

Analysis of the Performance of Slender High-Performance Reinforced Concrete Columns under the Effects of Slenderness and Reinforcement Ratio in Different Structural Conditions

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Abstract: The following report reviews recent developments in the framework of slender column design in different materials and in different conditions. Important parameters for stability and load capacity are slenderness ratio and load eccentricity and they affect failure modes such as buckling. The physical properties have been enhanced in systems such as: concrete-encased steel, concrete-filled steel tubulars, ultra-high performance fiber reinforced concrete, and timber-steel based hybrids. However, the ductility and strength can be improved through fiber-reinforced polymer strengthening and recycled aggregate concrete confinement methods, although their effectiveness can vary. Corrosion and environmental degradation can fast-track strength loss, requiring predictive models for section loss and changes in confinement. New insights and risk analyses have also found weaknesses in the existing design codes, which resulted in suggestions for enhanced safety criteria and adjustments to the prediction of slender column behavior. Using parameters such as slenderness and stiffening mechanisms, new analytical formulas and design methodologies were created to achieve accuracy. Overall, the findings support sustainable structural designs; however, further experimental validation and refined modeling will be essential to address future challenges.

1. Literature review

The second-order analysis in braced slender columns is under study, based on the computation of additional moment in these columns using established codes and their respective equations (Farouk, 2017). It posits an approximate equation for the computation of these moments, validated by elastic analysis, of single curvature columns that incorporate pin supports and rotational springs. The equation is shown to be more in line with the results of finite element analysis under elastic conditions taking in addition to the moment created by mid-span and rigidity of connected beams as well. In the forthcoming, we will adapt this equation and compare it to accredited equations in order to discuss the stiffness reduction due to cracking and yielding. Research on the stability of slender columns has gained importance with the advent of non-linear modeling approaches and **Strauss, A & others 2021** The objectives mainly focus on reliability; safety indices, as well as classical and extended probabilistic analysis formats (to be customized in the necessary way). Indeed,

slender concrete columns experience stability failures before they are capable of reaching their material capacity, and the results have implications that go against established design principles stipulated by EN 1992-1. These limitations are pointed out by its Probabilistic Non-linear finite element analysis (P-NLFEM) in that calculated axial forces often exceed experimental results, demonstrating inadequate safety margins. In particular, 1.04 for C45/55 columns and 1.06 for C100/115 columns, and global resistance factors of 1.06 and 1.10 were calculated with the model uncertainties. Higher model uncertainty factors ($\gamma_{Rd} > 1.10$) for slender column designs are advised to avoid overestimation of axial capacity. Sensitivity analyses show the heterogeneous effects of concrete properties upon normal and horizontal forces according to loads. Thus, it is critical to revise the safety formats for non-linear modeling to achieve reliable outcomes, because current Eurocode provisions are bound to account for large uncertainties and premature failures which underlines the necessity for supplementary safety factors in the national regulations. **Wu, N. 2025** CECFST columns have been gaining popularity in engineering for their good structural performance. We studied using a combination of compression and biaxial bending a study on six columns with different slenderness ratios and loading characteristics. The main features discovered were that structural failure was influenced by the increased slenderness and load eccentricity, inelastic buckling being the main failure mode. The study employed the validated finite element model that analyzed the stress distribution to compare European and American design codes, and the latter was concluded to be superior for its accuracy in predicting curves. With further experimental validation, future work should improve the calculation techniques of CECFST slender columns subjected to biaxial bending.

Ali, F. A., Hasan 2025 The study analyzed 166,320 hypothetical reinforced concrete (RC) columns to examine factors affecting flexural rigidity (EI). Based on our analysis of existing experiment data, a new EI expression was established for 131 slender RC columns using linear regression. The proposed EI is incorporated into ACI 318M-05 Code, which enables comparison of experimental data from 150 columns with theoretical strength estimates. Different types of specimens were tested, such as normal and high-strength concrete columns subjected to varying loading conditions. The study reviewed five ways of predicting nominal capacity found that the ACI 318M-05 Code tends to underestimate column capacity. The improvements were observed using Rangan and Mirza's methods, where the proposed method had the best predictions and consistent results when concrete compressive strain was controlled.

