Literature review on high-strength cold-formed steel beams

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Abstract - *This paper explores the literature review on material properties, structural behavior, and design methodologies for cold-formed high-strength steel CFHSS hollow sections and tubular beams. The review synthesizes existing studies on CFHSS, highlighting the significant residual stress distributions and enhanced strength characteristics associated with steel grades of 700, 900, and 1100 MPa. Key findings from tensile and bending tests indicate that current design codes tend to underestimate the strength and ductility of CFHSS beams. This underestimation underscores the need for revised slenderness limits and moment redistribution criteria. A critical analysis of design methods reveals that the Continuous Strength Method CSM and the modified Direct Strength Method (DSM) offer superior predictions of structural performance when compared to traditional design codes. The review also examines the role of finite element analysis in validating new design equations, alongside an evaluation of the influence of perforations on the load capacity and failure modes of CFHSS components. The research highlights significant gaps in current design guidelines and emphasizes the need for updated, more accurate approaches to improve the reliability and performance of CFHSS components in engineering applications.*

Key Words: **Cold-formed steel, High strength cold-formed steel, Literature review, Structural Engineering, Thin-walled structures**

1. INTRODUCTION

Cold-formed high-strength steel (CFHSS) has emerged as a critical material in modern structural engineering, renowned for its exceptional strength-to-weight ratio and versatility. This type of steel is produced through a cold-working process, which enhances its mechanical properties, making it ideal for applications that require both structural integrity and efficiency. CFHSS is commonly used in a variety of structural components, including beams, columns, and hollow sections, where its lightweight nature can lead to reduced material usage and lower construction costs.

As the demand for high-performance materials in construction continues to grow, it is essential to investigate the mechanical behavior of CFHSS and refine existing design methodologies. This research aims to explore the structural behavior of CFHSS under various conditions, assess the reliability of current design codes, and propose improvements based on experimental and numerical analyses. By enhancing the understanding of CFHSS, this study seeks to contribute to the development of more accurate design standards that align with the actual performance of high-strength cold-formed steel in structural applications.

2. LITERATURE REVIEW

2.1 Material Properties

The reference for the material properties is Material properties and residual stresses of cold-formed high strength steel hollow sections Jia-Lin Ma ,Tak-Ming Chan ,Ben Young [1].The study investigated the material properties and residual stress distributions of cold-formed high-strength steel (HSS) hollow sections with nominal yield stresses of 700, 900, and 1100 MPa. A total of 66 tensile coupon tests were conducted on square, rectangular, and circular hollow sections to assess properties such as modulus of elasticity, tensile proof stress, and ultimate strength. Residual stresses were measured using a wire-cutting method, revealing higher tensile stresses on the outer surface and compressive stresses on the inner surface, particularly in corners due to cold-forming. A new constitutive model based on the Ramberg-Osgood expression was proposed, highlighting the influence of residual stresses on the early yielding and stability of HSS sections.

2.2 Cold-formed high strength tubular beams

The paper "Experimental investigation of cold-formed high strength steel tubular beams [2]" conducted bending tests on circular, rectangular, and square hollow sections with nominal yield strengths of 700, 900, and 1100 MPa. A total of 25 four-point bending tests were performed to analyze the beams' flexural behavior, including load-deformation responses and failure patterns. The experimental results were compared to design codes from European, Australian, and North American standards, as well as predictions from the Direct Strength Method. The study found that current design standards tend to underestimate the strength of HSS tubular beams, making them conservative in their predictions. Additionally, the research highlighted that low material ductility in high-strength steel beams reduces their rotation capacity, which limits their ability to redistribute moments, especially in slender sections. This observation suggests that revisions to slenderness limits may be needed to more accurately assess the structural performance of these sections under bending. Furthermore, the study concluded that while HSS beams offer significant strength advantages, their limited ductility requires careful consideration in design, particularly for plastic moment redistribution.

2.3 High strength steel hollow sections

To investigate the performance of cold-formed high strength steel hollow sections, the authors initiated a research program in Hong Kong, which included both experimental and numerical investigations on cold-formed high-strength steel hollow sections. The reference for high strength steel hollow sections is Tests on high-strength steel hollow sections: a review. Considerable enhancements in material strength are found for cold-formed high-strength steel due to the coldworking effects, especially for the corner regions of rectangular hollow sections and square hollow sections. In the past few decades, researchers have been investigating the structural performance of built-up high-strength steel hollow sections, whereas investigation into the structural behavior of CFHSS hollow sections has been limited. The examined experimental investigation into CFHSS square hollow sections, rectangular hollow sections and circular hollow sections were principally conducted by the authors at the University of Hong Kong. Cold-formed steel sections of the research on BUHSS hollow sections has been on box sections. Typical fixed-ended stub column tests for CFHSS hollow sections 5.3 Beam tests A series of tests on CFHSS hollow section beams was presented by Jiao and Zhao and Ma et al.

