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Experimental Investigation on the Influence of Web Stiffeners in the Biaxial Bending Capacity of Cold-Formed Steel Z-Purlins

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ABSTRACT

Cold-formed steel Z-sections are widely used as roof purlins in industrial steel buildings. Due to their thin-walled nature, these members are highly susceptible to local, distortional, and lateral–torsional buckling, which often governs their ultimate load-carrying capacity. The flexural strength of Z-sections primarily depends on the mechanical properties of the material and the geometric characteristics of the cross-section. This study experimentally investigates the influence of web stiffeners on the biaxial flexural behavior of cold-formed Z-sections. Three specimens—two without stiffeners and one with an intermediate longitudinal web stiffener—were tested under simply supported conditions to evaluate the effect of stiffening on buckling behavior. The purlins were tested individually, without lateral bracing or roof sheeting, and were loaded in a sloped configuration to simulate actual roof conditions. A concentrated load was applied at midspan, aligned with the shear center of each section. The experimental results revealed that the stiffened specimen exhibited greater ductility and delayed local buckling compared with the unstiffened specimens. The addition of the web stiffener changed the failure mode from local buckling at midspan to lateral–torsional buckling, thereby improving overall stability and load-carrying capacity. It is concluded that introducing a web stiffener effectively enhances the flexural performance and buckling resistance of cold-formed Z-sections by providing additional stiffness and delaying local instability.

Keywords: Cold-formed steel Z-sections, web stiffener, flexural behavior, biaxial bending, local buckling, lateral–torsional buckling

1. INTRODUCTION

In In recent years, the use of cold-formed steel members has increased substantially due to their many advantages, such as a high strength-to-weight ratio, ease of fabrication, structural efficiency, and economic viability. However, because of their relatively large width-to-thickness ratios, cold-formed members are particularly prone to local, distortional, and lateral–torsional buckling, which can significantly compromise their structural performance.

Cheng and Schafer [1-3] proposed the Direct Strength Method (DSM) for the design of cold-formed steel members, which accounts for local, distortional, and global buckling (Fig. 1). The DSM, as developed by Schafer [4], provides a reliable prediction of critical loads without systematic errors and eliminates the need for effective width calculations. Schafer [5] reviewed the development and progress of DSM for cold formed steel design, which was officially adopted in 2004 as an alternative design approach in the North American Specification (AISI S100 [6]) and the Australian/New Zealand Standard (AS/NZS 4600 [7]) for cold-formed steel structures. He also compared the DSM with the effective width method, emphasizing the computational stability and analytical efficiency of DSM in structural design.

