



Comparative Analysis of Code Provisions for Built-Up CFT Columns with High Strength Concrete under Varied Loading Conditions

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ABSTRACT

Steel-concrete composite structures are gaining popularity for their advantages over traditional materials, yet the behaviour of concrete-filled tube (CFT) columns, particularly built-up sections with high strength concrete (HSC), remains underexplored. This study investigates the impact of concrete strength, cross-sectional dimensions, and loading types on the ultimate load capacity of built-up CFT columns. Seven specimens with concrete strengths of 48 MPa and 53 MPa and cross-sections of 100x100 mm, 125x125 mm, and 150x150 mm were tested under concentric and eccentric loading. Results showed a 46% strength increase compared to bare steel columns due to concrete infill, while higher concrete strength had a minimal effect on overall capacity. Eccentric loading reduced load capacity by approximately 50%. Analysis of design codes revealed that AISC-2010 is 14% less conservative than EUROCODE-4 for concentric loads, while for eccentric loads, failure points fell within the AISC-2010 safe zone, indicating underestimation of risks. EUROCODE-4 demonstrated better reliability, with failure points lying outside its safe zone. These findings underscore the need for more robust code provisions for built-up CFT columns under varied loading conditions.

1. Introduction

Composite columns effectively integrate the strengths of concrete and steel, combining their advantages while minimizing individual drawbacks. This unique synergy has made composite construction increasingly popular worldwide, reflecting its potential to enhance structural performance. However, despite its growing adoption, the field of composite construction remains underdeveloped, underscoring the critical need for continued research.

This study focuses on a specific type of composite column concrete-filled tube (CFT). The behaviour of CFT columns is inherently complex due to the distinct stress-strain characteristics of concrete and steel, as well as their interaction under load. Factors such as shape, length, diameter, steel tube thickness, and the material strengths of concrete and steel significantly influence the failure mechanisms of CFT columns.

Notable research efforts have explored the behaviour of CFT columns. Gardner and Jacobson (1967) conducted theoretical and experimental investigations into axially loaded CFT columns, discovering that while the steel tube often reaches failure at the ultimate load, the concrete core remains intact. Giakoumelis and Lam (2003) studied circular CFT columns with varying concrete strengths under axial loads, comparing their findings to predictions from Eurocode 4, Australian Standards, and American Codes. They found that all three codes underestimated the measured values, with Eurocode 4 providing the most accurate predictions for both normal and high-strength concrete. Rahman (2016) reviewed various design codes for composite columns, detailing specifications, capacity prediction equations, and guidelines for fully encased composite (FEC) columns in AISC-LRFD (2010), Eurocode 4 (2005), and ACI-318.

Recent studies by Pinto and Fonseca (2024) highlight that while confinement enhances ductility in high

strength concrete filled CFTs, the efficiency gains diminish relative to normal-strength concrete due to altered crack propagation and stress distribution mechanisms. Deng et al. (2024) further developed refined stress–strain constitutive models, grounded in both experimental and FE analyses. Additionally, recent experimental-numerical hybrid investigations into high strength concrete filled steel tubes confirm that structural strength and confinement interaction remain viable provided proper consideration of tube slenderness and material compatibility.

Building on this foundation, the present study examines the effects of high concrete strength, cross-sectional geometry, and loading type on the behaviour of built-up square-shaped CFT columns. It also evaluates the safety margins provided by AISC-2010 and Eurocode 4 in predicting the capacity of such columns, aiming to contribute valuable insights to the evolving field of composite column design.

2. Experimental Program

To evaluate the behaviour of built-up CFT columns, seven specimens were prepared with concrete strengths of 48 MPa and 53 MPa and cross-sectional dimensions of 100 mm × 100 mm, 125 mm × 125 mm, and 150 mm × 150 mm. Five specimens had a cross-section of 100 mm × 100 mm (designated as CFT 01 to CFT 05), one specimen measured 125 mm × 125 mm (CFT 06), and another measured 150 mm × 150 mm (CFT 07). All specimens had a uniform height of 1000 mm. The steel casing for each column was fabricated from 5 mm thick steel plates welded together to form a closed box section. The top end of each column was enclosed with a 100 mm × 100 mm steel plate of the same thickness. The test specimens did not include reinforcement or shear connectors.

