64
0.24	-0.35	-0.10	**0.02**	-0.10	-0.22	1.00	**0.00**	-0.11	-0.12	-0.49	-0.42
0.36	**0.11**	**-0.01**	**0.98**	**-0.03**	**0.12**	**0.00**	**1.00**	**-0.01**	**0.01**	**0.17**	**0.11**
-0.48	0.06	1.00	**0.05**	1.00	0.02	-0.11	**-0.01**	1.00	1.00	0.11	-0.47
-0.45	0.07	1.00	**0.05**	1.00	0.03	-0.12	**0.01**	1.00	1.00	0.12	-0.47
0.20	0.29	0.09	**0.14**	0.09	0.22	-0.49	**0.17**	0.11	0.12	1.00	0.58
0.44	0.68	-0.49	**0.07**	-0.49	0.64	-0.42	**0.11**	-0.47	-0.47	0.58	1.00
-0.44	-0.67	0.44	**-0.09**	0.45	-0.61	0.47	**-0.14**	0.43	0.42	-0.66	-0.99
0.40	0.10	-0.19	**0.35**	-0.19	0.08	-0.28	**0.41**	-0.17	-0.15	0.28	0.33

Sensitivity analysis of the ME with these three variables was conducted and Figures 12 - 14 show the effect of each of these variables on the model factor.

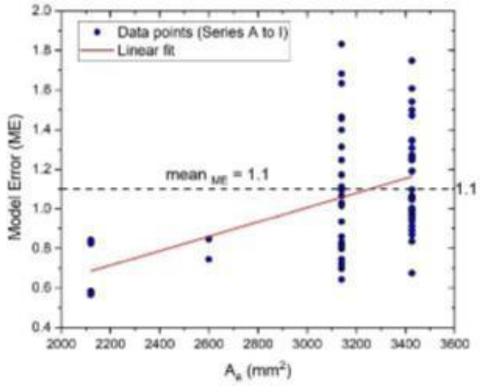


Figure 12 Effect of steel section cross-section area on the model error

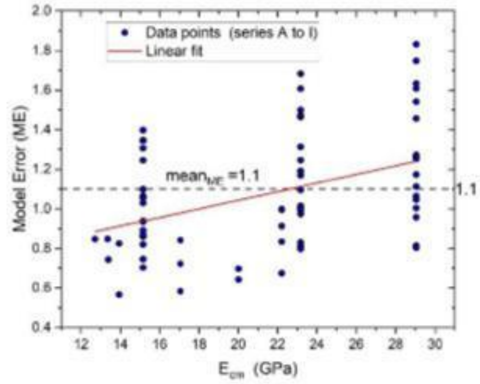


Figure 13 Effect of elastic modulus of concrete on the model error

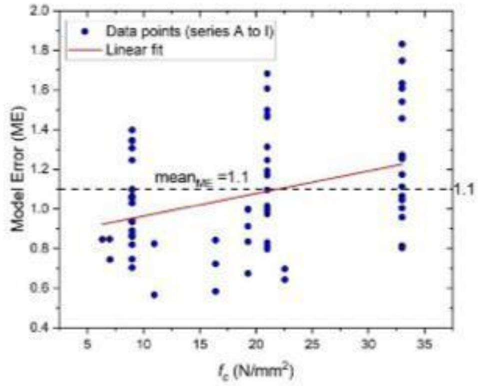


Figure 14 Effect of concrete compressive strength on the model error

Figure 15 shows a histogram and fit lognormal distribution of the ME. From Figure 16, the multiplicative modification factor K_{mod} was calculated as the *95%* fractile. This gave a value of $K_{mod}=0.6$. This value is implemented to modify the Eurocode provisions for compression design to include high strength steels and concretes. The *5%* fractile is found to be at $K_{mod} = 0.6$, as shown in Figure 16