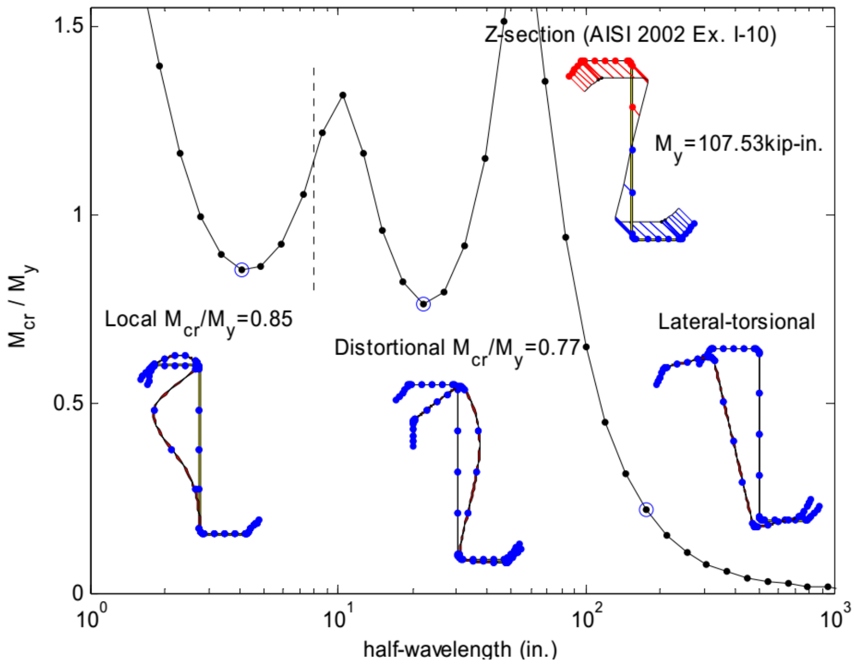


Figure 1. Signature curve of critical buckling for local, distortional, and global modes in the DSM (4)

Nguyen et al [8] proposed a method for calculating critical buckling and yield loads based on two key input variables in the DSM equations, aimed at determining the capacity of thin-walled members under local concentrated loading. Subsequently, Seek and Escobales [9] developed a computational procedure to determine elastic bending stresses in simple C- and Z-shaped cold-formed sections with end torsional restraints and one flange attached to sheathing, as outlined in the AISI-S100 design guide. This approach was employed to evaluate elastic bending stresses and to compute the flexural strength of cold-formed steel members within the DSM framework.

Previous experimental investigations have highlighted the beneficial effects of incorporating web stiffeners in cold-formed steel members. Pham et al. [10] conducted a series of experimental and numerical studies to evaluate the structural advantages of introducing longitudinal flange, web, and edge stiffeners, which enhance buckling resistance, enable higher utilization of yield strength, and allow the use of thinner sections. The primary objective of their study was to assess the suitability of these improved sections for DSM-based design as prequalified cross-sections in the AISI-S100 (6) and AS/NZS 4600 standards (7). Their tests demonstrated that the inclusion of four small longitudinal and edge stiffeners increased the ultimate bending capacity of cold-formed C-sections by approximately 4.5% to 22.4% compared with unstiffened sections.

Wang et al. [11] carried out a comprehensive experimental and numerical investigation on C-shaped cold-formed steel columns incorporating complex edge details and two types of web stiffeners, subjected to both axial and eccentric compression. The program included 18 axially loaded and 12 eccentrically loaded specimens to examine compression capacity, buckling modes, and deformation patterns. The findings revealed that intermediate longitudinal stiffeners effectively reduce the web width-to-thickness ratio, thereby improving the load-carrying capacity under both axial and eccentric loading conditions.

Cold-formed Z-shaped purlins, widely employed in sloped roof systems of industrial buildings, are typically subjected to biaxial bending. Put et al. [12, 13] performed biaxial bending tests on unbraced Z-sections with pinned and sloped supports. A total of ten specimens with five different span lengths were tested under concentrated loading conditions. The results indicated that the flexural strength of unbraced beams decreases as the roof slope increases in the positive direction relative to the horizontal plane, whereas negative slope conditions lead to slightly higher strength.

In the present study, V-shaped web stiffeners were introduced into Z-section members using a pneumatic press-brake machine. Experimental tests were carried out on three cold-formed Z-shaped beams—two unstiffened and one stiffened—subjected to biaxial bending with sloped supports. The load was applied through the shear center to replicate gravity loading under realistic roof conditions. The objective of this research is to experimentally assess the influence of web stiffeners on the flexural behavior, buckling modes, and failure mechanisms of cold-formed Z-shaped sections.

2. METHODOLOGY

2.1. Fabrication of Z-shaped Specimens with Web Stiffeners

The unstiffened Z-shaped purlins employed in this study were fabricated from commercially available cold-formed steel sections with a nominal depth of 180 mm and a thickness of 3.0 mm. In contrast, the stiffened Z-section purlins were custom-manufactured in the laboratory using a sheet-metal press-braking process. For the fabrication of the stiffened purlin, steel sheets were first cut to the required width using a laser-cutting machine (Fig. 2). Subsequently, the sheets were bent with a pneumatic press-brake, where seven consecutive bends were applied along predetermined lines to form the final Z-section.

