Probabilistic Buckling Analysis on Light Steel Compression Members

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Abstract. Cold-formed steel sections are thin-walled structural members with high width-to-thickness ratios, making them highly susceptible to initial geometric imperfections that may reduce their buckling capacity. Although SNI 8399:2017 specifies allowable limits for imperfections such as bow, twist, and camber, it does not provide a quantitative assessment of their influence on column strength reduction. This study aims to evaluate the effect of geometric imperfections on the compressive capacity of cold-formed steel columns using a probabilistic approach. The research adopts the geometric imperfection measurement technique used by Pariatmono (1994), in which circumferential data are transformed into linear coordinates. Imperfection data were collected at 6° intervals, yielding 60 measurement points for each specimen. Each imperfection profile was reconstructed through Fourier analysis, producing Fourier coefficients for 60 columns. These coefficients were then processed to obtain mean values and variations at ±10%, ±20%, ±30%, ±40%, and ±50% of the standard deviation, resulting in 11 imperfection models. All models were subsequently analyzed using nonlinear buckling analysis in ANSYS Workbench 2022 R1 to determine their influence on compressive behavior. The results indicate that geometric imperfections significantly affect the buckling capacity of cold-formed steel columns. However, the available probabilistic data are insufficient to establish generalized imperfection limits for design purposes. Further studies with larger datasets are required to develop more representative tolerances.

1 Introduction

1.1 Background

The series of processes experienced by the C+ profile material (**Fig. 1**) is illustrated in the form of a flower diagram, which explains the sequential stages of profile forming (**Fig. 2**).

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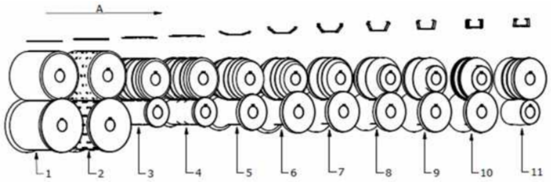

Fig. 1. Stages of C+ Profile Forming

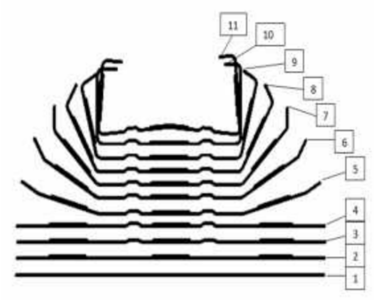

Fig. 2. Flower Diagram of C+ Profile Forming

Based on **Fig. 3**, the influence of the number of roll-forming stages can be described as follows: (a) too few forming stages may distort the product due to excessive elastic strain beyond the acceptable limit of the metal, resulting in edge waviness; (b) an optimal number of forming stages should be considered; and (c) too many forming stages may lead to non-competitive tooling and inefficient production [13].

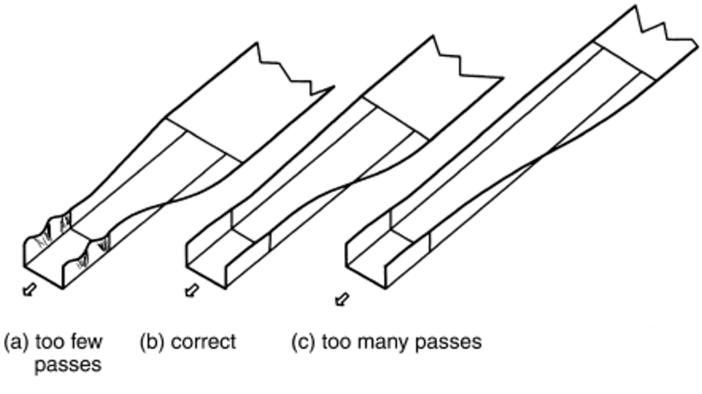

Fig. 3. Effect of the number of forming stages on forming results

Similar to other man-made structures, cold-formed steel members are not free from deviations from their ideal geometric profiles [14]. These deviations are referred to as geometric imperfections, whose forms and magnitudes largely depend on the skill of technicians operating manufacturing equipment, typically press brake machines [2]. The stability of thin-walled lightweight steel members can be significantly affected by geometric imperfections [3]. Then, **Fig. 4.(a)** shows an ideal cross-section followed by various possible types of geometric imperfections [**Fig. 4.(b–i)**].