2.4 Design of high strength tubular beams

This study seeks to enhance the codified design guidelines for cold-formed high-strength steel (HSS) tubular beams. The reference for the design is Design of cold-formed high strength steel tubular beams [4] demonstrating that the finite element model accurately reflects the failure modes observed in tests. It finds that the existing slenderness limits in EN 1993-1-1 are generally conservative for cold-formed hollow structural sections (SHS and RHS) under pure bending, and proposes a new set of slenderness limits based on the distribution of test and finite element analysis (FEA) results. Additionally, the study introduces a new equation derived from the Direct Strength Method (DSM) that improves the local buckling curve for these sections. For circular hollow sections (CHS), a new slenderness parameter is proposed, along with modifications to the AISI S100 design method. The study employs a validated finite element model that incorporates material properties, local imperfections, and residual stresses to simulate the flexural behavior of HSS beams, producing moment-curvature curves and demonstrating strong agreement with experimental results. It reveals that current design methods underestimate capacities by 22-55% on average, while the proposed methods for SHS, RHS, and CHS beams are shown to be more effective and reliable. Ultimately, the study concludes that these improvements to design guidelines are necessary for accurately assessing the structural performance of cold-formed high-strength steel beams.

2.5 Continuous Strength Method (CSM)

The study from the paper -The continuous strength method for the design of high strength steel tubular sections in compression [5], presents a continuous strength method (CSM) aimed at enhancing the design of high-strength steel tubular sections under compression, demonstrating that it outperforms the current direct strength method (DSM) and existing design codes in terms of accuracy and consistency. Through a comprehensive numerical analysis, the research develops and validates finite element (FE) models that effectively simulate the behavior of stub columns made from circular hollow sections (CHS), elliptical hollow sections (EHS), square hollow sections (SHS), and rectangular hollow sections (RHS). The findings reveal that the CSM provides reliable predictions for failure modes, load-shortening curves, ultimate loads, and corresponding end-shortenings, with mean load capacities closely aligned with experimental results and lower coefficients of variation (COV).

Importantly, the study highlights that the CSM incorporates beneficial effects such as strain hardening and element interaction, leading to more accurate and consistent capacity predictions for high-strength steel tubular sections. Additionally, it points out the absence of a specific design method for EHS in current codes, which reinforces the significance of the proposed CSM in filling this gap. The validated FE models are positioned as valuable tools for future parametric investigations, aiming to supplement the limited experimental data available for high-strength steel stub columns. Overall, the proposed CSM emerges as a simple yet effective design methodology for slender tubular sections, ensuring better alignment with actual performance and advancing the state of design practices in structural engineering.

2.6 Design of cold-formed stainless steel hollow sections

The study assesses the performance of the current Direct Strength Method (DSM) for cold-formed stainless steel circular hollow section (CHS) columns, finding it to be unconservative and unreliable, with a mean P_u/P_{DSM} ratio of 0.96 and a reliability index of 2.36, below the target threshold. In response, a modified DSM is proposed, which demonstrates greater accuracy and reduced variability, achieving mean ratios of 0.121, 0.139, and 0.079 for all specimens, those with slenderness $\lambda_l < 0.77$, and $\lambda_l \geq 0.77$, respectively. The reference for the paper is Design of cold-formed stainless steel circular hollow section columns using direct strength method [6]. Measurements of local imperfections revealed they were about 3.2% of the plate thickness. The study highlights that the current DSM fails to account for slender sections with λ_l greater than 0.776, as previous research did not cover this range. Using a validated non-linear finite element analysis (FEA) model, which incorporated results from a broad parametric study of 108 CHS columns, the findings indicate that the modified DSM provides reliable predictions across all specimens, achieving a reliability index of 2.50, thus demonstrating the need for updated design rules for stainless steel CHS columns.

2.7 Stress-Strain curves for cold-formed steel

The study from the paper Description of stress-strain curves for cold-formed steels [7], introduces a two-stage Ramberg-Osgood model aimed at accurately representing the stress-strain behavior of cold-formed steels, validated through a comprehensive analysis of experimental data. It identifies the Mirambell and Real expressions as providing the best fit for experimental stress-strain curves and recommends predictive expressions for key material parameters, such as Young's modulus, proof stresses, and ultimate strength. Notably, the research finds that using a 0.05% proof stress yields more precise predictions for the strain hardening exponent (n) and proposes new expressions for calculating both n and the strain hardening exponent (m) based on extensive experimental data. Furthermore, the study critiques the existing predictive expression for ultimate tensile strength (f_u) from Yun and Gardner, pointing out that it overestimates the f_u/f_y ratio for cold-formed steels, and offers a revised formula for improved accuracy. The findings underscore that the model is suitable for advanced simulations and design applications in cold-formed steel structures, emphasizing that the accuracy of predictions improves with a better understanding of input parameters. This comprehensive approach allows for reliable assessments and can inform the design processes for cold-formed steel components in various structural applications.

