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Performance of Cold-Form Steel (CFS) Sections Under Flexural Action

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Abstract

Cold-form steel (CFS) members have become increasingly popular because of its high strength with respect to weight, low conveying costs, and ease of fabrication and erection. Standard CFS sections generally fail as flexural members where high section modulus is required. For such cases, using built-up sections made up of nesting or back-to-back connection could be a viable solution. The present study extensively reviews recent advances in the design and analysis of CFS under flexural behavior. As per the most recent research in the field, it was revealed that CFS sections could benefit from the addition of stiffeners, namely intermediate stiffeners for closed built-up sections and stiffeners at the flange/web junction for open built-up sections, with or without edge stiffeners. In addition, several investigations of the behaviour of different CFS sections were presented. However, further research is required to determine how to analyse the flexural behaviour of open and closed built-up sections using finite element models (FEM).

Keywords

Built-up section; Cold-Form Steel; CFS; flexural strength; FEA

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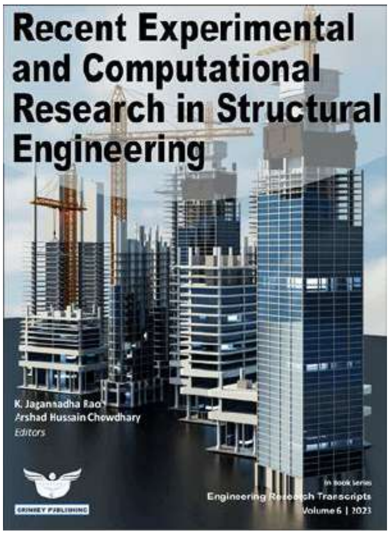

1. Introduction

Complex shapes in cold-form steel (CFS) are achieved by cold-rolling or press-breaking thinner metal sheets. Wall girts, purlins, and stud walls are the most common secondary load-bearing building components and have a wide range of applications. However, in recent decades, the range of applications for CFS has expanded beyond these conventional fields. Also, in composite construction, trapezoidal steel decking made from CFS is frequently used for larger span lengths, such as cladding works and storage brackets [1]. Modernization and standardization in CFS frame techniques have made it possible to use the component exclusively to construct low and medium-rise buildings [2]. Another instance is using CFS in portal frames for manufacturing buildings. In both cases, the principal load-bearing components are made of CFS, making it imperative that they bear more load and comply with longer-span requirements.

The use of CFS structural members has numerous advantages. CFS members particularly have a lower weight to strength ratio, indicating that the material can be used efficiently while also providing tangible sustainability benefits due to their recyclable character [3]. These sections are lightweight, which makes them easy to manage, transport, stack, and mount. They are formed at ambient temperature and can be easily moulded into any kind of required shape [4]. Modern, complicated cross-sectional shapes with intermediate stiffeners, return lips, web openings, and corrugations, etc., are now available in the market as a result of developments in manufacturing technology. Figure 1 shows many commercially available cross-sections, viz. hat sections, sigma section, Z section, hat section with intermediate stiffeners. This adaptability in the production process enables the creation of cross-sections that are highly tailored [5].

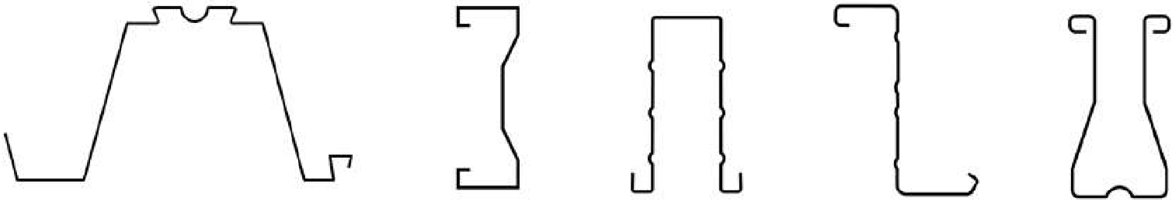

Fig. 1. Various CFS Sections [5]

The 'minimum thickness' of the material that can be employed is the primary structural advantage of CFS components, resulting in a lightweight structure. This, together with the tendency toward higher-strength steel, prevents failure patterns unusual in conventional steel structures. However, when designing CFS members, the responsiveness of these members to multiple buckling (local, distortional, or global) modes may be crucial (Figure 2). However, they may also occur simultaneously and have negative impact on structural capacity. Almost every cold-formed structural steel member needs to consider local buckling in compression because of the thin walls. In the elastic range, local buckling is very strong, and members that have buckled locally may still be quite strong after the initial buckling event. However, local buckling alters a member's behaviour; thus, designers must account for this form of buckling and how it interacts with other buckling mechanisms. Local, distortional buckling and their interaction are responsible for the failure of the lipped channel sections, as studied by Yang and Hancock (2004) [6]. It appears from the results of the tests that distortional buckling and the interaction between them may have a major effect on the strength made from such thin high strength steel.