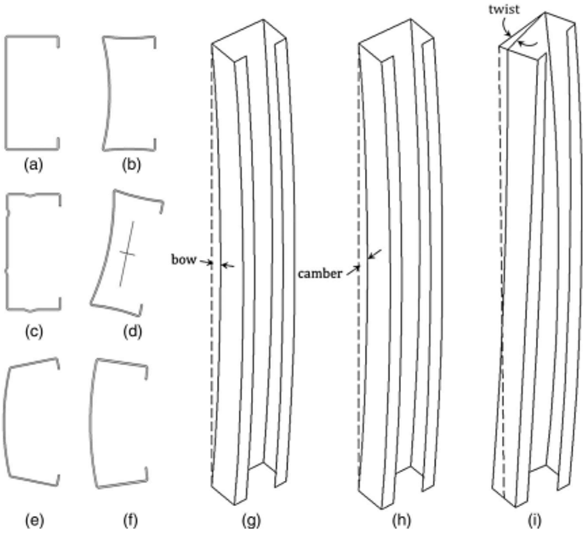

Fig. 4 Types of Geometric Imperfections in Cold-Formed Steel (CFS) Members: (a) ideal cross-section; (b) crown; (c) dent; (d) torsion (cross-sectional view); (e) flare; (f) overbend; (g) camber; (h) curvature; (i) twist (global view) Source: [12].

1.2 Analysis of Geometric Imperfections

Various methods have been used to measure geometric imperfections in lightweight steel. Some studies conduct direct measurements in laboratory settings, while others scale imperfection values based on data obtained from experiments carried out by previous researchers [4]. In this study, however, geometric imperfection data were obtained through analogy with data from prior research [5].

The concept of analogy, according to [11] refers to an attempt to draw conclusions by substituting what is being proven with something similar but more familiar, and then inferring conclusions related to the original reasoning. Defines analogy as a process of reasoning from one phenomenon to another similar phenomenon, concluding that what occurs in the first phenomenon will also occur in the second [1] . Similarly, [6] describes analogy as a reasoning process used to draw conclusions based on similarities with another object or phenomenon.

Previous researchers have conducted studies on lightweight steel using various configuration modifications, such as back-to-back sections, back-to-back sections with gaps, back-to-back sections with perforations, as well as single profiles. These studies analyzed buckling behavior using both linear and nonlinear approaches, and some included measurements of geometric imperfections and material properties. However, none of these studies performed nonlinear buckling analysis incorporating geometric imperfection analogy and probabilistic buckling analysis [5]. Therefore, this study aims to conduct a nonlinear buckling analysis that incorporates geometric imperfection analogy and probabilistic buckling behavior [12].

2 Method

This study employed a probabilistic nonlinear buckling analysis approach focused on cold-formed steel compression members. Secondary data of geometric imperfections were obtained from previous experimental studies and adopted using an analogy method. The imperfection shapes were modelled using Fourier series representation, where Fourier coefficients describe the amplitude and distribution of imperfection modes along the member length.

Statistical analysis was conducted to define the probabilistic distribution of geometric imperfections. A range of imperfection profiles was generated based on mean values and standard deviations. These profiles were then introduced as initial geometric imperfections in a finite element (FE) model. Nonlinear buckling analysis was performed using ANSYS Workbench, considering material nonlinearity and geometric nonlinearity. Parametric studies were conducted to evaluate the influence of imperfection magnitude on buckling capacity.

3 Results and discussion

3.1 Results

The results indicate that geometric imperfections have a significant impact on the buckling behavior of lightweight steel compression members. Imperfection magnitudes within the allowable limits specified by design standards resulted in noticeable reductions in load-carrying capacity, with a maximum observed reduction of approximately 29%. This finding confirms the high sensitivity of cold-formed steel members to initial geometric imperfections.

The geometric imperfection shapes, after interpolation, are transformed into a vertical axis, which will later be selected as the geometric imperfection data for cold-formed steel columns after a probability analysis is conducted to determine the data to be used in the buckling analysis of cold-formed steel compression members. **Fig. 5** presents the interpolation graphs of geometric imperfection data at 6°, 12°, and 18°, from rows 1 to 40. The x-axis represents the slant height of the truncated cone, while the y-axis represents the magnitude of geometric imperfection in millimetres.

