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Recent Advancements and Challenges in Flexural Buckling Analysis for Cold-Formed Steel Structures

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Abstract: Flexural buckling is an essential variable to consider when designing thin cold-formed steel components since it has a substantial impact on their stability and structural efficiency. Cold-formed steel (CFS) elements have become more common in modern building techniques due to their several benefits, such as a high ratio of strength to weight, straightforwardness of production, and cost efficiency. However, CFS components are susceptible to several types of instability, especially flexural buckling, due to their lightweight structure. The objective of this investigation is to improve the understanding of flexural buckling analysis by thoroughly investigating relevant studies, design principles, analytical approaches, and experimental tests. In addition, the study discusses recent progress in the field, including the application of modern materials such as high-strength steel and the incorporation of finite element analysis (FEA) to accurately model and anticipate flexural buckling behavior. It emphasizes the difficulties that come with these advancements, highlighting the need for improved material models and computing resources. The study emphasizes how important cold-formed steel constructions' structural performance and flexural buckling behavior are in relation to their longevity, material aging, and prolonged exposure to different loads. The goal of this literature review is to provide structural engineers, scholars, and practitioners with an extensive resource. It provides crucial insights into the behavior of flexural buckling analysis for cold-formed steel structures, summarizing recent advancements and difficulties in the field to help with construction design and integration decision-making.

Keywords: Flexural Buckling; Cold-formed Steel; Buckling Analysis; Structures

1. Introduction

With the rapid global shift towards low-carbon economies and green buildings, environmental preservation and conservation have become increasingly prominent in the construction industry. In the building sector, lightweight steel has gradually taken center stage as a material that protects the environment. [1]. Cold-formed steel (CFS) is favored in structural engineering for its high strength-to-weight ratio, adaptability, and cost-effectiveness. In the steel construction sector, the use of cold-formed steel (CFS) thin-walled buildings has surged in recent decades, particularly in applications such as light gauge steel frame systems and modular construction. This trend reflects growing recognition of CFS's versatility, efficiency, and cost-effectiveness in modern building practices [2].

Cold-formed steel (CFS) thin-walled structures are increasingly popular in light gauge steel and modular construction, driven by advancements in manufacturing technology. These structures use built-up sections assembled with screws or fasteners, widely applied in light gauge steel framing systems for various structural elements [3]. It is important to note that the current nominal yield limit of steel sheets is between 250 and 550 MPa, and the thickness that is most frequently used is less than 1.00 mm. Whereas hot-rolled steel sections do not show structural stability problems, cold-rolled steel sections do [4]. However, the slender structure of CFS members makes them vulnerable to flexural buckling, a critical mode of structural instability figure 1 shows the different forms of Buckling in cold formed steel sections [5]. Understanding and effectively mitigating flexural buckling is necessary to guarantee the safe and effective design and construction of CFS structures. Comparing sections with stiffeners at the flange-web junction to those with stiffeners in the webs and lip regions, the former showed a far higher load-carrying capability. This is because the webs and lips, which are essential for supporting heavier loads, have improved stress distribution and increased structural stability. In order to maximize the load-bearing efficiency and overall toughness of cold-formed steel sections, stiffeners must be placed strategically [6].

A multidisciplinary research team conducts extensive theoretical and experimental analyses to fully understand the properties of thin-walled composite materials, particularly focusing on post-buckling behavior when abrupt collapse loads are challenging to predict [7]. The modified slenderness method (MSM) from the current AISI standard is commonly applied in designing cold-formed steel (CFS) built-up columns. This method, well-regarded in hot-rolled steel research, typically provides conservative strength predictions, ensuring robust and safe structural designs that integrate advancements in material science and engineering techniques [8]. Combining cold-formed steel with materials like concrete enhances stiffness, strength, and buckling resistance in composite structures. Designing built-up members involves addressing partial composite action, where welded joints along the entire length ensure full composite behavior in the webs, while unconnected sections act independently without composite interaction [9]. Two methods are used in the construction of the composite columns, namely the hot rolled sections: enclosed steel sections and Concrete Filled Steel Tubular (CFST) sections. The confinement effect in the CFST portion has shown to be more advantageous than its counterpart when these two methods are evaluated in terms of tolerating larger gravitational loads [10].