CFT 01 was designed as a hollow steel column, serving as the control specimen, while all other columns were infilled with concrete. Two high-strength concrete mixes

were employed in this study. The first mix, used for CFT 02 and CFT 04, had a cement: coarse aggregate: fine aggregate ratio of 1:1.25:2.5 and a water-to-cement (w/c) ratio of 0.40. The second mix, applied to the remaining concrete-filled specimens, followed a ratio of 1:1.64:2.6 with a w/c ratio of 0.421. On the day of testing, cylinder tests confirmed compressive strengths of 48 MPa and 53 MPa for the two respective mixes. Additionally, coupon tests on the steel plates indicated a yield stress of 345 MPa and an ultimate tensile strength of 487.25 MPa.

Testing was conducted using a Universal Testing Machine (UTM) with data acquisition facilitated by Horizon software. Three Linear Variable Differential Transformers (LVDTs) were positioned horizontally at the mid-height of each column to measure lateral deformations, and two were placed vertically to capture axial deformations as shown in Figure 1. Data acquisition was carried out using DEWESOFT software from DEWETRON.

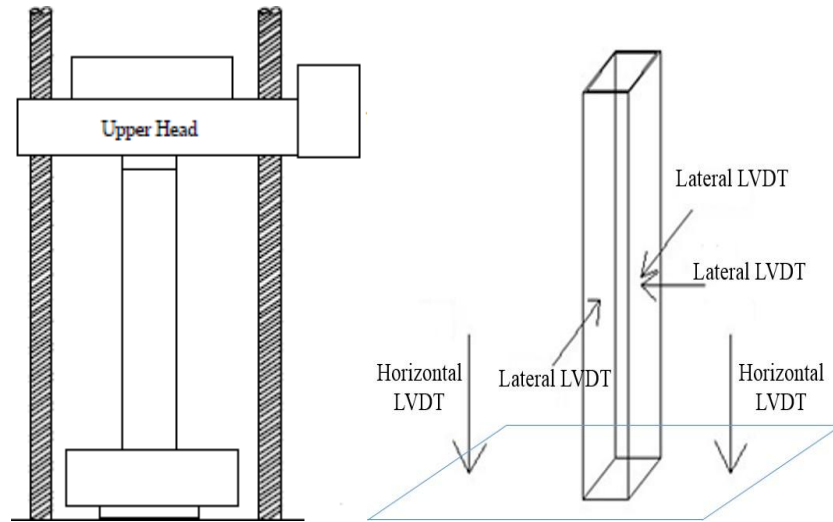


Figure 1. Machinery for testing (Schematic Drawing)

Specimens were tested under two loading conditions: concentric and eccentric axial loads. CFT 01, CFT 02, and CFT 03 were subjected to concentric loading. For eccentric loading, applied to CFT 04, CFT 05, CFT 06, and CFT 07, a steel bar was fixed at the top of each column, and grooved plates were used to ensure precise

application of load with the desired eccentricity as shown in Figure 2. This experimental setup allowed for a comprehensive analysis of the influence of concrete strength, cross-sectional size, and loading type on the performance of built-up CFT columns.



Figure 2. Capping Provided on the Top of Rod during Eccentric Loading

3. Discussion on Test Results

Seven columns were subjected to testing under both pure compression (concentric loading) and (eccentric loading) conditions. The specimens initially deformed axially before reaching failure. Observations revealed that lateral buckling was minimal compared to axial

deformation and was, in some cases, barely perceptible to the naked eye. As the columns were fabricated using welded steel plates, the welded joints emerged as weak points, leading to splitting in these areas during failure. Figure 3 illustrates the failure mode of CFT 02, which was representative of the behaviour observed in the other specimens.