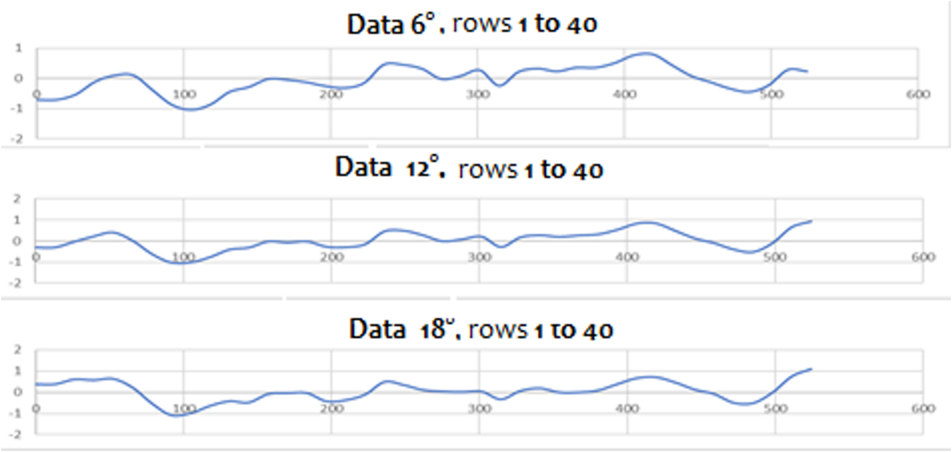

Fig. 5. Graph of geometric imperfections in members at 6°, 12°, and 18°, rows 1 to 40.

3.2 Discussion

Based on the study, the trend of P/Pe versus δtotal/L for all specimens shows that the reduction in load capacity due to geometric imperfections does not exhibit a linear relationship with the magnitude of the imperfection. The member with (mean +10% stdv.) has a lower load capacity (28 N) than the (mean +20% stdv.) member (28.5 N). For (mean +30% stdv.), (mean +40% stdv.), and (mean +50% stdv.), the load capacity decreases sequentially to 28.4 N, 28.1 N, and 27.9 N, respectively.

For the (mean –20% stdv.) member, the load capacity is close to the critical load Pcr, at 39.1 N, while the (mean –10% stdv.) member shows a lower capacity of 36.7 N. For (mean –30% stdv.), (mean –40% stdv.), and (mean –50% stdv.), the load capacity further decreases to 36.7 N, 35.8 N, and 35.7 N, respectively.

The expected trend where larger geometric imperfections lead to lower load capacity was not consistently observed. This is attributed to the presence of both positive and negative mean values of the Fourier coefficients. Positive values indicate outward geometric imperfections, while negative values indicate inward imperfections relative to the member axis. This indicates that the reduction in load capacity is influenced not only by the magnitude but also by the shape and direction of the geometric imperfection in compression members.

The maximum geometric imperfection at midspan for all specimens is less than 1 mm per 100 mm. This remains below the limit specified in SNI 8399:2017, Clause 6.5.3, which allows a maximum of 1 mm per 1,000 mm length for C, Z, and U sections (for bow and twist), while lateral camber for lengths of 3,000 mm or more must be straight when placed. Imperfections below 1 mm per 1,000 mm are within tolerance. However, Table 4.10 shows P/Pcr values ranging from 0.995 to 0.71, corresponding to a load capacity reduction of 0.458% to 29%, indicating the need for further study on allowable geometric imperfection tolerances for cold-formed steel members.

4 Conclusion

This study demonstrates that the buckling behavior of cold-formed steel compression members is strongly influenced by geometric imperfections and exhibits probabilistic characteristics. Nonlinear buckling analysis incorporating geometric imperfection analogy provides a more realistic representation of structural behavior than conventional linear methods. Significant reductions in buckling capacity were observed even for imperfection levels within current design tolerances. Therefore, probabilistic approaches should be considered in the design and evaluation of lightweight steel structures. Further experimental measurements and advanced probabilistic modeling are recommended to improve imperfection representation and support the refinement of design standards.

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