Despite the limitations of the North American cold-formed steel specification (AISI-S100 2012), current research is concentrated on optimizing the behavior of built-up cold-formed steel (CFS) members. Shear slip resistance at the end connections is critical to total column strength, as demonstrated by experimental experiments conducted on successive CFS channel sections. The AISI-S100 (2012) corrected slenderness ratio may be too cautious for some sections [11]. It has been demonstrated that using carbon fiber-reinforced polymer (CFRP) for reinforcement enhances the ultimate load and delays buckling [12]. As building practices evolve, the integration of composite steel structures provides a promising pathway to enhance the safety, efficiency, and structural performance of cold-formed steel applications. This approach leverages the complementary strengths of different materials to achieve optimal design solutions that meet modern construction challenges.

This literature review is an essential resource that not only consolidates existing information but also identifies critical research gaps and prospective pathways toward additional investigation. It seeks to promote safer, more efficient building techniques in a changing setting and is an essential tool for professionals and scholars researching cold-formed steel structures. The objective of this literature review is to investigate the most recent advances in analytical methods for predicting and mitigating flexural buckling in cold-formed steel structures. It also evaluates the shortcomings of present design codes and standards and makes recommendations based on contemporary research findings. The research also looks at unique technical techniques and procedures for optimizing cold-formed steel structures against flexural buckling, as well as their consequences for the construction industry.

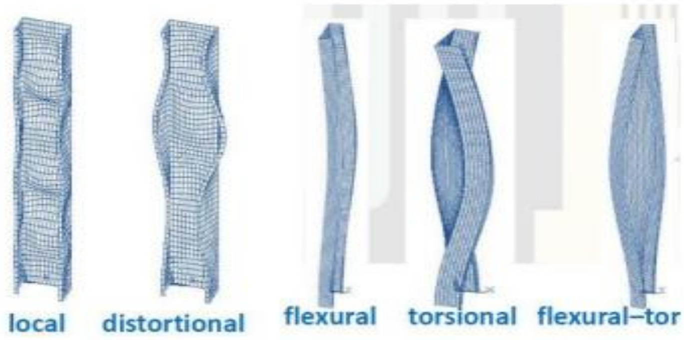

Figure 1. Different forms of Buckling in cold formed steel sections [5].

2. Methodology

This research study's section on the relevance of the research topic focuses on an overview of the journal results that were retrieved from sources like Scopus and Google Scholar. The methodical process for locating and selecting the pertinent papers and journals that have to be part of this study is depicted in Figure 1. With the use of operators like "and," "not," and "or," users of boolean syntax may combine keywords to narrow down their searches and locate certain research papers and publications. This method is supported by databases like Google Scholar and Scopus, where users may search for relevant publications or papers using phrases like instability, flexural buckling, and cold-formed steel. These search phrases aid in locating papers and articles pertinent to the researcher's field of interest. As shown in Figure 2, the main objective of this literature review is to pinpoint and address the researcher's queries.