Ali, F. A & others 2023 The experimental program aimed to evaluate the effectiveness of slender recycled aggregate concrete (RAC) columns externally restricted by CFRP composites. Eight slender circular reinforced concrete columns evaluated the capacity of the CFRP system to compensate for load-carrying capacity reductions due to the use of 100% recycled concrete aggregate (RCA). Results identified improved ultimate carrying weight as well as first cracking load, load-displacement curves, and load-strain responses. Performances showed that the modality of transverse strengthening and external reinforcement greatly affected the performance of that column. In particular, tied RC columns with 100% RCA and CFRP confinement exhibited 5.5%, 44.97%, and 112.85% improvement in strength compared to control columns and spirally reinforced (RC) columns recorded similar increases of 10.32%, 42.81%, and 113.51% in strength. Main findings showed that CFRP wrapping, especially at 100% CFRP, substantially increased the ultimate and safety factor values compared as well, producing higher anticipated maximums than the initial expectations. In addition, as the loading of reinforced CFRP grew higher, the use of spiral reinforcement consistently outperformed the tied reinforcement at fixed RCA content on the load-displacement curves, as noted by the obtained improved flexural stiffness and shape regarding CFRP wrapping and spiral reinforcement. The load-strain responses,

notably at 100% ratio, improved while spiral reinforcement greatly helped in the reduction of strain at mid height. Lin et al.2025 In this study, chloride corrosion on concrete-encased steel (CES) slender columns under axial loading was examined. There were 12 specimens tested to see the effects of corrosion on failure modes and mechanical performance. We concluded that corrosion expedited structural deterioration and shifted failure from the end region to mid-span, and increased slenderness ratios increased the loss of load bearing capacity and stiffness. The axial load capacity was predicted using section loss and confinement as aspects. Stability analysis shows that corrosion and slenderness reduce safety margins due to increases in corrosion and slenderness; however no instability failures were reported. The research emphasizes significant damage mechanisms and performance metrics. The duration and current intensity of corrosion also play a very important role in the load resistance and stiffness response. The study results are presented on a general scale and offer important information for the structural analysis and maintenance planning of CES in corrosive scenarios. The study was funded by the National Natural Science Foundation of China, and no competing interests declared by the authors. 6

Sun, P. X., Bai, Y. L., & Peng, K. D. (2025) Study that investigated the flexural performance of eighteen FRP-strengthened slender reinforced concrete (RC) columns subjected to eccentric compression and examined the effect on parameters including eccentricity, slenderness ratio, FRP type and layer count. The results indicate that FRP confinement greatly improves strength and ductility, while CFRP specimens frequently failed brittly but PET FRP material efficiently utilized capacity from fractured rebar and marked deformation. Each phase of the axial load response were classified according to the nature of the load response: an initial parabolic phase, followed by a rapid descent caused by cracking, and in the end, softening. Notably, ultimate loads reduced on increasing eccentricity and slenderness, combined with the presence of fewer FRP layers, while the performance of PET FRP was less influenced by the variations and strengths of these two variables. The plane section assumption was substantiated by measurement validation using axial strain from LVDTs and 3D DIC, which identified diagonal fiber pattern in PET FRP columns characteristic of cracking. Moreover, **Jiang and Teng's** theoretical model was both accurate and underestimated post-peak deformation in estimating load capacity. According to the findings, LRS FRP exhibited better ductility and load carrying ability, however, concern for the degradation of post-peak strength remains, and more investigation is required to improve flexural stiffness and residual capacity of FRP-confined slender columns. Recognitions were awarded for financial support from several Chinese research institutes, including contributions by Peng-Xuan Sun, Yu-Lei Bai and Kai-Di Peng, and no conflicts of interest are reported. 7

Shujie Jiang et al. study on the axial compressive performance of concrete-encased steel (CES) components impacted by chloride corrosion. The corrosion and axial forces on 12 slender CES columns were accelerated as shown in the literature and the corrosion-induced expansion caused a degradation of the concrete cover, with higher slenderness ratios making performance problems worse. On the average, 20% corrosion increased the slenderness ratio from 32 to 51, resulting in a 17.1% decrease in axial capacity and 18.3% decrease in initial stiffness. This analysis suggests that legacy methods usually underestimate confinement effects caused by corrosion propagation and must generate new confinement stresses. By incorporating the contribution of corrosion from the corroded steel and confinement generated by corrosion products, the analysis achieved better predicted axial stability which was confirmed via experimental results. The new finite element model did a good job of replicating test results, and also showed that improved models were required to judge the stability of the corroded CES columns. Key results indicate significant reduction in ultimate load-carrying capacity and initial stiffness under corrosion, especially over 15% corrosion,

in addition to failure modes as well as ductility.