2.8 Sections under combined compression and bending

The study comprehensively investigates the structural behavior of cold-formed high-strength steel (CFHSS) beam-columns subjected to combined compression and bending, focusing on the evaluation of existing design codes relevant to high-strength steel beam-columns with grades above 700 MPa. The reference of this paper is Cold-formed high-strength steel rectangular and square hollow sections under combined compression and bending. [8]. The findings reveal that the current design codes are generally conservative, with predictions averaging 13%–21% lower than actual experimental outcomes; among these, ANSI/AISC 360-10 is noted for providing the closest estimates. Additionally, the AISC 303-10 code, which incorporates a two-phase P-M interaction curve, is particularly recommended for application to short CFHSS beam-columns, suggesting a more accurate reflection of their behavior under load. The research involved an extensive experimental program testing 51 beam-column specimens with varying section sizes and loading eccentricities, alongside advanced finite-element modeling techniques. This modeling effectively replicated critical parameters such as ultimate capacities, load-end rotation curves, and failure modes observed during experimental tests. The comparison of these results justifies the reliability of the proposed finite-element model, showcasing its potential utility in predicting structural responses.

The study concludes that a reevaluation of current design codes is essential, urging updates that integrate experimental findings to enhance prediction accuracy, especially regarding interaction curve endpoints. Furthermore, it emphasizes the importance of using the finite-element model in future parametric studies involving CFHSS tubular beam-columns, as this approach could lead to significant improvements in design methodologies, ensuring that structures are both safe and efficient. The overall insights provided by this research could foster better-informed practices in the design and application of high-strength steel in structural engineering.

2.9 Hollow beam behavior under flexural loading

The study in the paper Behaviour of cold-formed steel hollow beam with perforation under flexural loading [9],investigates the impact of perforations and their locations on the behavior of cold-formed steel hollow beams under single-point flexural loading, comparing experimental results with analytical findings. It reveals that rectangular hollow beams exhibit a 41% increase in load-carrying capacity compared to square hollow beams, with failure modes differing significantly; rectangular beams primarily fail through local outward buckling, while square beams fail by both local and overall buckling. Additionally, rectangular beams demonstrate greater stiffness, and while beams with single square or circular holes experience reduced load resistance and strain when load is applied, those with two perforations show enhanced suitability and energy absorption capacity. The research combines experimental testing of ten hollow beams with varying cross-sections and perforation characteristics and employs finite element analysis using ANSYS 20.0 for modeling. The results indicate a strong correlation between experimental and analytical outcomes, with a mean ratio of 1.02 and a standard deviation of 0.036. Ultimately, the study concludes that the developed analytical model is effective for analyzing cold-formed steel hollow beams with diverse cross-sections and web openings, offering valuable insights into how perforations influence their load-carrying capacity and deflection.

2.10 Behavior of CFS circular hollow sections

The study in the paper Cross-sectional behaviour of cold-formed high strength steel circular hollow sections [10] examines the cross-sectional behavior of high-strength steel circular hollow sections (CHS) under compression, bending, and combined loading, finding that the tested CHS can support axial loads exceeding the plastic load capacity (N_{pl}) by at least 11.1% and achieve their plastic moment capacity (M_{pl}) under uniform bending moments. It reveals that both Eurocode 3 (EC3) and AISC significantly underestimate the cross-sectional capacity of stocky CHS, largely due to the omission of strain hardening effects. Additionally, the Class 3 limits and the design equations for effective area and section modulus in EC3 are noted to be overly conservative, affecting the accuracy of predictions for combined loading. The study employed an extensive experimental program, including tensile tests, local imperfection measurements, and various bending tests, alongside validated finite element models to generate over 1,650 cross-sectional resistance data points. These results were assessed against existing design codes, underscoring the need for improved design provisions for CHS. Ultimately, the study highlights significant deficiencies in current design guidelines, emphasizing the necessity for revisions to enhance the accuracy of capacity predictions.