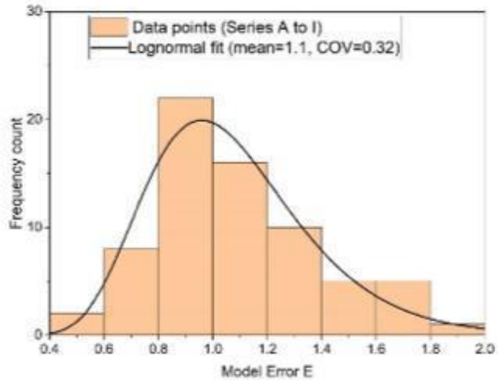


Figure 15 Histogram and lognormal probability fit of ME

24

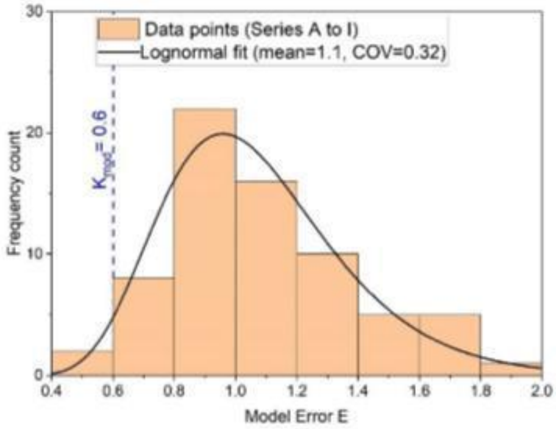


Figure 16 Calculation of K_{mod} from the frequency distribution of ME

1.1.2 Modified EN-1994-1-1 compressive provisions

The proposed EN-1994-1-1 compressive design provisions are presented in this section. Similar to the current Eurocode 4 method, in the proposed modified EN1994-1-1 method, calculating the resistance of a column under pure axial compression (P_o) using Equation 6 is also a necessary step for computing second-order effects in columns. However, every point on the axial force-bending moment strength interaction diagram represents a column that experiences an eccentric load lower than the pure axial compression. This means that the interaction diagram considers the impact of bending moment on the column's axial load-carrying capacity, which is lower than its pure axial compression strength, but this time modified with a multiplicative factor $K_{mod} = 0.6$ as given in see Equation 6

$$P_o = K_{mod} \chi N_{pl} \tag{6}$$

where

$$\chi = \frac{1}{\varnothing + \left[\varnothing^2 - \bar{\lambda}^2\right]^{0.5}} \leq 1 \tag{7}$$

with

$$\varnothing = 0.5\left[1 + \alpha\left(\bar{\lambda} - \bar{\lambda}_o\right) + \bar{\lambda}^1\right] \tag{8}$$

and

$$\bar{\lambda} = \frac{L_e}{\pi}\left(\frac{A_s f_{ys} + 0.85 A_c f_c + A_r f_{yr}}{E_s I_s + 0.6 E_{cm} I_c + I_r I_r}\right)^{0.5} \tag{9}$$

4.2 Assessment of the modified compressive design provisions

Figure 17 shows the comparison of the proposed EN1994-1-1 compressive design provisions with the entire database. The proposed design provisions have led to most of the data points lying above the perfect prediction line. Despite being conservative across the entire database, this led to overly conservative designs for columns under series D. Careful analysis of series D shows that the columns that are overly designed have a very low concrete strength of less than 9 MPa. It was observed that the higher the compressive strength the better the prediction. This implies that the modified equation should be restricted to concrete strength classes above C25/30 but more accurate for high strength concretes.

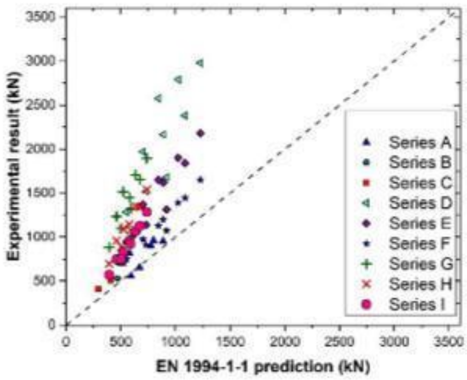


Figure 17 Comparison of CEC sections for results of entire database (Series A to I) with predictions from modified proposed EN1994-1-1.

Furthermore, a sensitivity analysis of the ME of the modified EN1994-1-1 compressive design provision with these three variables was conducted and Figures 18 - 20 below show the effect of each of these variables on the model factor.