Zhang, et al.2025 Mechanical behaviour of steel tube restrained laminated bamboo columns incorporating high-strength steel and light bamboo. Overall, its analysis on slenderness ratio reveals important factors regarding the modes of failure and load capacity, namely, the short columns are end-strength failures, whereas in medium and long columns, the overall buckling process occurs. Steel tube restraint is found to provide greater lateral deformation resistance, and the axial compressive strength is found to be significantly greater than bamboo restoration in the steel tube resting mode of columns. Predictive formulas for load-carrying capacity have extremely low gaps of correspondence against experimental results—highlighting the promising role these composite materials would play in energy-saving design. Authors are part of the group that wrote, edited and validated these inputs.

Hassanein, M.F. and Others 2025 This study investigates the structural behaviour of slender concrete-filled double-skin tubular (CFDST) columns that are fitted with stainless steel outer tubes and carbon steel inner tubes through a validated finite element model. A careful parametric analysis was done: considering factors such as slenderness, material properties, hollow ratio and interfacial contact behavior. Findings show the significance of slenderness on buckling resistance, with the column classification thresholds defining limits. Normalized strength and lateral deflection are minimally affected by the slenderness ratio of the outer tube. Note that increased concrete strength increases the post-peak response of intermediate-length columns compared to medium columns, but this effect is lower in longer columns compared to longer columns. Additionally, the hollow ratio has a positive relationship with the strength-to-weight ratio but a less significant correlation with the axial strength. Contact pressure drops with increasing slenderness, and at section corners. Column strength is predicted correctly by the AISC 360–16 guidelines to within $\pm 10\%$ of finite element results. The work also presents two of these new research models for practical use in structural engineering, and stresses the significance of slenderness, establishing a three-stage model for failure modes. The authors declare that no competing interests for the research were reported and the first author was funded by **Xihua** University Talent Introduction Fund.

Albero, V et al, The present study focuses on ultra-high performance concrete-filled dual steel tubular (UHPCFDST) slender columns under eccentric axial loading, in terms of four different column types: double-skin (DS), double-tube (DT) and single-tube (OT, IT) reference. All columns showed ductile behaviour with the principal failure mode of global flexural buckling. Regarding the axial load, the UHPC-DT column had the highest axial load ($N_{exp} = 1676.7$ kN), and the UHPC-DS had the highest relative efficiency ($n = 0.308$) due to the reduced slenderness. DT configuration yielded 5% less relative axial capacity in the inner concrete core, exhibiting an overall compromise between core benefits and increased slenderness. The relative efficacy of the UHPC-DS column was modestly improved compared to the UHPC-OT (3%), while the relative efficiency of the UHPC-DT had a slight negative effect. While UHPC is not covered under the current Eurocode 4, the design approach in EN 1994-1-1 did conservatively predict the failure loads and confirmed its suitability for slender composite columns with UHPC in them. In general, UHPC increases axial bulk strength by up to 85% relative to normal-strength concrete, but its propensity to increase slenderness might lead to decreased efficiency in buckling scenarios. Due to the lack of experimental evidence involving UHPCFDST columns, further effort to verify our designs in order to increase the understanding and calibration is still required. This research paves the way for future studies on the benefits of sustainable construction in terms of lighter construction and less resource use. 11