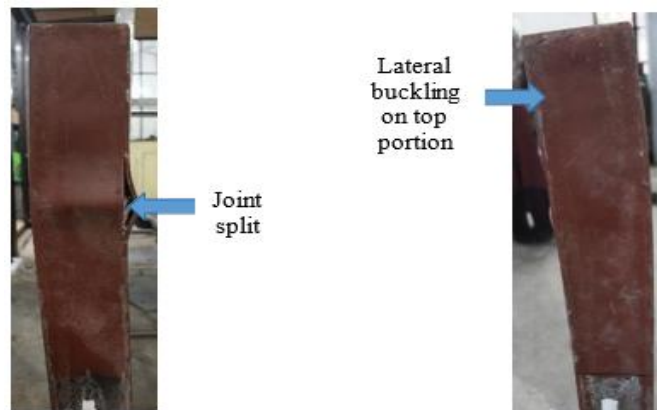


Figure 3. Failure mode of CFT 02

Axial and lateral deformation along with their load capacity of different specimens is shown in **Table 1** and **Table 2**.

Table 1. Load capacity for different specimens

Column Title	Dimension	Infill Concrete Strength (MPa)	Axial Load (KN)	Axial Deformation (mm)	Axial Stiffness (KN/mm)
	(mm x mm)				
CFT 01	100 x 100	No concrete	689.74	8.82	78.2
CFT 02	100 x 100	48	957.54	9.67	99.02
CFT 03	100 x 100	53	1068.3	7.046	151.62
CFT 04	100 x 100	48	510.87	8.12	62.92
CFT 05	100 x 100	53	539.76	7.81	69.12
CFT 06	125 x 125	53	720.07	10.24	70.38
CFT 07	150 x 150	53	669.32	8.85	75.63

Table 2. Lateral Deformation for different specimens

Column Title	Dimension	Axial Load (KN)	Lateral Deformation [from LVDT 1] (mm)	Lateral Deformation [from LVDT 2] (mm)	Lateral Deformation [from LVDT 3] (mm)
	(mm x mm)				
CFT 01	100 x 100	689.74	-4.7	0.54	4.58
CFT 02	100 x 100	957.54	-0.71	2.42	0.78
CFT 03	100 x 100	1068.3	-0.08	-3.55	1.61
CFT 04	100 x 100	510.87	-0.49	2.03	1.5
CFT 05	100 x 100	539.76	6.66	1.21	-6.6
CFT 06	125 x 125	720.07	-2.45	0.67	1.8
CFT 07	150 x 150	669.32	-4.46	0.88	3.51

4. Effect of Variation in Concrete Strengths on Axial Capacity

The axial load-carrying capacity of the reference hollow steel column (CFT 01) under concentric loading was recorded at 689.74 KN. With the addition of high-

strength concrete (HSC) infill of 48 MPa (CFT 02), the capacity increased to 957.54 KN which is a 38% enhancement over the hollow section. When 53 MPa concrete was used (CFT 03), the capacity further improved to 1068.3 KN, reflecting a 54% increase

compared to the bare steel tube. This indicates that the composite interaction between steel and high-strength concrete significantly improves axial capacity, even without altering the column's cross-sectional area.

These findings are consistent with recent research, which has shown that HSC contributes meaningfully to the axial performance of CFT members by enhancing composite behavior and increasing confinement effectiveness (Pinto and Fonseca, 2024; Deng et al., 2024). However, as noted by Bai et al. (2023), the benefits of increasing concrete strength tend to diminish at higher strength levels due to decreased ductility and reduced confinement efficiency in ultra-high-strength concrete systems.

For the eccentrically loaded columns, a similar but more modest trend was observed. CFT 04 (48 MPa) exhibited a peak load of 510.87 kN, whereas CFT 05 (53 MPa) failed at 539.76 kN, representing only a 5.7% increase in axial capacity. This suggests that while higher

5. Effect of Loading Type on Axial Capacity

Eccentric loading significantly affects the axial load-carrying capacity of concrete-filled steel tube (CFT) columns. Even when the cross-sectional dimensions and concrete strength remain constant, columns subjected to eccentric loads exhibit substantially reduced capacity compared to those loaded concentrically. For instance, both CFT 02 and CFT 04 have a 100 mm × 100 mm cross-section and are filled with 48 MPa high-strength concrete. However, under eccentric loading, the capacity of CFT 04 decreased to 510.87 kN, compared to 957.54 kN under concentric loading in CFT 02—reflecting a reduction of approximately 47%. A similar pattern is observed between CFT 03 (concentric) and CFT 06 (eccentric), both using 53 MPa concrete, where the capacity dropped by around 50%.