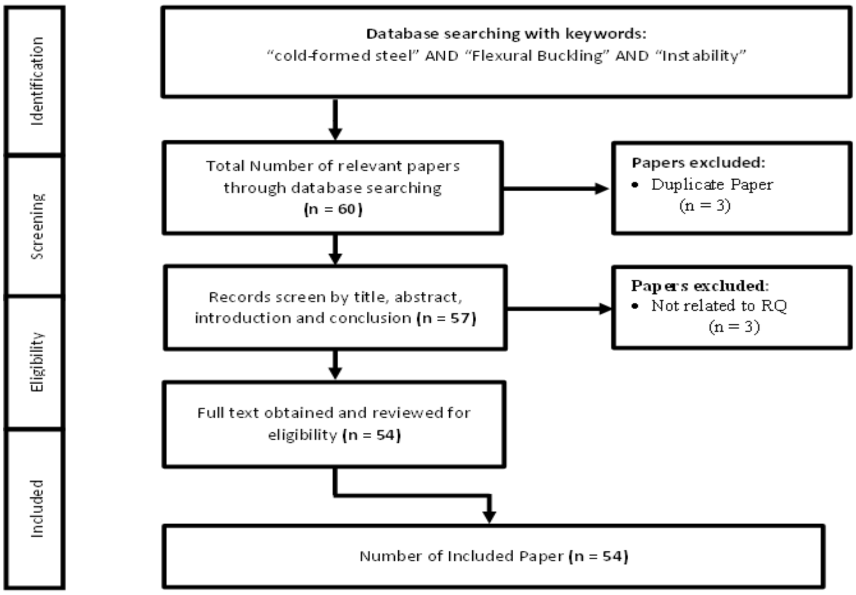

Figure 2. Literature Review Flow Chart.

The aforementioned keyword was used to retrieve sixty (60) related papers and publications from journals and research studies published between 2013 and 2023. Three duplicate papers and three irrelevant articles have been uncovered after a thorough examination and review of each research article's abstract, findings, and conclusion. Therefore, the researcher employs the remaining fifty-four (54) to create this literature review in this respect.

3. Discussion

3.1. Development in the flexural buckling design of Cold-formed steel

The use of analytical tools to predict and minimize flexural buckling in cold-formed steel structures has advanced significantly in recent years. Strong computer simulations, improved understanding of material behavior, and finite element analysis have transformed engineers' approaches to this crucial problem. Flexural buckling is an important factor to consider when designing cold-formed steel structures since it can affect stability and structural integrity [13]. Flexural buckling is an important factor to consider when designing cold-formed steel structures since it has the potential to affect safety and structural integrity. Recent research has resulted in considerable advances in analytical methodologies, allowing for improved design correctness and efficiency. In addition to producing stable elastic buckling solutions, the fastener element shows how the shear stiffness of the screw fasteners used to build standard built-up cold-formed steel components affects global flexural buckling [11]. The behavior of outer stiffened specimens is comparable to that of inner stiffened specimens. In addition to improving lateral confinement on the concrete core, longitudinal stiffeners help postpone local plate panel buckling. Higher flexural rigidities are needed for stiffeners to be effective [14]. A fascinating advancement in the construction sector, cold-formed steel composite buildings combine the strength and longevity of steel with the adaptability of composite building materials. Concrete-dominant composite members will act more like members made of reinforced concrete, while steel-dominant members will act more like structural steel [15]. Design continues to evolve to accommodate more difficult scenarios such as coupled instabilities, loads under numerous actions, stiffness forecasts with cross-section deformation, and system reliability [16]. Table 1 summarizes some of the developments in the design of cold-formed steel with regard to buckling, along with problems and solutions.

Table 1. Recent Development of Cold-formed Buckling Design

Type of Structure	Methodology/Code Used	Key Results and Challenges	Reference
- Columns made of double-skin steel tubular sections filled with concrete	- Experimental Analysis - Finite Element Analysis - Direct Design Method Analysis - North American Specifications	- The outer section's dimensions, member slenderness, and concrete compressive strength significantly affect column flexural buckling, while the inner section's dimensions have a less pronounced impact - Composite columns in the center enhance flexibility, while steel columns at the corners boost overall structural stability.	J. Li et al. [1], H. Debski et al. [7], T. Zhou, et al. [8], R. P. Rokade, et al. [17], G. Beulah Gnana Ananthi and B. Ashvini [18], J. Ye et al. [19]
- Optimized Cold-Formed Steel Columns	- Experimental Analysis - Finite Element Analysis - Direct Design Method Analysis - North American Specifications	- Experimental tests and validated FE models found that optimized CFS columns had up to 35% higher axial capacity than standard-lipped channel columns with the same material. - The effects of nonlinear stress-strain characteristics in CFS fire design guidelines.	R. Senthilkumar et al. [10], M. Rokilan and M. Mahendran [20], S. Selvaraj and M. Madhavan [21], S. F. Nie et al. [22]
- Steel Built-Up Back-To-Back Section Columns	- Experimental Analysis - Finite Element Analysis - Direct Design Method Analysis - North American Specifications	- The DSM expression provides the critical flexural buckling load and the related buckling strength. - The column's stability and strength are increased by widening the flange. In comparison to the strong axis, the axial compression strength falls more quickly along the weak axis. Furthermore, the concentrated axial compression strength falls with increasing slenderness ratio (web height to thickness). - While the amount of composite action in a built-up section is generally improved by more fasteners, the specimen geometry distortions brought on by more screws may also reduce member strength.	K. J. R. Rasmussen et al. [9], D. K. Phan et al. [23], R. Feng et al. [24]
- Beams	- Experimental Analysis - Finite Element Analysis - Direct Design Method Analysis - North American Specification	- The perforated midspan is crucial in aluminum square and rectangular beams with circular perforations under gradient and continuous bending forces.	J. M. Jacinto et al. [25]