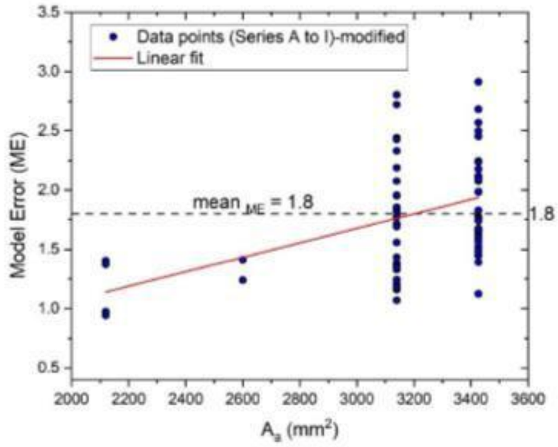


Figure 18 Effect of steel section cross-section area on the model error of the proposed provisions

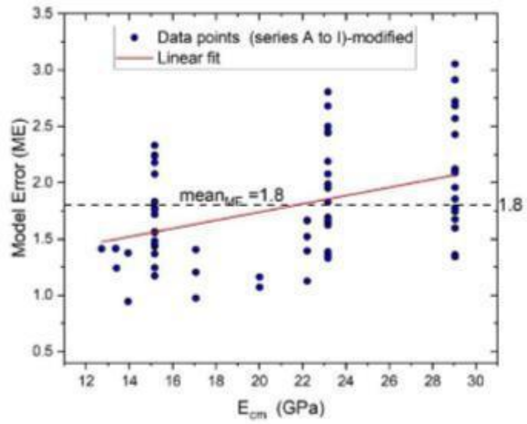


Figure 19 Effect of elastic modulus of concrete on the model error of the proposed provisions

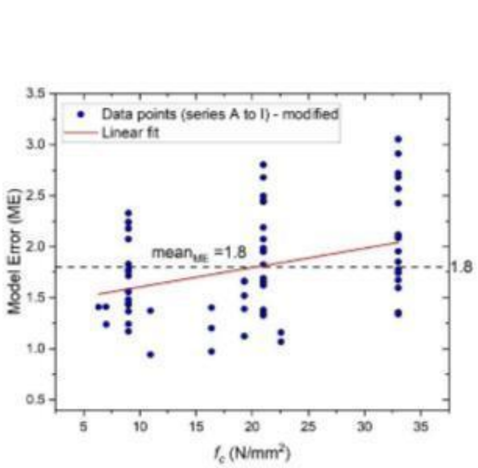


Figure 20 Effect of concrete compressive strength on the model error of the proposed provisions

Likewise, before a positive correlation can be observed between ME and the basic variables, that is the steel cross-section area, the elastic modulus of concrete and the compressive strength of concrete. However, the mean value of the ME is seen to increase from *1.1* to *1.8*. The frequency distribution of the ME of the modified EN1994-1-1 provisions is shown in Figure 21.

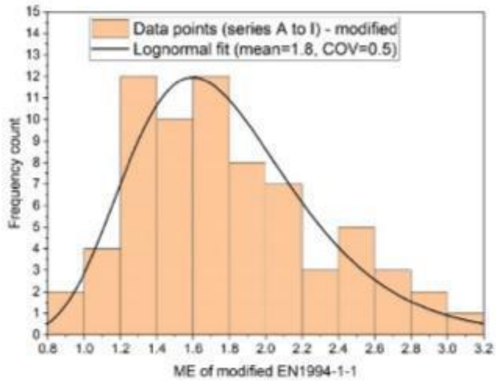


Figure 21 Frequency distribution of the ME of the modified EN-1994-1-1 provisions

5. Conclusions

This study aimed to assess the existing compressive design provisions for concrete-encased steel composite columns with out-of-code parameters and propose potential modifications based on experimental and FEM results. The following conclusions were drawn:

- The existing compressive design provisions in EN-1994-1-1 accurately predict the behaviour of concrete-encased steel composite columns with out-of-code parameters under axial compression but show significant inaccuracies in predicting their behaviour under eccentric loading.
- The experimental and FEM results show that the current design provisions produce overly under conservative predictions for the axial load-carrying capacity of the columns with out-of-code parameters under eccentric loading, resulting in a significant reduction in the column's ductility and energy absorption capacity.
- The proposed compressive design provisions, which incorporate modified model factors and reduced effective length, demonstrate improved accuracy in predicting the behaviour of concrete-encased steel composite columns under eccentric loading and with out-of-code parameters. These proposed provisions can result in an increase in the columns' ductility and energy absorption capacity, thereby enhancing their overall structural performance.