These results emphasize the critical influence of load application type on structural performance. While the use of high-strength concrete enhances axial capacity under concentric conditions, its effectiveness is considerably less under eccentric loading. This reduced performance can be attributed to uneven stress distribution and the limited ability of concrete to resist secondary bending effects when the load is offset, a phenomenon consistently reported in recent studies (Pinto and Fonseca, 2024; Deng et al., 2024). Furthermore, although high-strength concrete improves confinement interaction with the steel tube under concentric loads, its comparatively brittle behavior under eccentric compression makes it less capable of absorbing energy and resisting deformation. Bai et al. (2023) noted

concrete strength still provides performance benefits under eccentric loading, its influence is notably less significant compared to concentric conditions. The reduction in capacity gain may be attributed to the complex stress distribution induced by eccentricity, which limits the effectiveness of axial confinement, an observation also supported by Gupta, Sarada, and Kumar (2007) and Deng et al. (2024).

Overall, the results underscore the importance of considering loading conditions when selecting concrete strength for CFT columns. While high-strength concrete (HSC) yields substantial improvements under concentric loading, its benefit under eccentric loading is more nuanced. Therefore, optimal design of built-up CFT columns should carefully balance strength enhancement with confinement behavior and ductility to ensure structural reliability under realistic load scenarios.

that as concrete strength increases, the ductility of the composite section often decreases, limiting its ability to accommodate complex loading patterns such as those induced by eccentricity.

This study is limited to high-strength concrete (HSC), and the absence of normal-strength concrete (30–40 MPa) restricts broader applicability. Since many practical applications involve such grades, future research should include a wider strength range and varied eccentricities. While HSC improves capacity under concentric loading, its benefits are less evident under eccentric conditions, underscoring the need for context-specific use in structures susceptible to non-axial forces.

6. Comparative Study on Axial Stiffness

Axial stiffness for each column was calculated as the ratio of ultimate axial load to the corresponding axial deformation measured at mid-height (i.e., stiffness = Load / Deformation). This approach aligns with standard practice for assessing initial stiffness in short composite columns.

The comparison among CFT 01 (hollow), CFT 02 (48 MPa), and CFT 03 (53 MPa) shows a significant improvement in stiffness due to concrete infill, 21% and 48% increases for CFT 02 and CFT 03, respectively, compared to the hollow section. The 34% higher stiffness of CFT 03 over CFT 02 highlights the beneficial role of increased concrete strength, supporting earlier findings that high-strength concrete contributes more to initial stiffness than to ultimate load capacity.

However, eccentric loading markedly reduced stiffness. CFT 04 and CFT 05 (eccentric) showed 36% and 54% lower stiffness than their concentric counterparts (CFT 02 and CFT 03), despite having identical materials and cross-sections. These results align with existing literature indicating that eccentricity introduces secondary bending and uneven stress distribution, which reduces the effectiveness of confinement and stiffness, especially in high-strength concrete.

A comparison among CFT 05, CFT 06, and CFT 07 reveals that increasing cross-sectional size offered only limited improvement due to higher eccentricity, suggesting that size alone cannot mitigate the stiffness loss caused by load offset. These findings emphasize the importance of considering both material strength and load path in the design of built-up CFT columns.

7. Code Analysis for Concentric Loading

AISC-2010 and EUROCODE-4 has provisions for composite column design but there are no special requirements for composite columns with built-up sections. For this study, analytical values are found using the existing equations in AISC-210 and EUROCODE-4. Design of composite column is given in chapter I in

AISC-2010 guideline. In this study the strength of composite sections is computed based on the plastic stress distribution method. (Equation 1) which is used for calculating capacity in pure axial condition for filled compact composite member is given below.

$$P_{no} = F_y A_s + C_2 f_c' \{A_c + A_{sr}*(E_s/E_c)\} \quad (1)$$

Here, A_c and A_s indicates area of concrete (mm^2) ; steel section, (mm^2) respectively. P_{no} means nominal axial capacity of CFT column. Using equations (1), axial capacity for concentrically loaded columns were determined as shown in **Table 3**. For finding axial capacities of column using EUROCODE-4, (Equation 2) is used.

$$N_{pl,Rd} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd} \quad (2)$$

Here, $N_{pl,Rd}$ is design value of the plastic resistance of the composite section to compressive normal force f_{cd} and f_{yd} means design value of the cylinder compressive strength of concrete and design value of the yield strength of structural steel respectively.

