Comparative Study of Hole Stiffeners for Improved Compressive Strength of Cold-Formed Steel C-Section Members

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Abstract: Cold-formed steel (CFS) is widely used in construction due to its high strength-to-weight ratio and versatility, with web holes providing utility accommodation; however, existing local design provisions for CFS sections with holes lag behind current research. The primary objective of this study is to evaluate the influence of different stiffener configurations (one-sided web, two-sided web, and intermediate stiffeners) on the structural integrity of CFS sections with holes. Forty-five specimens were categorized into solid, one-holed, and two-holed sections. The specimens were subjected to axial compressive loads using a hydraulic jack setup and monitored using displacement transducers and a load cell, while visual inspections were conducted to identify failure modes and buckling locations. Results revealed that solid members exhibited the highest compressive strength, while the introduction of holes generally led to a reduction in strength. Stiffeners provided limited benefits, with marginal improvements in two-hole web stiffener configurations and no significant effect in one-holed specimens. Notably, the one-sided web stiffener performed best among two-holed members, with an average strength increase of 4.36%. The study concludes that while web stiffeners can enhance the strength of two-holed CFS members, their effectiveness is limited for one-holed configurations. The presence and placement of holes significantly influence buckling behavior, underscoring the need for further research to refine design provisions for perforated CFS members and ensure safety and structural integrity in practical applications.

Key Words: cold-formed steel; stiffeners; axial compressive strength; buckling failure

1. INTRODUCTION

Cold-formed steel (CFS) is widely used in construction due to its high strength-to-weight ratio, durability, and fire resistance, among others. It serves various structural applications such as columns, beams, main frame members, and roof trusses. A notable feature of CFS members is the inclusion of holes to accommodate utilities such as electrical wiring, plumbing, and HVAC systems (Raj & Navas, 2020).

The National Structural Code of the Philippines (NSCP) regulates CFS design primarily based on the American Iron Steel Institute's (AISI) 2007 edition of the North American Specification for the Design of Cold-Formed Steel Structural Members

(AISI S100-07). Latest printing of the NSCP (2nd printing, 7th edition) show CFS design provisions in Chapter 5, Part 3. However, local provisions have not been updated in 15 years and do not include standards for CFS sections with punched holes, as specified in AISI S100-16T. The discrepancy highlights the need for further investigation to ensure that local design guidelines are up-to-date and reflective of current practices.

This study aims to expand the local research on CFS by investigating the effects of stiffeners on the compressive strength of perforated CFS C-section members, building on findings by Quiroga, Guico, and Oropel (2023) that increasing hole length and number reduces compressive strength. Various stiffener configurations (one-sided web, two-sided web, and intermediate stiffeners) are evaluated to determine stiffener effectiveness based on their compressive strength, buckling location, and failure mode.

2. METHODOLOGY

2.1 Materials and Equipment

The CFS C-section members were locally sourced and manufactured by a single supplier, using CNC machines that followed AISI standards. The flat CFS sheets were bent into C-sections, punched with web holes, and bolted or molded to apply the CFS stiffeners.

A manual experimental set-up was used for compressive buckling strength tests using a hydraulic jack, metal end caps, and test frame to simulate concentric loading. Two displacement transducers and a load cell connected to a data logger monitored axial resistance and displacement for analysis.

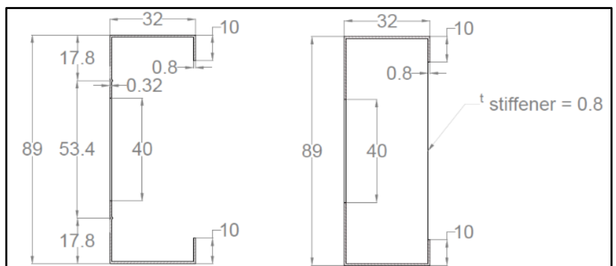
2.2 Research Design

The solid and perforated CFS C-section members were adapted from the sections used by Quiroga et al. (2023). All members have a constant C-section of 89 x 32 x 10 x 0.8 mm and a length of 1000 mm. Holes for perforated specimens measure 40 x 80 mm, with one-hole members having the hole centered at mid-length (L/2 or 500 mm from edge), while two-hole members have them at quarter length (L/4 or 250 mm from edge).

The independent variables are the type of stiffener used and the number of holes, while the dependent variables are the compressive buckling strength, buckling location, and failure mode. The specimens, as summarized in in Table 1, consist of a total of 45 specimens. The specimens are distinguished by hole count (H) and stiffener type (S), encompassing one-sided web (S1W), two-sided web (S2W), and intermediate stiffeners (SI).

Table 1. Summary of Specimens.

Label	Holes	Location	Stiffener	Replicate
H0-S0	0	N/A	No stiffener	5
H1-S0	1	L/2	No stiffener	5
H1-S1W	1	L/2	One-sided web	5
H1-S2W	1	L/2	Two-sided web	5
H1-SI	1	L/2	Intermediate	5
H2-S0	2	L/4	No stiffener	5
H2-S1W	2	L/4	One-sided web	5
H2-S2W	2	L/4	Two-sided web	5
H2-SI	2	L/4	Intermediate	5
		Total no. of specimens		45



(a) With intermediate stiffener (b) With web stiffener *(one and two sides)*

Fig. 1. Cross-section view of the stiffened samples.

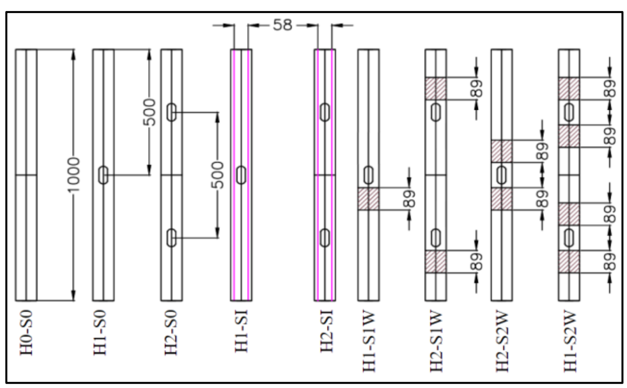


Fig. 2. Side view of samples.

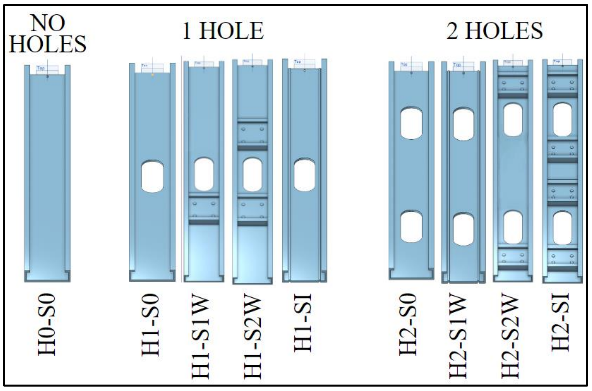


Fig. 3. Three-dimensional view of the samples.

2.3 Material Properties

Samples of the CFS material were tested for its material and strength properties. The yield strength was tested using ASTM E8: Standard Test Methods for Tension Testing of Metallic Materials, resulting in an average of 274.17 MPa. Table 2 presents a summary of the results from the tensile strength tests conducted. The modulus of elasticity was assumed to be 203 GPa, as specified in AISI S100-16 A3.3.

Table 2. Summary of Yield Strength Results of Sample Specimens.

Sample No.	Lower Yield Strength (MPa)
1	274
2	274
3	274
4	279
5	272
6	272
Average	274.17

2.4 Compressive Strength Test

The experimental set-up (Figure 4) subjected specimens to axial concentric compressive loads using a hydraulic jack until failure. Pin-pin end supports were simulated using a ball and socket mechanism to simplify axial force calculations. Customized metal end caps were used to minimize horizontal movement, and a steel bearing ball was aligned to the CFS centroid for precise loading. A load cell was used to monitor axial strength, and two displacement transducers placed at midspan of the web and at the bottom of the steel plate monitored the axial and vertical displacement of the specimen. A digital camera was also employed to observe and record the various ways in which buckling failures occurred.

2.5 Code-based Computation using NSCP

Theoretical computations were conducted using both local (NSCP Section 553 and Section 1) and international provisions (AISI S100-16, Section E) for solid and perforated stiffened members. No code provision is present for perforated stiffened CFS members.


Fig. 4. Actual Experimental Setup.

Failure modes, including distortional and local buckling, were analyzed by calculating yielding and flexural-torsional strengths of CFS members without stiffeners for comparison. The nominal axial strength was determined as the lowest computed or governing strength. This value is utilized to quantify the difference between the experimental and computed strength of the solid and unstiffened perforated member by obtaining the ratio between the two, which is then used as a basis for analyzing the results. Meanwhile, the failure modes of the stiffened perforated members were assessed through visual inspection only.

2.6 Statistical Analysis

Independent sample t-tests were performed in Microsoft Excel to determine significant differences between stiffened and unstiffened members. Normality tests (Shapiro-Wilk) and Grubbs tests were conducted to validate data and eliminate outliers. Scatter plots and regression analysis were also performed for data visualization to compare the experimental results with code-based strengths.

3. RESULTS AND DISCUSSION

The experimental results included the location of buckling and failure modes through a numerical and visual analysis. Results were also compared to values calculated using theoretical standards from NSCP and AISI to inspect its conformity to expected values.

3.1 Experimental Compressive Strength

The experimental compressive strengths of CFS members with zero, one, and two holes using different stiffener configurations are summarized in Table 3.

Table 3. Summary of Experimental Comp. Strengths.

Label	P_{ave} [kN]	P_{ave} vs H0-S0 [%]	P_{ave} vs HN*-S0 [%]
H0-S0	16.4834	-	-
H1-S0	15.276	-7.32%	-
H1-S1W	14.3518	-12.93%	-6.05%
H1-S2W	14.5852	-11.52%	-4.52%
H1-SI	14.2856	-13.33%	-6.48%
H2-S0	15.2846	-7.27%	-
H2-S1W	15.9504	-3.23%	4.36%
H2-S2W	15.6838	-4.85%	2.61%
H2-SI	14.6186	-11.31%	-4.36%

**HN represents H1 or H2*

Solid members showed the highest compressive strength at 16.48 kN, serving as the baseline. One-holed members (H1-S0) exhibited a 7.32% reduction, and adding stiffeners further decreased strength by at least 4.52%. The best-performing stiffener for one-holed members (H1-S2W) still did not exceed the strength of unstiffened members, indicating their ineffectiveness.

Unstiffened two-holed members (H2-S0) showed a 7.27% reduction, while adding web stiffeners (H2-S2W and H2-S1W) improved strength by 2.61% to 4.36%. Independent sample t-tests verified that H2-S1W and H2-S2W did not differ significantly from solid samples (H0-S0), indicating that these configurations may be associated with solid samples. Intermediate stiffeners (SI), on the other hand, caused the greatest strength reduction for both hole variations.

Although the study hypothesized that stiffeners would enhance the strength of perforated CFS members, the results did not align with this expectation. Improvements were inconsistent with the hypothesis and the strength did not fully return to that of solid CFS members.

While holes typically reduce the compressive strength, intermediate stiffeners amplify this effect, likely due to web dimension loss from the manual punching process. Moreover, the strength reduction for web-stiffened samples can be attributed to additional bolt holes, which introduced weak points and compromised structural integrity, diminishing the stiffeners' intended benefits.

3.2 Code-based Compressive Strength

The theoretical calculations considered in this study for unstiffened solid and holed members include three states of buckling: Local Buckling (P_{nl}), Distortional Buckling (P_{nd}), and Yielding, Flexural-Torsional, and Torsional Buckling (P_{ne}), computed using the Direct Strength Method (DSM) as outlined in Section C-1 of AISI S100 and Section 553 of the 2015 edition of the NSCP.

Practical and common use of CFS C-Section members includes perforations for utility purposes, which are not addressed by the formulas in the current NSCP code. DSM was utilized to estimate member strengths without applying effective widths, while still supplementing the main specifications. The most recent edition of AISI S100 has addressed the lack of formulas for computing the nominal axial strengths of perforated CFS members. The summarized computed values for the three limit states are shown in Table 4, derived from standard cross-sectional and material properties collected from CUFSM.

Table 4. Calculated nominal strengths based on the NSCP 2015 and AISI S100-16.

Member	P_{nl} [kN]	P_{nd} [kN]	P_{ne} [kN]
H0-S0	13.72	17.03	23.24
H1-S0	13.53	15.29	22.73
H2-S0	13.45	15.29	22.53

3.3 Experimental vs Code-based Compressive Strength

Fig. 5 presents a comparison of experimental versus code-based compressive strengths for unstiffened cold-formed steel (CFS) members. Due to the absence of standards for web and intermediate stiffened members, the focus remains on unstiffened specimens. The experimental compressive strengths for both solid and holed specimens exceed the predicted local buckling strengths but are lower than those for distortional buckling and yielding, indicating that both the NSCP and AISI S100 provisions provide conservative estimates for these members.

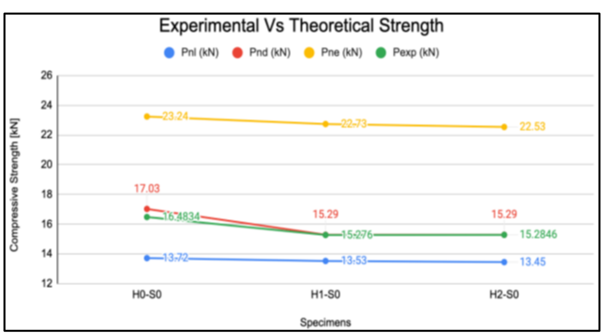


Fig. 5. Comparison of Experimental vs. Theoretical (Code-Based) Compressive Strength.

For example, the unstiffened solid member (H0-S0) exhibited an experimental strength (P_{exp}) of 16.48 kN, surpassing the local buckling strength (P_{nl}) of 13.72 kN, but falling short of distortional buckling (P_{nd}) at 17.03 kN and yielding (P_{ne}) at 23.24 kN. This trend was consistent across all unstiffened CFS members.

Moreover, Fig. 6 further illustrates the relationship between experimental and theoretical compressive strengths. Points above the equality line indicate conservative estimates, while those below are nonconservative. Notably, only the distortional buckling strength (P_{nd}) was found to be nonconservative.

Experimental data for members with web stiffeners, such as the H1-S1W and H1-S2W specimens, showed strengths of 14.35 kN and 14.59 kN, respectively, indicating that web stiffeners generally enhance compressive strength. However, further theoretical analysis is needed for a comprehensive evaluation.

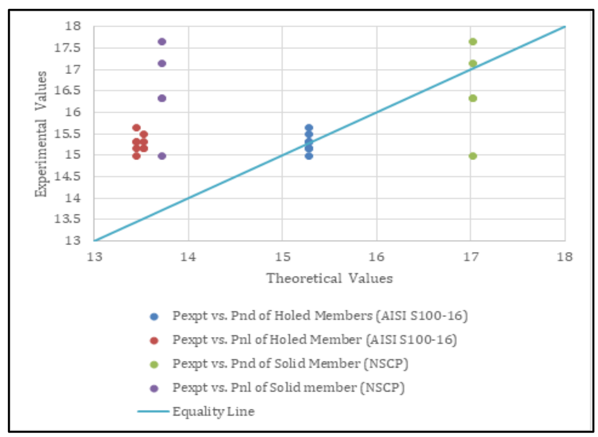


Fig. 6. Experimental vs. Predicted Local Buckling (P_{nl}) and Distortional Buckling (P_{nd}) strengths.

3.4 Failure Modes

For the cold-formed steel samples used in this study, three types of failure modes were examined: local, distortional, and flexural-distortional buckling. Full yielding, where the cross-section reaches its yield stress, was not considered due to the member's slenderness, which makes it more susceptible to buckling.

By visual inspection using a digital camera, it was found that all 112 specimens exhibited both local and distortional buckling, as shown in Figures 7, 8, and 9. Since the sections of the samples were consistent across all cases, the compression tests resulted in similar failure modes. However, the location of buckling varied for solid, one-holed, and two-holed samples. For solid samples, local buckling occurred approximately at the mid-height, consistent with the anticipated behavior for a pinned-pinned member boundary condition. On the other hand, for samples with holes, local buckling occurred along the location of the holes, attributed to the reducing of areas and concentrating stresses. Two-holed samples exhibited an identical failure mode, but only one of its holes experienced local buckling as the other hole experienced minimal to no buckling, remaining unbent but with slight dents as presented in Figure 7 and 9. Moreover, the behavior of the failure modes remained consistent for all cases. Despite the variations in stiffeners, the failure modes and location of buckling are similar for one-holed and two-holed samples as observed in Figures 7, 8, and 9.

Fig. 7. Local buckling of samples without stiffeners: a) solid; b) one-holed; c) two-holed.

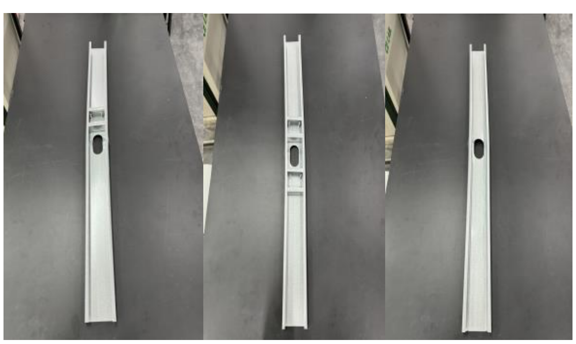


Fig. 8. Local buckling of samples with one hole and with stiffener: a) one-sided web; b) two-sided web; c) intermediate.

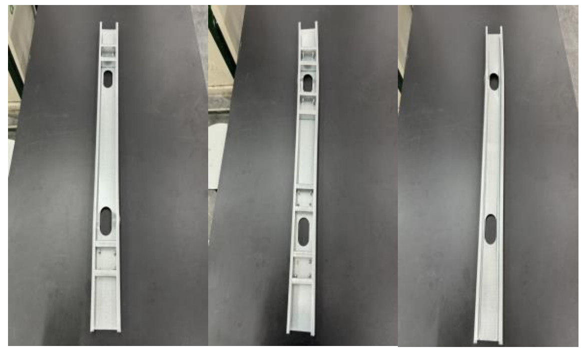


Fig. 9. Local buckling of samples with two holes and with stiffener: a) one-sided web; b) two-sided web; c) intermediate.

3.5 Load Displacement Curves

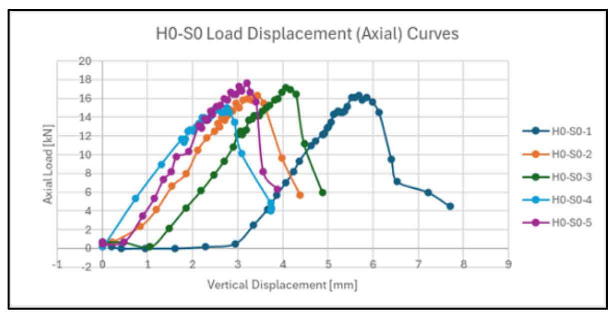


Fig. 10. Graph of Load Against Axial Displacement for H0-S0.

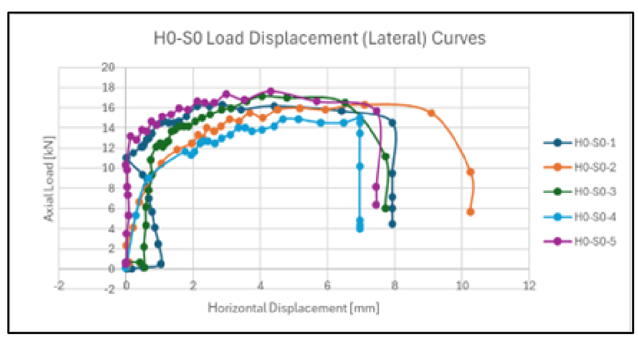


Fig. 11. Graph of Load Against Lateral Displacement for H0-S0.

A displacement transducer positioned at midspan recorded the lateral and axial displacements of the CFS members. The data, plotted against compressive axial load reveals consistent patterns across all specimens.

In the axial load-displacement plots, all specimens exhibited a common trend wherein the axial load increased gradually to the ultimate load before declining. This is typical in compressive strength tests on slender members. Conversely, the load-lateral displacement curves showed an initial rise followed by a sudden drop at the ultimate load, indicating immediate failure or buckling. This pattern was consistent across specimens.

Fluctuations in the curves, especially near buckling, were attributed to support movements and slight decompression of elastic components during loading. Variability in material properties and human factors also contributed to these deviations, highlighting the sensitivity of the test setup to external influences.

4. CONCLUSIONS

The key findings of this comparative study are as follows:

- Web stiffeners significantly improved compressive strength, with one-sided web stiffeners (H2-S1W) performing best for two-holed members, while that of one-holed members showed a slight, non-significant strength reduction.
- Intermediate stiffeners unexpectedly reduced load-bearing capacity, likely due to inconsistencies in ribbing formation.
- Unstiffened members showed consistent results between the theoretical and experimental compressive strength.
- Failure modes included distortional and local buckling, with stiffeners having minimal impact on buckling behavior, which was influenced by hole configuration.
- Load-displacement curves highlighted stiffener effects on lateral and axial displacement, although external factors influenced the results.

Based on these observations, the study recommends:

- Optimizing web stiffener configurations, exploring alternative stiffening options (e.g. edge or knurling), and considering hole placement.
- Developing stiffener simulation tools for predicting stiffener performance.
- Informing future code provisions and design codes, particularly under Chapter 5 of the NSCP (2015 Edition), by recommending clearer guidance on hole configurations and stiffeners. The observed influence of holes and stiffener configurations on the load-bearing capacity and buckling behavior suggests that design standards should incorporate these factors to ensure accurate prediction of member performance.

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6. REFERENCES

Guico, J. J. M., Oropel, Q. A. A., & Quiroga, A. P. G. (2023). Investigation on the Effect of Web Holes in the Compressive Strength of Cold-Formed Steel C-Sections [Unpublished undergraduate thesis]. De La Salle University Manila.

Raj, A. B., & Navas, R. (2020). Study on Stiffened Cold-Formed Steel Sections with and without Web Openings. IRJET. https://www.irjet.net/archives/V7/i6/IRJET-V7I61279.pdf