Another factor complicating CFS design is that, these members are typically open, making them very flexible and torsion-resistant (Figure 3). This involves ensuring loads are delivered to such structures in a way that reduces torsional activity, as torsional, torsional-flexural, and lateral-torsional buckling. The procedures employed to link CFS members are likewise problematic. Welding is employed to a far smaller extent than in hot rolled structures, and numerous connection forms and methods exist, viz. bolts, adhesives, screws, rivets, and other connection types that are formed by deforming neighboring sections to shape the joints. The semi-rigid character of CFS member connections has a significant impact on structural behaviour.

Fig. 2. Buckling Modes [7]

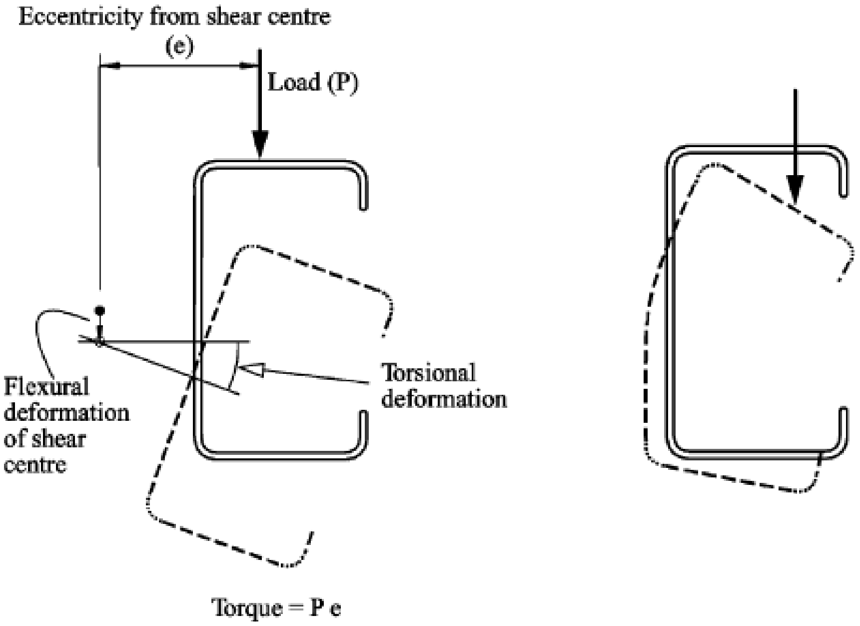

Fig. 3. Torsional and distortional deformations of channel sections [1]

2. Design of CFS

Because of the complexity of cross-sectional geometries and the difficulty of stability concerns in CFS, designing CF members is complex. With the majority of the research work resulting in the formulation of CFS design standards assist designers universally [7].

Several studies have explored the behaviour of CFS sections under bending. Both C and Z sections are examples of standard CFS shapes that are used in modern construction. It is essential for the reliability and effectiveness of CFS structures to have an accurate estimate of the bending behaviour of these sections [8]. Young and Hancock (2002) [9] investigated the CFS Channel section subjected to bending and crippling in an experimental setting. There were three types of tests: pure bending (6 specimens), pure web crippling (12 specimens), and a combination of pure bending and web crippling (32 specimens). An interaction equation for strength prediction under combined circumstances is proposed.

Current CFS sections like C and Z shaped are mostly adopted sections due to their simple forming techniques and connections; yet, they are subject to a number of buckling modes. These buckling modes must be delayed or eliminated altogether if the final capacity of these members is to be increased. There is a need of post-buckling study to examine the load-deflection behaviour. Some techniques may be possible, as stated by Schafer et al. (2006) [10], while others may not be applicable due to boundary circumstances or the specified approach. Flexural-torsional buckling is the primary buckling mode affecting CFS beam capacity. It was reported by Selvaraj et al. (2019a) [11] that the flexural strength of CFS beams was raised by roughly 50% when strengthened with a low modulus CFRP strengthening scheme. Having a substantial impact on the strength of the members, Selvaraj and Madhavan (2019b) [12] advocated for a more conservative approach to the effective design of CFS.

The results of a new set of flexural tests conducted and the impact of web slenderness on the occurrence of failure due to buckling in CFS C, Z section flexural members were studied [13]. To determine how section shape affects elastic buckling moment, the Finite Element Method (FEM) was employed along with the Constrained and Unconstrained Finite Strip Method (CUFSM). Different design criteria were used to evaluate the test and finite strip flexural strengths. The Direct Strength Method (DSM), meanwhile, gave moderate outcomes for both slender and non-slender samples. In addition, CFS Channels with open or closed drop flange profiles were subjected to experimental and numerical studies to determine their strength and behaviour in pure bending. A FEM was created and compared to the test findings. It was demonstrated that finite element analysis (FEA) results agreed well with the investigational statistics. It was found that the flexural strength of closed-drop flange channel beams was greater than that of open-drop beams [14].

Researchers have investigated the bending strength of a CFS Z beam with edge stiffeners that included a lip [15]. Thirty beam samples were tested for combined bending strength using the DSM and confirmed using FEA in accordance with AISI criteria. These beams varied in length, cross-section area, and slenderness of flanges. Flexural testing on comparable sections with intermediate stiffeners was also conducted by Yu and Schafer (2006) [16], who reported that all members failed due to distortional buckling. Compared to Australian norms, the obtained findings are in the lower range. The results were compared to the design strength based on the Canadian, European, Australian/New Zealand, and AISI Specifications and the DSM.

For the purpose of determining the nominal distortional buckling strength of CFS Z and C components during bending, Yu & Yan (2011) [17] suggested an effective width approach. They were compared to DSM results, and additional design considerations for flexural distortional buckling strength were implemented. As compared to obtained results through experimentation, the proposed technique provided a reasonable prediction of the buckling of commercially available sections.

Further, experimental and numerical methods were used to assess the flexural behaviour of complex hat-shaped members, and the results were verified using FEM and the finite strip model (CUFSM) [18]. Systematic parametric study revealed that a geometric defect existing in sections has a major impact on the strength and behaviour. Experiment findings were consistent with AISI requirements. The results, however, are conservative when compared to the Hancock and Winter equations. An experimental study of open U sections and sigma sections found that the depth and thickness of the material directly influenced the strength and failure pattern of the sections under bending. On the other hand, the same is unaffected by the flange width or the location of the applied load [19].

Built-up sections were typically utilized as flexural members if conventional sections could not sustain the rated capacity. There was no design equation to estimate the flexural capability of the built-up section. Georgieva et al. (2012) [20] undertook a systematic experimental evaluation of double-Z built-up members in compression as well as bending. Extensive testing was used to determine the geometric defects of the specimens. Compression members failed when subjected to torsional-flexural buckling, while flexural members failed when subjected to distortional buckling.

Moreover, CFS built-up box beam's flexural performance under eccentric and edge stresses was also examined by Serrette (2004) [21]. There was a bend in the box beam due to the eccentric loading and load transfer mechanism. However, with full bracing, the edge-loaded box beam was proven to resist flexural loads of 85-90% of its rated capacity. In addition, Authors have investigated the action of built-up beams with various screw arrangements. The results of the analysis, which combined experimental and numerical data, demonstrated that anticipated strengths were more precise [22].

Table 1 summarizes studies carried out by various researchers on the behaviour of various sections along with varying parameters under bending action.

Table 1. Various CFS Sections under Bending

Type of the CFS member	Investigation	Specifications used	Results	Source
C section	Experimental investigation	AS/NZS (2001)	Strength prediction under combined web crippling and bending circumstances is proposed.	[9]
Z section	Experimental and Numerical investigation.	Canadian, European, Australian/New Zealand, and AISI Specifications and the DSM	Failure as a result of distortional buckling. Results are validated using FEM and FSM	[16]
Hat shaped	Experimental and Numerical investigation.	AISI specification, Hancock equation and Winter equation.	Systematic parametric study revealed that a geometric defect existing in sections has a major impact on the strength and behaviour. Results are validated using FEM and FSM	[18]
Open U section	Experimental investigation	Eurocode 3: EN 1993-1-1-3	Depth and thickness of the material directly influenced the strength and failure pattern of the sections under bending	[19]
Sigma section	Experimental investigation	Eurocode 3: EN 1993-1-1-3	Effect of flange width and point of load application is insignificant.	[19]
Built-up box beams	Experimental and Numerical investigation.	AISI specification	Edge-loaded box beam was proven to resist flexural loads considerably.	[22]

3. Modes of Failure

Under bending and non-pure bending loading situations, twenty-four channel specimens were tested, including three distinct cross-sections with vertical, inclined, and complex edge stiffeners [23]. The beams' strength and behaviour were investigated using ANSYS. The design results closely matched the experimental work. Non-pure bending was shown to have more bending strength than pure bending. Providing edge stiffeners in the channel portion, on the other hand, was discovered to consistently improve the specimens' strength and behaviour. Likewise, CFS beams with identical cross-sections (i.e., equal area and width-to-height ratio) subjected to bending were studied under two different loading circumstances to determine the strength and behavior of these beams [24]. Both the beams' strength and behaviour were thoroughly studied using the FEA programme. The failure mode was highly consistent with that seen in the experiments. Anti-symmetrical bending in the beam section increased its load capacity in comparison to conventional CF I-beams and with double flanges.

Pham et al. (2013) [25] investigated the behaviour and strength of a variety of CFS C-sections in pure bending. The study looked at both standard C-sections and special (SupaCee) CFS sections: plain C-sections with 4 longitudinal stiffeners and return lips on web and the flanges respectively with varying thickness and sectional depths were evaluated for local and distortional buckling throughout a range of beam lengths. The ultimate strength of the SupaCee was more than the strength of plain C-sections impacted by local buckling. It was discovered that DSM measured the strength of these flexural parts with adequate precision for practical uses. Chakravarthy et al. (2017) [26] investigated the ultimate strength and design of built-up steel sections using an experimental and American (AISI-2007) standard approach. For the experimental tests, two CFS channel members were joined back to back to produce built-up I section. Plain and carbon fibre reinforced polymer (CFRP) built-up strengthened columns were developed. In a series of parametric trials, two alternative thicknesses and column lengths were utilized. Using the modular ratio concept approach, the test results were compared to AISI and the recommended design equation.

Despite the fact that the differential equations that describe the behaviour of thin-walled metal objects are known, only a few studies have found explicit solutions. As a result, the emphasis has shifted to numerical solutions. The investigation of global buckling (both lateral and lateral-torsional) of beams is the most beneficial to find the same.

4. Numerical Analysis

When it comes to numerical approaches for solving governing differential equations, the FEM is by far the most popular choice. In theory, appropriate FEM can model all required phenomena. Various researchers have developed non-linear FEM for CFS and validated it against experimental data. It was observed that, the FEM does account for the presence of initial geometric flaws and material nonlinearities but not for residual stress. Therefore, extensive parametric analysis was performed with the developed FEM to examine the impact of the moment gradient on buckling [27]. Schafer (2002) [28] provided a comprehensive procedure for determining the sectional properties of latticed elements for which no standard method existed previously. Using two reduction factors, βm and β for moment of inertia and torsional constant respectively, they showed that laced bar or battens and their connections could transfer shear flow, proving the structural soundness of latticed elements. Also, new equations for determining sectional properties for seismic analysis and capacity estimate were presented.

To produce an accurate prediction for the most popular sections, researchers have looked at the bending behaviour of various sections. The characteristics of the specimen were selected to enhance the emergence of local buckling while preventing the occurrence of distortional and lateral-torsional buckling [13]. The study revealed inconsistencies between the AISI and CSA's design rules for stiffened web parts subject to a stress gradient. It was observed that, for both thin and short specimens, the DSM provided the best test-topredicted ratios, and several advancements in elastic buckling and successful width measurements for channel and zed sections are achievable.

When investigating the CFS sections' web-crippling behaviour, FEM was extensively used. Through FEM Ren et al. (2006a) [29] simulated web crippling in CFS channels subject to both exterior end and inner flange loading (EOF & IOF). As a technique of accurately assessing web crippling strengths within an appropriate safety margin, it was recommended to modify design formulas based on plastic theory. Parametric experiments using the confirmed FEM showed that the AISI interaction equations for combined effect of crippling and bending were usually conservative for CFS channels with web slenderness limitations ranging from 8 to 109. With the help of a FE non-linear analysis, In order to model the behaviour of flexural CFS channel sections with complicated edge stiffeners under pure bending, a finite element model (FEM) was developed by researcher [10]. Existing experimental data validated the suggested model's accuracy. Nonlinearity in the materials and geometry were also included in the model. This research finds that the flange element's complex edge stiffener enhances its bending strength, overall behaviour, and minimizes its local buckling. In addition, it was demonstrated that the DSM was conservative when predicting design strength for the CFS channel section with complex edge stiffeners, but the AISI was typically optimistic.

A cold-formed mono-symmetric open-section beam with sinusoidal corrugated flanges was studied to determine its ideal design under pure pending and uniformly distributed loads [30]. Parametric tests were conducted with varying the section's length, flange width, and the thickness. The section's flexural strength was enhanced and its behaviour was improved due to the corrugated flanges, which were not present in non-lipped channel sections or those with rectangular corrugations. The double box and lipped flanges of the plain C-section were analyzed. The Finite Strip Method's numerical predictions were verified, leading to the development of a novel C section featuring two box flanges. The twin box flanged C-sections performed better than the standard design. Further, the local buckling mode with a CFS lipped channel beam was investigated [31]. The research of plastic strains showed the location and proliferation of strains, as well as the type of failure mechanisms. The behaviour of CFS Lipped Channel beams after buckling has been studied numerically under uniform major axis bending with a local-distortion mode. The study concluded that beams had geometric defects formed in the flange and web in the form of displacement, and the effects of these imperfections on the bending behaviour of the beams.

Built-up box sections made from CFS C-shape sections were studied by Xu and Sultana (2008) [32] for their flexural responses under eccentric loading. A number of FEA models were simulated in ANSYS to test the reliability of the design methodologies' estimates of ultimate moment capacity. Finally, researchers found that the ultimate moment capacities were most affected by thickness, screw spacing, section depth, and yield stress. Similarly, the built-up girder was developed using a stud section and a track section. In order to do a FE study considering geometric and material nonlinearities, authors relied on ANSYS (version 10). Parametric analysis was used to examine the relationship between the ultimate moment capacity of CFS built-up box girders and their thickness, depth, screw spacing, support condition, and material yield stress. More than thirty FE tests were performed, each investigating a different combination of thickness, depth, screw spacing, flange and yield stress in the material. Sabbagh et al. (2011) [33] investigated seismic moment-resisting frames that incorporate CFS beams with curved flanges. Researchers found that the new cold-formed beam cross-section and connection had very good ductility. This study indicates that curved flange beam sections can be used to overcome the width/thickness ratio constraints and delay the local buckling failures.

An in-depth review of the relevant literature has allowed for the acquisition of the necessary information in the following areas: a) CFS section used as flexural members; b) CFS design criteria; c) Failure modes; d) Current design specifications and procedures; and e) FEA and experimental review of CFS beams. Various studies on CFS sections revealed that flexural members, such as C, Z, and hat sections, are more susceptible to structural instabilities than other types of CFS sections because of the geometry of these sections. On the other hand, buckling behaviour can be affected by the monosymmetric structure of the C-sections. Cold working during the fabrication of CFS sections can impact the mechanical properties of CFS. This is due to the fact that cold working can produce strain hardening and strain ageing. When developing CFS members, the consequent changes in material properties must be considered in order for the resulting members to achieve optimal structural efficiency. The present design guidelines consider the average yield strength of CFS Sections, allowing this phenomenon to occur.

The local and post-buckling strength influence CFS member design. To create cost-effective structural members, these buckling processes must be incorporated into the design. It is also a crucial factor because rigidity of an open section is related to thickness, resulting in poor torsional rigidity. Flexural - torsional buckling is a critical failure mechanism that affects the usefulness of CFS beams. However, there are no precise design principles accessible in the current standards to address this problem. Examining the flexural behaviour by FEA has been done before. When the beam is modelled with reasonable geometric imperfections, residual stresses, loading, and boundary conditions, it is shown that FEA can reliably forecast the CFS's structural behaviour.

5. Conclusion

The experimental, theoretical, and computational methods for studying flexural behaviour were evaluated by a literature survey. There are a lot of techniques to increase the strength and performance of CFS members that are determined by the material and sectional properties. A large body of research has been done on the behaviour of both single and composite CFS subjected to flexural loads. Intermediate stiffeners for closed built-up CFS sections and stiffeners for flange/web of open built-up CFS shall be used with or without edge stiffener to improve flexural strength, as noted. The study's future scope could include formulating an experimental programme that generates observations and findings that can be used to build FEMs and conduct analytical research into the flexural behaviour of CFS open and closed built-up sections.

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