AM Yousef, & others To this end, this study studies the effects of slenderness ratio and the heating forces on the damaged RC spiral columns, repairing with CFRP rope. Twelve

columns were tested for bearing concentric loads (high slenderness ratio (17.75, 26.65, 33.34)) and subjected to high temperature (600°C for 3 hours). High slenderness ratios lead to lower load capacity while repaired columns showed increased strength of 36-97% after CFRP application. Even though ductility increased some, it was still under the unheated condition. Columns with lower slenderness ratios in the spacing (300 mm) also showed a relative decrease in toughness compared to the high slenderness ratios (150 mm). However, CFRP ropes improve delayed failure while effective bonding between CFRP and concrete assists recovery of load capacity and increases load capacity, mainly at the near spacing. Furthermore, the increase in the pressure of air under stress affected load capacity and a greater effect on ductility was detected over the increase caused by heat exposure, whereas the slenderness ratio had a considerable negative impact on load capacity in FRP-strengthened columns. In general, CFRP ropes provide a strong response to the applied axial strain and therefore are capable of enhancing confinement, thereby improving performance in repaired columns. Concrete (2025 AM Yousef & others)

In this work, we analyzed slender Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) columns subjected to eccentric axial loads in the following experimental or numerical methods. There were 9 columns tested with slenderness ratios of 66.67 and 55.56 and compared with ACI 318-19, EC-2, and ECP-203-2020. Important variables to investigate were longitudinal reinforcement ratio, transverse reinforcement ratio, and end eccentricity. Experimental evidence also showed that a small eccentric load ($e/t=0.2$) decreased load capacity by 53.3%, but larger load ($e/t=0.5$) reduced load capacity by 70.2%. Expanding the longitudinal reinforcement ratio from 2.01% to 4.52% increased capacity by 22.9% at $e/t=0.2$ and 20.8% at $e/t=0.5$. UHPFRC primarily provides confinement with minimum concrete fragmentation attributed to fibers. An increased slenderness ratio reduced load capacity by 28.5% and increased lateral displacement by 61.3%. ACI 318-19 and EC-2 provisions provided for ductile failure (suggestion was to change stirrup bar diameter from D10 mm to D8 mm). EC-2 and ECP-203-2020 design equations were also safely applied to UHPFRC columns, and led to conservative load prediction. It was determined that the ACI 318-19 moment magnification method overestimated the second order moments, causing the suggested stiffness reduction and moment limit recommendations. Finally, a modeling technique is more than accurate to model for UHPFRC column responses to concentric and eccentric loads.

R Mata et al, 2025, evaluates the seismic durability of composite moment frames with compact and slender CFT columns for bidirectional moment connections. This illustrates the growing demand for resilient structures as they evolve to respond to seismic design codes. Through advanced numerical modeling of two office building models, according to the Chilean standard, results show that slender CFT columns demonstrate good ductility and have a small incidence of pinching effects in the presence of high drift levels. By analyzing connection behavior, the study underscores the importance of bidirectional connections in improving structural performance by preventing brittle failure. It also highlights the significance of optimum beam-to-column stiffness ratios for obtaining plastic moment capacity and improving ductility. The model of resilience is robust to functional loss after earthquake and calls for sustainable building design by minimizing the environmental impact of the CFT columns. Research on the different parameters of buildings and earthquake prevention are recommended by this study to further improve the resilient design systems. G Li et al 2025 The axial compression behavior of square ultra-high strength (UHS) steel tubular columns loaded with C110 concrete with respect to different slenderness ratios have been investigated. It investigated the failure modes, the load-induced responses, the strains, and the critical loads. Nonlinear finite element models, supported by experience, have been demonstrated to predict column stability with respect to the structural parameters.

Relevant design equations derived from experimental data were valid for predicting the ultimate axial load capacity incorporating the effect of slenderness. The results showed that UHCFST columns had ductile mechanics, steel yields preceded concrete failure rates, and that three failure modes could be identified. Axial load-deflection responses consisted of linear segments, plastic-hardening segments, and descending segments, while slenderness ratio was important in performance optimization. Moreover, improvements in concrete strength, steel yield strength and material ratios were associated with improvements in load capacity, but at high slenderness ratios, the overall strength was decreased. The design equations are aligned with unified strength theory provided in the design codes.