3.2. Design Approach for Cold-formed Steel Structure

The design of structures made of cold-formed steel is a multifaceted process that involves a thorough understanding of material properties, a thorough structural analysis, adherence to regulations and specifications, and a focus on sustainability and cost effectiveness. The most popular techniques for cold-formed steel shear walls are the Effective Strip Method (ESM), AISI S400 Standard, AISI S240, Direct Design Method, Experimental Method, Fire Resistance Test Method and ASCE 7-10. These techniques offer a comprehensive framework for ensuring the structural integrity and performance of cold-formed steel shear walls under various conditions. [26]. To ensure safety, efficiency, and cost-effectiveness, cold-formed steel structures must be designed with care and precision. The first step in developing cold-formed steel structures is to have a complete grasp of the properties of the material. Unique characteristics of cold-formed steel include its high strength, ductility, and potential for local buckling. When establishing the suitable section shapes and dimensions, engineers must take these qualities into account.

Because of its durability and applicability, the finite strip method (FSM) is widely used in the field of cold-formed steel design to anticipate elastic buckling. This approach is fundamental to structural analysis because it provides important information for the first elastic buckling solution, which is the foundation for precise strength calculations and design optimization. [27]. The Direct Strength Method (DSM) has evolved over the past 20 years into a thorough method for estimating the strength of CFS members. It strikes a compromise between design economy and the intricacy of thin-walled structures. For almost all cold-formed steel components, localized buckling of thin walls under compression is essential. Within the elastic range, these buckling stays stable, and members that are impacted can still exhibit strong post-buckling strength [28]. Because there are so many different design options available for cold-formed steel structures, engineers and architects are able to meet a wide range of project requirements. Whether driven by simplicity, performance, economy, or seismic resistance, the methodology should be in line with the project's objectives and constraints. Table 2 lists some of the most popular design philosophies for cold-formed steel structures along with a few of its benefits and drawbacks.

Table 2. Advantages and Disadvantages of Different Design Approach

Design Approach	Advantage	Disadvantage	Reference
Direct Design Method	- Member strength is predicted via local, distortional, and global elastic buckling calculations using empirically determined equations. - Investigates and incorporates all stability limit states - Instead of accurately determining empirical effective widths, the technical focus is on accurately determining elastic buckling behavior and the potential for far wider applicability and breadth.	- Combines axial and bending elastic buckling responses using modified linear interaction equations for beam-columns. - There are no restrictions on the quantity or geometry of pre-qualified members, no web crippling techniques, no shear requirements, no provisions for members with holes, and no provisions for cold forming strength increase.	B. W. Schafer [29], B. W. Schafer [30], Z. He and X. Zhou [31], K. S. Sivakumaran and N. Abdel-Rahman [32]
Finite Element Analysis	- Provides a clear model for the cross-sectional areas where the material's ability to support the load is lacking. - Leads to the idea of a local buckling-induced sectional neutral axis displacement in a clean manner. - Provides a clear method for incorporating local-global interaction, affecting global buckling. - The ultimate loads and deformation behavior were in great agreement with the test and finite element findings.	- Ignores compatibility and inter-element equilibrium when assessing elastic buckling behavior (between the flange and the web, for example). - As attempts to optimize the section are performed, defining the effective section gets progressively challenging.	B. W. Schafer [30], Y. Majdi et al. [33], L. Laím et al. [34]
Experimental Methods	- Permits the theoretical models used in the design of cold-formed steel structures to be validated and improved. - Experimental data regarding the performance of cold-formed steel members, connections, and systems serves research, risk assessment, and design purposes effectively.	- It can be challenging to guarantee data reliability and correctness, and inaccurate interpretations could result in false conclusions. - It is frequently time-consuming, especially when studying long-term behavior like creep or tiredness. This can cause research and project timeframes to be pushed back.	L. Laím et al. [35], W. F. Maia et al. [36], Y. Guo and X. Yao [37]
Effective Width Method	- Predicting the ultimate strength of CFS-lipped channel stud columns with holes is both accurate and reasonable. - Simplifies the design process and guarantees that structures meet industry standards.	- Overdesign results in the use of more material than is necessary. This could result in higher construction costs and resource consumption. - There is a lack of consistency in safety margins among projects.	B. W. Schafer [30], K. S. Sivakumaran and N. Abdel-Rahman [32], Y. Xingyou et al. [38], C. Yu and W. Yan [39], A. D. Martins et al. [40]