Here, $f_{cd} = (f_c / \gamma_c)$, $f_{yd} = (f_y / \gamma_s)$, γ_c is partial reduction factor for concrete which is taken as 1.5 and γ_s is partial reduction factor for steel which is taken as 1.15. Values obtained by using (Equation 2) are shown in Table 3.

Table 3. Ultimate Load Capacity of concentrically Loaded Columns

Specimen Designation	Experimental Program (KN)	Using AISC-2010 (KN)	Using EUROCODE-4 (KN)
CFT 1	689.74	648.17	570
CFT 2	957.54	971.3	829.2
CFT 3	1068.3	1005.6	856.17

Comparing the experimental value with the AISC code predicted values; it is found that the ultimate load capacity for CFT-01 (Hollow Steel Tube) can be predicted by the code with 6% conservative value. For CFT-03, code-predicted value is 5.8% more conservative than the experimental result. These values indicate that code predicted values are not significantly conservative. Again, value for CFT-02 shows greater capacity in the code prediction than in the experimental result. The values are about 1.5% higher than the code predicted value. This column had joint split during failure. This can be a probable reason for lower experimental value in this case as the code is not designed for built-up sections. Again, EUROCODE-4 predicts the ultimate load capacity of hollow column 17.4% conservatively. For CFT-02 and CFT-03, the value of ultimate load capacity is predicted to be 14% and 19% more conservative for the respective columns in comparison with experimental value. This indicates

that EUROCODE-4 is more conservative than AISC-guideline and thus recommended in design where source of uncertainty is greater.

8. Code Analysis for Eccentric Loading

For CFT-04, CFT-05, CFT-06, and CFT-07 were subjected to eccentric loading with varying eccentricities: 25 mm for CFT-04 and CFT-05, 37.5 mm for CFT-06, and 50 mm for CFT-07. To evaluate the combined effects of axial force and flexure, P-M interaction curves were generated based on the AISC-2010 guidelines as shown in Figure 4. The region inside the curve represents the safe zone, where failure is not expected under any combination of axial force and bending moment. However, for all eccentrically loaded columns in this study, the observed failure points fell within the predicted safe zone, indicating that AISC-2010 underestimates the risk of failure under eccentric

loading. This suggests that designs based on AISC-2010 for structures likely to experience eccentric loads should incorporate a larger safety margin.