2.11 Behavior of CFS oval hollow section beams

The study in the reference paper Flexural behaviour of cold-formed steel oval hollow section beams [11] thoroughly investigates the flexural behavior of cold-formed steel oval hollow sections (OHS) and critically evaluates the performance of existing design standards, including Eurocode 3, North American Specification, and Australian/New Zealand Standards. The results indicate that these codes produce unconservative predictions, which fail to meet the reliability target value of 2.5, thereby questioning their suitability for the design of cold-formed steel OHS beams. In contrast, the Direct Strength Method (DSM) is highlighted as the most accurate and consistent approach, while the Continuous Strength Method (CSM) is found to be slightly more conservative and scattered. Both the DSM and CSM yield reliability indices that exceed the target threshold, affirming their reliability for design purposes.

The research employs a robust methodology, combining experimental four-point bending tests on various OHS beam specimens with non-linear finite element analysis to simulate loading responses. The FE model closely aligns with experimental outcomes, achieving a mean ratio of finite element to test ultimate moments of 1.00 and a low coefficient of variation of 0.042, showcasing the model's precision. The parametric study included 36 specimens with varying cross-sectional dimensions and imperfections, further validating the findings. Ultimately, the study concludes that the DSM and CSM are superior in accurately predicting the flexural behavior of cold-formed steel OHS beams, while existing design standards fall short, necessitating a reconsideration of their applicability in engineering design.

3. RESULTS AND DISCUSSIONS

1. The study reveals that cold-formed high-strength steel hollow sections exhibit significant residual stress distributions, influencing their mechanical properties and structural stability.
2. While cold-formed high-strength steel tubular beams exhibit significant strength, their low ductility necessitates careful design considerations and potential revisions to slenderness limits to enhance moment redistribution capabilities.
3. The research highlights significant enhancements in material strength for cold-formed high-strength steel hollow sections, particularly at the corners, while emphasizing the need for more extensive investigations into their structural behavior compared to built-up high-strength steel sections.
4. Revised slenderness limits and a new equation for cold-formed high-strength steel tubular beams, demonstrating that current design methods was proposed and it significantly underestimate their capacities and highlights the need for improved guidelines.
5. The proposed continuous strength method (CSM) offers a superior and more accurate design approach for high-strength steel tubular sections under compression, effectively addressing gaps in current design codes and improving prediction reliability.
6. The current Direct Strength Method (DSM) is unreliable for cold-formed stainless steel CHS columns, prompting the proposal of a modified DSM that significantly improves prediction accuracy and reliability across all slenderness ranges.
7. A two-stage Ramberg-Osgood model for cold-formed steels that enhances the accuracy of stress-strain predictions was proposed and it introduces improved expressions for key material parameters, supporting better design practices in structural applications.
8. The need for reevaluation and updates to current design codes for cold-formed high-strength steel beam-columns is highlighted in the study [8], revealing that existing predictions are overly conservative and advocating for the integration of experimental findings and advanced finite-element modeling to enhance accuracy in structural design.
9. Perforations significantly affects the load-carrying capacity and failure modes of cold-formed steel hollow beams, with rectangular beams outperforming square beams in stiffness and load resistance, while an effective analytical model is developed to analyze these effects.

10. The current design codes, including Eurocode 3 and AISC, significantly underestimate the cross-sectional capacity of high-strength steel circular hollow sections due to neglecting strain hardening effects, highlighting the urgent need for revised design provisions to improve prediction accuracy.
11. The existing design standards for cold-formed steel oval hollow section beams provide unconservative predictions, while the Direct Strength Method (DSM) and Continuous Strength Method (CSM) demonstrate superior accuracy and reliability, warranting a reevaluation of current guidelines.

4. CONCLUSIONS

The research on cold-formed high-strength steel (CFHSS) and related tubular sections reveals significant discrepancies in current design codes, which often provide overly conservative predictions that underestimate load-carrying capacities. Factors such as substantial residual stress distributions, low ductility, and the neglect of strain hardening effects highlight the urgent need for updated guidelines that incorporate advanced modeling techniques and empirical data. This underscores the necessity for updated design guidelines that incorporate advanced modeling techniques and empirical findings to enhance the accuracy of predictions.

Methods like the Direct Strength Method (DSM) and Continuous Strength Method (CSM) demonstrate greater reliability and accuracy, emphasizing the necessity for reevaluation of slenderness limits and other critical parameters. Overall, these findings advocate for refined design practices in structural engineering to ensure they align more closely with the actual performance characteristics of cold-formed steel components.

5. ABBREVIATIONS

MPa – Mega Pascal
HSS – High-strength steel
P_u – Ultimate Load
P_{DSM} – Load from Direct Strength Method
λ_l – Slenderness ratio
f_u – Ultimate Tensile strength
f_y – Yield stress of the material
N_{pl} – Plastic load capacity
M_{pl} – Plastic moment capacity

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