3.3. Optimizing cold-formed steel structures against flexural buckling

Unique engineering approaches and procedures have been developed in recent years to enhance cold-formed steel structures against flexural buckling, changing the construction sector. The thin walls and open cross-sections of cold-formed steel columns render them more susceptible to torsional stresses. This vulnerability results from the section's shape, which influences how well it can withstand rotating forces. Therefore, in order to guarantee the best possible performance and structural integrity under a range of loading circumstances, thorough consideration of torsional effects is essential in the design and analysis of cold-formed steel structures. The open cross-sections, such as C-sections or Z-sections, lack the torsional rigidity of closed sections, making them more prone to twisting under eccentric or lateral loads. Additionally, the thin walls, while efficient in material usage, are more prone to local buckling and instability, further exacerbating their vulnerability to torsion. Consequently, engineers must carefully design these columns, incorporating adequate bracing and considering the effects of load eccentricities to mitigate the risk of torsional failure [13]. Large interconnection spacing has been shown to be a major cause of built-up doubly symmetric CFS columns failing in flexural torsional buckling or interactive buckling; as a result, the interconnection spacing needs to be taken into account when determining the critical elastic global buckling stress in expressions [21]. Because it affects the global buckling nature, the initial geometrical defect form is significant in the post-buckling (elastic or elastic-plastic) behavior of columns experiencing distortional-global (D-G) interaction [40]. By taking into consideration the impact of fastener stiffness, spacing/layout throughout the member's length, and accounting for shear deformations in the connecting components, the flexural buckling of built-up members may be subtly represented. Fastener stiffness can be captured using a basic element [12]. Flexural buckling is a major concern in cold-formed steel structural design. It happens when slender steel members under compressive pressures fail by abruptly bending or buckling.

Because this occurrence can jeopardize structural integrity, safety, and functionality, its prevention is critical. Shape optimization must include the utilization of a shape generation subroutine to optimize the geometry of the member, but the connectivity or topology may not be greatly altered [41].

Through formal optimization of a long (4.9 m) cold-formed steel column under conditions of global buckling, the efficiency of an S-shaped column with coincident shear center and centroid, almost equal moments of inertia about the principal axes, and reasonably significant warping stiffness is demonstrated [42].

Detailed finite element simulations of the revised sections showed increased axial and bending capacity compared to commercially available baseline sections [43]. Cold-formed steel shapes that have been optimized have substantially higher load capacities than frequently used shapes; one example shows a 300% improvement over the standard C-shape [44]. While multiple optimum forms were obtained for columns depending on the approach utilized, optimization findings for beams are significantly more consistent [45]. Lately, mixed loading scenarios have been added to the list of loading conditions for CFS sections, moving beyond simple bending and compression. Throughout the design phase, several optimization strategies have been applied as a result of this transition. By using these methods, cold-formed steel sections with varying and complicated loading circumstances will perform better structurally and adhere to strict technical standards [41]. These advances' practical implications include cost savings, design flexibility, increased safety, sustainability, and efficiency. Cold-formed steel structures equipped with these procedures will play a critical role in developing safe, efficient, and sustainable buildings as the construction industry evolves.

4. Research Gaps

Due to its lightweight nature, versatility in form, and speed of construction, CFS considerably lowers the cost of mid-rise structures [20]. Local buckling is the main reason for failure and is contingent on the length of the sleeve. The length of the loading apparatus may have an impact on short sleeves, affecting the ultimate load and the place of failure [46]. Many studies have been conducted on the flexural buckling analysis of cold-formed steel structures; however, there is still a large body of unanswered research regarding how these structures function under dynamic loading conditions in the real world. To make educated decisions about maintenance, retrofitting, and replacement, it is essential to have a solid understanding of how cold-formed steel structures evolve with time, particularly those that are utilized in infrastructure and long-span applications. Table 3 shows some of the research gaps from previous research studies used in this study.

Table 3. Research Gaps

Research Gaps/Key Challenges	Reference
- A thorough design methodology for cold-formed steel structures	[4], [10], [16], [29], [35], [47]
- Composite Cold-Formed Steel Structure Failure and Collapse	[1], [8], [11], [12], [13], [29], [36], [48], [49], [50], [51]
- Limited Design Code and Standards	[27], [30], [47], [51], [52]
- Limited Design Methodology and Examination of Various Cold-Formed Steel Structure Types	[28], [29], [35], [51], [53]
- Simplified Design and Approach Procedure for Optimization of Cold-Formed Steel Structure	[41], [42], [43], [44], [45], [54]

The failure and collapse behavior of composite cold-formed steel structures is a topic that has not received much attention in the literature. Simplified design methods and design standards have also not advanced much. The large body of research on the mechanical and structural properties of cold-formed steel structures, especially as they relate to flexural buckling, stands in stark contrast to this vacuum.

This research gap emphasizes the significance of examining cold-formed steel constructions' structural performance and flexural buckling behavior in the context of longevity, material aging, and extended exposure to shifting loads. Closing this gap will help to develop more complete and long-lasting design criteria for cold-formed steel structures, assuring their safety and functionality throughout their existence. Addressing these gaps will not only advance the discipline of cold-formed steel buildings, but will also help to produce more durable, environmentally responsible, and human-friendly construction processes. This understanding is going to promote more informed decisions in construction and retrofitting projects that balance structural efficiency.

4. Conclusions

An important trend in the construction industry is the increasing prevalence of cold-formed steel composite buildings, leveraging the strength and durability of steel in combination with the versatility of composite materials. Design work is moving forward to address more complex scenarios, like coupled instabilities, loads under various forces, stiffness forecasts taking deformation of the cross section into account, and system reliability. The study highlights advancements in flexural buckling design for cold-formed steel structures, utilizing analytical methods like computer simulations and finite element analysis to significantly improve prediction and mitigation. These advancements enhance design accuracy and efficiency. In order to enhance structural performance and stability, the study highlights the significance of longitudinal stiffeners, fastening elements, and the integration of cold-formed steel with composite materials. The advancement of cold-formed steel columns through optimization has resulted in enhanced resistance to buckling and higher axial capacity. Moreover, developments in design methodologies, such as Finite Element Analysis and the Direct Design Method, offer thorough answers to a range of structural problems, enhancing the sustainability, economy, and safety of cold-formed steel constructions. In conclusion, while studying complicated structures, a thorough and multifaceted methodology is required. Even though we now understand a great deal more about the mechanical characteristics and behavior of cold-formed steel (CFS), certain crucial aspects still require more research. It is imperative that researchers and experts work together to tackle these shortcomings and guarantee the continued appropriateness of cold-formed steel structures for the building sector. In order to achieve the main goals of sustainability and safety, this cooperation is necessary.

An advanced and innovative approach to the development of cold-formed steel structures is essential, incorporating advanced engineering principles and state-of-the-art techniques. This approach provides a comprehensive and efficient design strategy, taking into account factors such as material behavior, connection details, and load resistance, to ensure the structural integrity and long-term durability of these systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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