Z Chen, G Yang 2025 study investigates the axial compressive response of PBL-stiffened DSSC slender columns, which have widely been used in infrastructure systems like bridges and offshore platforms. Based on experiments and mathematical analyses of data from five specimens identified some key design parameters including the hollow ratio, length-to-width ratio, and stiffening configurations. Parametric analysis was performed on PBL stiffeners through a validated finite element model, suggesting improvements in slenderness and hollow ratios which have been shown to significantly attenuate the effects of slenderness and thus improve load-bearing efficiency. Because current design codes, such as GB 50396 and AISC, do not fully consider stiffening effects, conservative predictions may be the result. Our proposed reduced design approach for calculating stability coefficients emphasizes the slenderness of the unit and the hollow ratio. Key findings include the lack of global instability where failure manifests as local buckling at column ends, which PBL stiffeners can offer, in contrast to stud connectors, as buckling restraint. We also noticed that lower hollow ratios and a higher length-to-width ratio result in better axial performance while the latter is more feasible. Moreover, design codes overstate slenderness effects resulting in conservative capacity predictions, to which our proposed method has been validated against test results before it is actually put to use. 17

P Gunasekaran, et al. In recent years, a surge in the demand for tall mass-timber structures poses particular challenges to structural designs, with effects of slenderness and large column sizes being specific. This paper reviews that timber columns, when combined with steel reinforcement, are able to enhance their performance through a combination of the two types of methods. The influence of load capacity and buckling behavior on slenderness are addressed by means of a comprehensive testing program of 85 Radiata pine column specimens, current design standards and a review of analytical models for slenderness calculations are reviewed. However, off-center reinforcement is found to be much the better option when it comes to reducing buckling and improving strengthening strength than centered reinforcement is. Moreover, reinforced columns often failed as a result of delamination and buckling of internal steel bars, and the study shows that increasing the ratio of reinforcement reduces the size effect, with slenderness reduction factors being consistent in all cross-sections. It also identifies deficiencies in numerical models used to determine the accurate buckling curve for timber-steel hybrid columns, with constructive statements for future investigation into the fabrication effects on performance..18

Conclusion

Looking to the studies mentioned, these reviewed papers collectively draw attention to remarkable research in the development and the problem of thin composite and reinforced concrete columns for the performance of slender composite and reinforced concrete columns as a whole under a wide range of loading and environmental conditions. Key conclusions include:

1. Effect of the Slenderness Ratios of Slenderness: More slender strength ratios consistently limit load-bearing capacity, stiffness, and strength in different materials for concrete-encased

steel, ultra-high performance fiber-reinforced concrete, recycled aggregate concrete (or recycled aggregate concrete/bran), and timber-steel hybrids and may cause an undesirable change in failure mode from the material exhibiting flexural or tensile force to a buckling or local stability.

2. Material and Reinforcement effects: Reinforcement of the structures can be made better by adding such materials: FRP, carbon fibre ropes, CFRP confinement and hybrid reinforcement (e.g., steel in timber columns), although the performance is subject to selection based on various reinforcement types, configurations and environmental conditions (corrosion, or heat). Spiral reinforcement and external strengthening are better than tied reinforcement for slender structures.

3. Corrosion and Environmental: Chloride-induced corrosion and high-temperature exposure considerably reduce column performance, resulting in low axial capacity and stiffness, different failure modes, or an accelerated degradation. Novel modeling and experimental methods highlight the importance of incorporating corrosion impact into design and evaluation processes.

4. Modeling and Design Code Adequacy: FEA models validated by experimental data have been required in order to accurately model such complex properties as buckling, load-strain response or confinement. The Eurocode, ACI 318, AISC, and GB codes for example often give conservative forecasts and miss the slenderness, corrosion and individual composite behavior, causing under- or over-estimation of possibilities being considered. Safety factors can be adjusted, and a more efficient moment magnifying method can be adopted, particularly in its formulation than if employing a slenderness reduction formula.

5. New Composite and Sustainable Material: Novel materials show high level of performance concrete, laminated bamboo with steel restraint, for instance, and ultra-high strength steel tubes are being developed due to the potential structural efficiency and sustainability but their slenderness effects need to be determined to improve design as well as resilience. Future work is a must because more experimentation tests should be carried out to verify new methods of confinement and stiffening, predictive models on slender composite columns under biaxial bending, eccentric loading, and engineering design provisions should be made to suit environmental degradation and non-linear behavior better. Robust numerical modeling and fine-grained parametric studies will be needed to facilitate these enhancements. Ultimately, a holistic response to slenderness effects -- via material improvements, better reinforcement designs, solid modelling, and revised design codes -- is crucial for the future of the safety, durability, and sustainability of slender structural column designs in contemporary engineering applications.

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