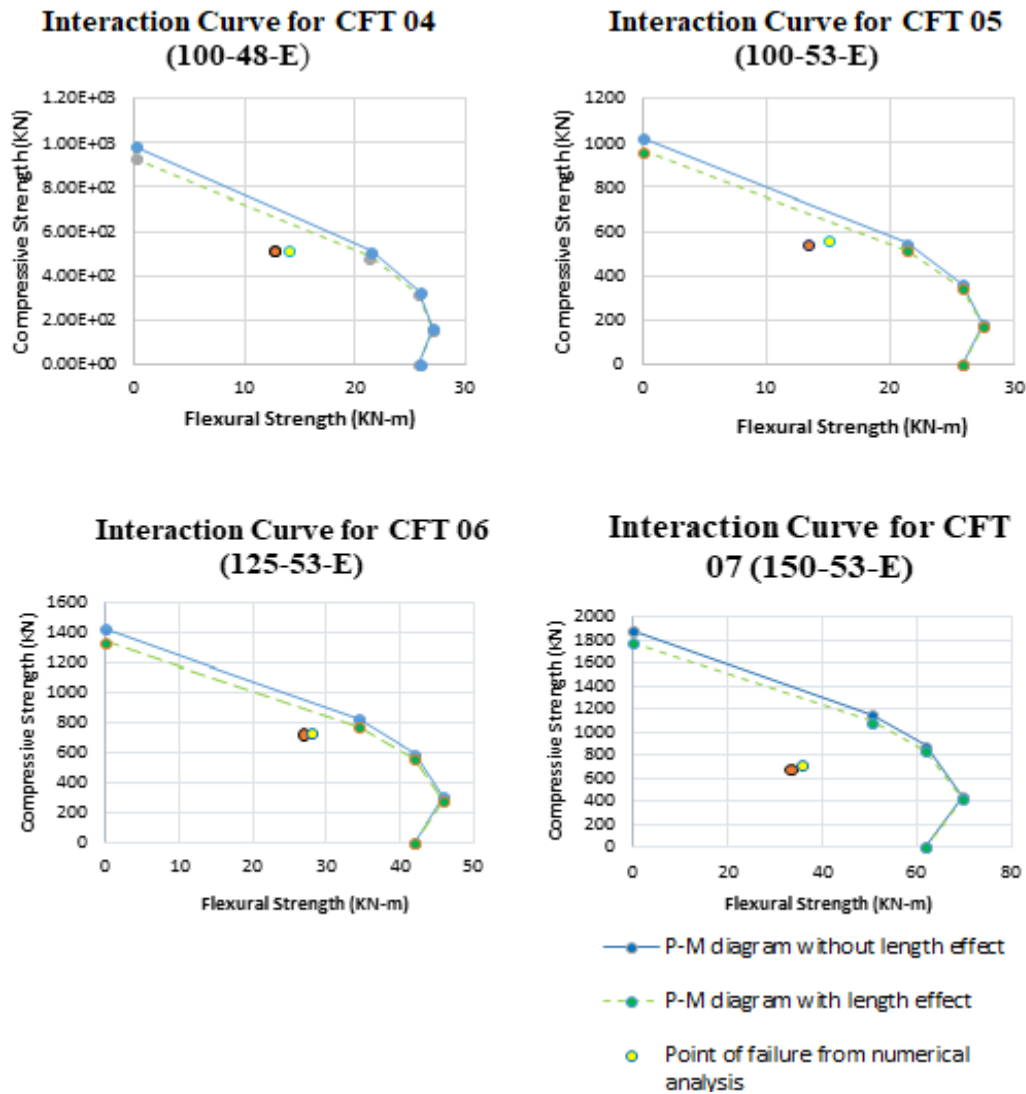


Figure 4. P-M Interaction Curve using AISC-2010

The experimental and numerical results were also compared with predictions from EUROCODE-4. P-M Interaction diagrams in Figure 5 generated according to this code, without accounting for length effects, showed that failure points for CFT-04, CFT-05, CFT-06, and CFT-07 consistently fell outside the predicted safe zone. This finding highlights the superior reliability of EUROCODE-4 in estimating load capacity under

eccentric loading conditions. Figure 3 illustrates the interaction curve for CFT-04 as per AISC-2010 and EUROCODE-4, with similar patterns observed for the other eccentrically loaded columns. These results emphasize the importance of selecting appropriate design codes to account for the effects of eccentric loading in composite column structures.