Based on the study's findings, the following recommendations are proposed:

- The current design provisions for concrete-encased steel composite columns under eccentric loading should be revised to incorporate modified model factors for application with high strength concretes and steels. The proposed provisions can result in more accurate predictions of the columns' behaviour and improved overall structural performance.
- Further experimental and numerical studies should be conducted to validate and refine the proposed eccentric compressive design provisions.
- The proposed compressive design provisions should be considered for inclusion in future updates to the EN-1994-1-1 code for concrete-encased steel composite columns with out-of-code parameters.

CRediT authorship contribution statement

Caron Kasumba: Conceptualization of this study, Methodology, Software, Writing. **Charles Kahanji**: Methodology, Supervision, Writing – review & editing.

Declaration of Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The financial supports are gratefully appreciated.

Data availability

All the data that support the findings of this study are available from the first author upon reasonable request (**Caron Kasumba**).

References

[1] Y. Du, H. Zhou, and J. Y. R. Liew, "Experimental study on behaviours of ultra-high strength concrete encased steel columns under static load," *Jianzhu Jiegou Xuebao/Journal Build. Struct.*, 2022, doi: 10.14006/j.jzjgxb.2019.0776.

[2] W. Xu, L. H. Han, and W. Li, "Seismic performance of concrete-encased column base for hexagonal concrete-filled steel tube: Experimental study," *J. Constr. Steel Res.*, 2016, doi: 10.1016/j.jcsr.2016.02.003.

[3] X. Zhou, T. Xu, J. Liu, X. Wang, and Y. F. Chen, "Seismic performance of concrete-encased column connections for concrete filled thin-walled steel tube piers," *Eng. Struct.*, 2022, doi: 10.1016/j.engstruct.2022.114803.

[4] K. Zhou and L. H. Han, "Experimental performance of concrete-encased CFST columns subjected to full-range fire including heating and cooling," *Eng. Struct.*, 2018, doi: 10.1016/j.engstruct.2018.03.042.

[5] B. Lai, J. Y. Richard Liew, and T. Wang, "Buckling behaviour of high strength concrete encased steel composite columns," *J. Constr. Steel Res.*, 2019, doi: 10.1016/j.jcsr.2018.11.023.

[6] EN-1994, "Eurocode 4," *Des. Compos. steel Concr. Struct. - Part 1-1 Gen. rules rules Build. Eurocode*, 2009.

[7] B. Lai, J. Y. R. Liew, and M. Xiong, "Experimental study on high strength concrete encased steel composite short columns," *Constr. Build. Mater.*, vol. 228, 2019, doi: 10.1016/j.conbuildmat.2019.08.021.

[8] B. Lai and J. Y. R. Liew, "Design and testing of concrete encased steel composite beam-columns with C90 concrete and S690 steel section," *Eng. Struct.*, 2020, doi: 10.1016/j.engstruct.2020.110995.

[9] C. C. Chen, C. C. Chen, and J. H. Shen, "Effects of steel-to-member depth ratio and axial load on flexural ductility of concrete-encased steel composite columns," *Eng. Struct.*, vol. 155, pp. 157–166, 2018, doi: 10.1016/j.engstruct.2017.11.036.

[10] E. Ellobody, B. Young, and D. Lam, "Eccentrically loaded concrete encased steel composite columns," *Thin-Walled Struct.*, 2011, doi: 10.1016/j.tws.2010.08.006.

[11] B. Lai, J. Y. R. Liew, A. Venkateshwaran, S. Li, and M. Xiong, "Assessment of high-strength concrete encased steel composite columns subject to axial compression," *J. Constr. Steel Res.*, vol. 164, 2020, doi: 10.1016/j.jcsr.2019.105765.

[12] E. Ellobody and B. Young, "Numerical simulation of concrete encased steel composite columns," *J. Constr. Steel Res.*, 2011, doi: 10.1016/j.jcsr.2010.08.003.

[13] S. Morino, C. Matsui, and H. Watanabe, "Strength of biaxially loaded SRC columns," 1985.

[14] SSRC Task Group 20, "A specification for the design of steel–concrete composite columns," *AISC Eng. J. Fourth Quart.*, pp. 1101–115, 1979.

[15] A. M. Al-Shahari, Y. M. Hunaiti, and B. A. Ghazaleh, "Behavior of lightweight aggregate concrete-encased composite columns," *Steel Compos. Struct.*, 2003, doi: 10.12989/scs.2003.3.2.097.

[16] Jcss, "Probabilistic Model Code - Part 1," *Struct. Saf.*, 2001.

Declaration of Interest Statement

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: