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Application of The Continuous Strength Method in Investigating Sectional Capacities of Cold-formed Steel Rectangular Hollow Columns

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Abstract

The existing guidelines for structures made from cold-formed steel are based on the simplified assumption of how the material behaves plastically. The stress-strain response of the material, however, is more intricate due to the impact of strain hardening resulting from the cold-forming processes. Strain hardening is the term used to describe the increase in strength beyond the yield stress as a result of plastic deformation during the cold-forming process. This results in overly cautious estimations according to the current standards when compared to the actual strength of cold-formed steel sections. Therefore, this paper introduces a novel design approach known as the Continuous Strength Method, which takes into account the effects of strain hardening when designing cold-formed steel sections for compression. The paper subsequently using this method carries out an investigation of such sectional capacities regarding the variety of material properties in comparison with the strength predictions outlined in the Eurocode.

Keywords: Sectional capacities; The Continuous Strength Method; Cold-formed steel; Rectangular hollow columns; Cold-forming process

Abbreviations: CSM: Continuous Strength Methd; EWM: Effective Width Method

Introduction

Cold-formed steel structures have been widely used in construction projects due to their merits over traditional steel structures [1]. Many countries around the world have established design standards for this type of structure, providing a basis for practical applications [2]. These standards are fundamentally based on the elastic-plastic behaviour of steel material along the ideal stress-strain curve. However, this stress-strain curve has become much more complex due to the influence of strain hardening phenomena, as presented in Hancock et al [1]. As a result, the application of current standards has shown to produce overly conservative design results when calculating structures operating through the linear phase of material behaviour, as mentioned in [3]. Therefore, Gardner proposed the Continuous Strength Method (CSM), considered a new calculation method in cold-formed steel section design. It acknowledges the influence of cold hardening due to the forming process, allowing the utilization of material beyond the yield limit and enhancing the efficiency of the design [3-5]. The CSM method has been successfully applied in proposed designs for stainless steel structures and aluminium structures, demonstrating its advantages [6-8].

The goal of the paper is to introduce the Continuous Strength Method and its application in determining the sectional capacities of cold-formed steel columns. The method is then applied to investigate the capacities of rectangular hollow cold-formed steel sections. This investigation is conducted in comparison with the capacities calculated according to the current European Standard [9] using the Effective Width Method (EWM). The study considers variations in section thickness and material strength. The obtained results provide deep insights into how the material's strain hardening affects the sectional capacities of rectangular hollow cold-formed steel columns.

The Continuous Strength Method in the determination of sectional capacities of cold-formed steel columns

Gardner introduced and developed the Continuous Strength Method to analyse the behaviour of steel materials beyond the elastic range. This method is particularly effective when considering the cold-forming process, where the plastic range becomes unclear, and it can be applied to various types of steel or aluminium alloys. The Continuous Strength Method is built upon the foundation of the European Standard EN 1993-1-3 [9], but it also includes some specific adjustments: 1) Instead of providing classifications of cross-sections as specified in the European Standard EN 1993-1-3 [9], this method introduces the concept of non-dimensional deformation capacity of cross-sections determined based on experimental data; 2) The design process considers the stress-strain curve of the steel material, including the strain hardening effects.

This approach is based on a combination of the base curve and material model. The base curve, formed based on the output results of experiments, describes the relationship between the nominal deformation capacity of the cross-section and its slenderness. This deformation capacity is defined as the ratio of strain at the ultimate load point to the stress at the yield point, while slenderness is described as the square root of the ratio of yield stress to the elastic buckling stress of the section. This slenderness is subsequently multiplied by the ratio $(c_{flat}/c_{cl})_{max}$, representing the relative value of the width of the flat part to its centreline, as expressed in Equation (1), where c_{flat} and c_{cl} respectively represent the width of the flat part and its centreline, $\sigma_{cr,cs}$ is the local buckling stress.

With the material model, it is characterized by linear behaviour, followed by the strain hardening range, as described in Figure 1. In this figure, E is Young's modulus in the elastic linear range, while Esh is the slope of the strain hardening range, determined by Equation (2). The parameters (f_y, f_u), $(\varepsilon_y, \varepsilon_u)$ represent stress and strain components corresponding to the yield and ultimate limit states of the material. These concepts can be further understood in the reference document [10].

$$\bar{\lambda}_p = \sqrt{\frac{f_y}{\sigma_{cr,cs}}}\left(\frac{c_{flat}}{c_{cl}}\right)_{max} \quad (1)$$

$$E_{sh} = \frac{f_u - f_y}{0.16\varepsilon_u - \varepsilon_y} \quad (2)$$

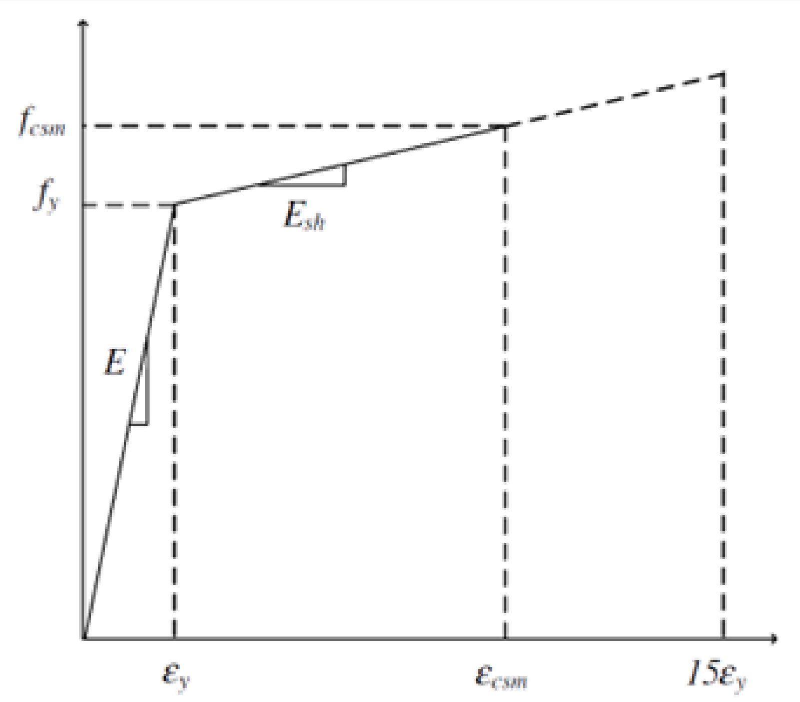

Figure 1: The stress-strain material model [5].

The Continuous Strength Method (CSM) is only applicable if the slenderness of the cross-section determined by Equation (1) is less than or equal to 0.68 as in reference [10]. When ductility exceeds 0.68, the capacity of the cross-section is calculated according to the guidelines of the European Standard EN 1993-1-3 [9]. In cases of high slenderness, the elastic buckling stress decreases significantly, increasing the ability of local buckling, leading to section failure at stress values lower than the yield stress. The determination of the capacities of cold-formed steel sections under compression is presented as follows:

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$$N_{c,Rd} = N_{csm,Rd} = \frac{Af_{csm}}{\gamma_{M0}} \quad (3)$$

where A is the sectional area and f_{csm} is the limiting stress, as determined in [6-8].

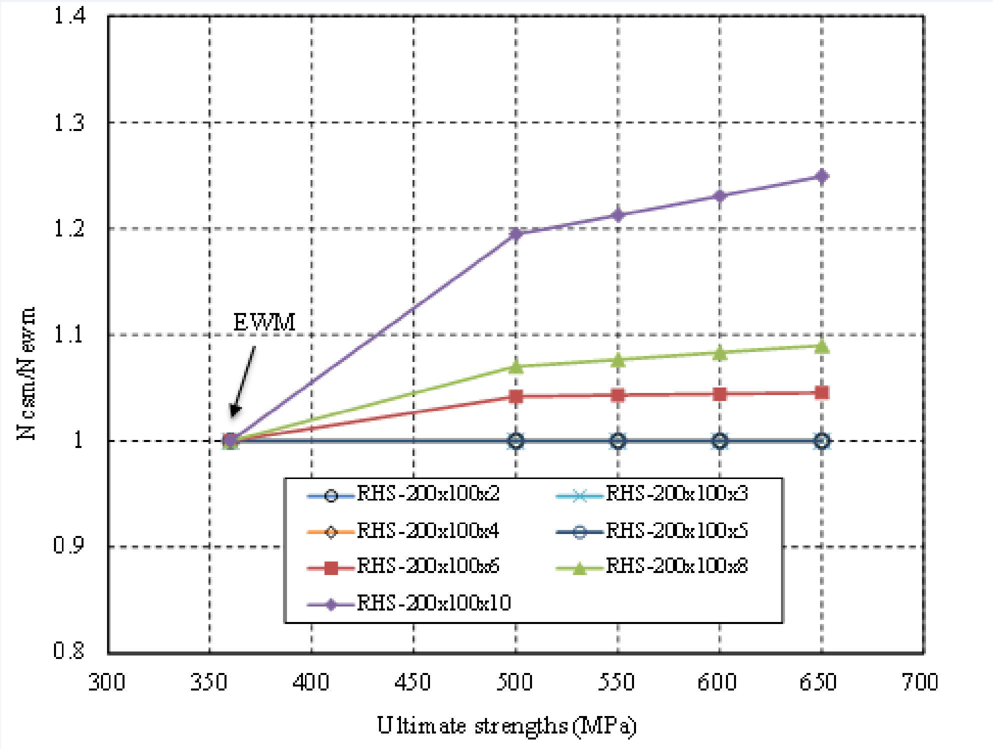

Figure 2: The ratios of sectional capacities between CSM and EWM
Note: NCSM, NEWM are the sectional capacities calculated by The CSM and EWM methods, respectively.

Investigation of sectional capacities of cold-formed steel rectangular hollow columns

The paper conducts an investigation based on cold-formed steel hollow sections according to the European Standard EN 10219 S355J0H [12]. The material has a minimum yield strength of 355 MPa and ultimate tensile strength ranging from 470 MPa to 680 MPa. This investigation utilizes hollow sections with dimensions of 200mm × 100mm and thicknesses ranging from 2mm to 10mm, as specified in Table 1. The influence of strain hardening is examined by varying the ultimate tensile strength of the material, with values ranging from 500 MPa to 650 MPa, and the yield strength, set at 360 MPa.

From Table 1, it is evident that the Continuous Strength Method is not applicable if the local buckling occurs because this would lead to section failure before reaching the yield limit, as observed for sections with thicknesses ranging from 2.0mm to 5.0mm. As the section thickness increases, the stability of the section also increases, allowing the ultimate stress of the section to surpass the yield limit. Therefore, the Continuous Strength Method is applied and has shown its effectiveness in increasing the load-bearing capacity of the section by approximately 5% for sections with a thickness of 6.0mm and up to about 25% for sections with a thickness of 10mm. These comparisons are also illustrated in Figure 2. Regarding the influence of the ultimate tensile strength, the results indicate that varying this parameter has a negligible effect on the compressive load-bearing capacity of the sections, with differences of less than 5% observed for ultimate tensile strengths ranging from 500MPa to 650MPa.

Conclusion

The paper examined the changes in material behaviour related to strain hardening phenomenon during the forming process of cold-formed steel sections. This variation is considered in design through the application of the Continuous Strength Method in determining the capacities of cold-formed steel sections. The paper subsequently also investigated of the capacities of a series of cold-formed steel rectangular hollow sections with different

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thicknesses to assess the influence of strain hardening on the sectional capacities of such sections. The obtained results have demonstrated the effectiveness of applying the Continuous Strength Method (CSM) in determining the capacities of cold-formed steel sections with large thicknesses.

Table 1: The sectional capacities of cold-formed steel rectangular hollow columns (Unit: kN).

Cross sections	EWM	CSM with the variations of ultimate strength (MPa)				Δ (%)
		500	550	600	650	
200×100×2.0	130.81	-	-	-	-	-
200×100×3.0	293.84	-	-	-	-	-
200×100×4.0	589.92	-	-	-	-	-
200×100×5.0	890.98	-	-	-	-	-
200×100×6.0	1187.84	1237.75	1239.04	1240.37	1241.71	4.53%
200×100×8.0	1608.81	1721.95	1732.25	1742.83	1753.55	8.99%
200×100×10.0	1982.77	2369.04	2404.21	2440.33	2476.93	24.93%

Note: EWM stands for Effective Width Method; CSM stands for Continuous Strength Method.

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