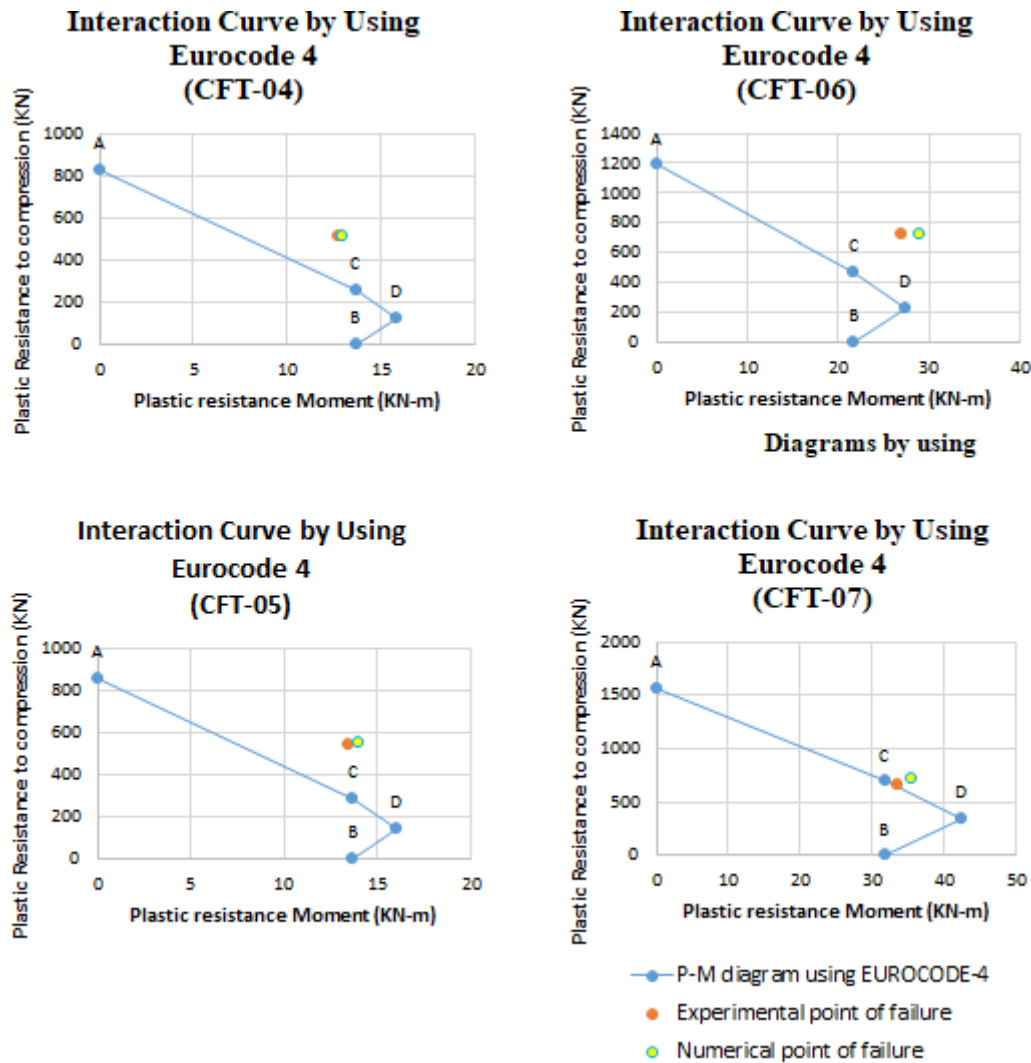


Figure 5. P-M Interaction Curve using EUROCODE-4

9. Conclusions

Composite columns demonstrate significant advantages over bare steel columns, carrying an average of 45% more load for the same cross-sectional area. For concentrically loaded columns, a 5 MPa increase in concrete strength results in a 10% gain in load capacity. However, under eccentric loading, the same strength increase yields only a 5% improvement. Loading type has a substantial impact, as eccentric loading reduces load capacity by approximately 48% compared to concentric loading. In terms of stiffness, composite columns exhibit about 30% greater axial stiffness than bare steel columns. Notably, a 5 MPa increase in concrete strength enhances stiffness by 34%, underscoring the material's significant contribution to stiffness, even though its effect on load capacity is less

pronounced. However, eccentric loading markedly reduces stiffness, emphasizing the critical role of load application conditions.

Regarding design code predictions, the AISC-2010 guideline is not significantly conservative for concentric loads. Moreover, for eccentrically loaded columns, failure points were found within the code's predicted safe zone, indicating that AISC-2010 does not adequately account for the risks posed by eccentric loading. This highlights the need for incorporating a greater safety margin when using this code for eccentrically loaded CFT structures.

In contrast, EUROCODE-4 provides more conservative predictions for concentric loads and demonstrates greater reliability under eccentric loading. For all eccentrically loaded specimens tested in this study, failure points were located outside the predicted safe zone in the P-M interaction curves, reflecting the code's

ability to better capture the behaviour of composite columns under complex loading conditions. Given these findings, EUROCODE-4 is recommended for designs where uncertainty is higher or where eccentric loading is expected.

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