Figure 2. Preparation of steel sheets for Z-section fabrication.

The dimensional limitations of the press-brake machine presented the primary challenge in fabricating Z-sections with a web stiffener, namely determining the optimal bending sequence to avoid geometric distortion during forming. The process began with a 90° bend along the mid-width of the sheet, followed by two 45° bends positioned symmetrically on either side of the central bend to create the V-shaped web stiffener. Subsequently, two additional 90° bends were introduced at the edges of the web to define its boundaries, and two further 90° bends were applied at the ends of the top and bottom flanges to complete the Z-section profile with a longitudinal web stiffener, as illustrated in Fig. 3. The bending angles were precisely controlled according to the applied forming force, while the bending radius was selected based on sheet thickness to ensure dimensional accuracy and to prevent localized cracking during forming.

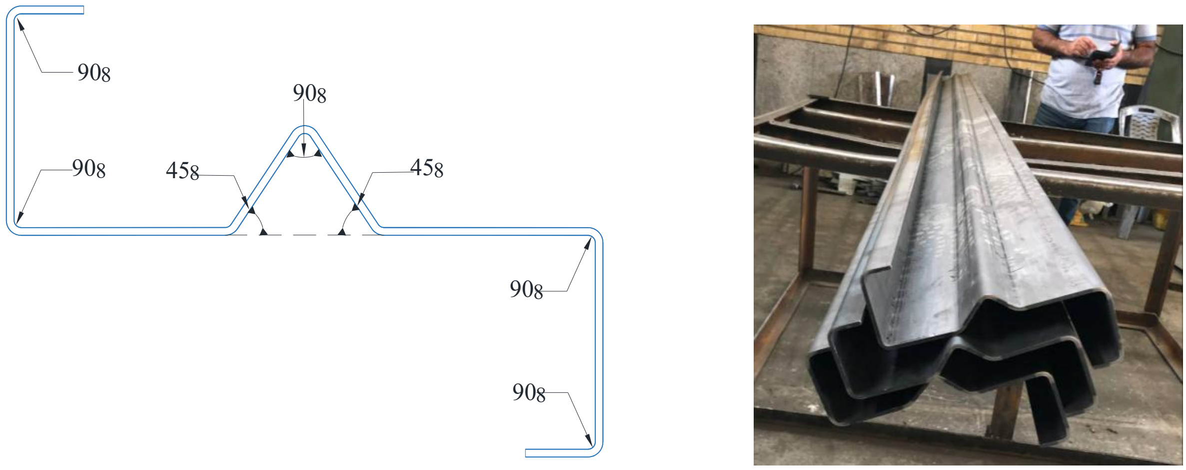


Figure 3. Final Z-section geometry with V-shaped web stiffener.

2.2. Geometrical and Mechanical Properties of Specimens

The geometric details of the cold-formed Z-sections, both with and without web stiffeners, are presented in Fig. 4. Each purlin specimen had a total length of 3.0 m, and the measured dimensions of the tested specimens are summarized in Table 1. The specimens were fabricated from steel sheets with nominal thicknesses of 2.0 mm and 3.0 mm. The base metal thickness was determined by testing tensile coupons extracted from the web region of each Z-section. To remove surface coatings, the coupons were immersed in a ferric chloride bath for 100 minutes.

To evaluate the mechanical properties of the steel, tensile tests were conducted on coupons prepared from the same sheets used in the Z-section specimens. The coupons were laser-cut from the web portion of the sections (Fig. 5). The specimen geometry and dimensions complied with the requirements of ASTM E8 [14]. Each flat specimen had a nominal width of 20 mm and a gage length of 200 mm.

The specimens were subjected to uniaxial tension under displacement control at a loading rate of 2 mm/min. The modulus of elasticity (E) was determined using a clip-on extensometer attached to one of the flat specimens, as illustrated in Fig. 5. Testing was conducted with a STM1000 universal testing machine (UTM) under displacement-controlled loading, employing friction-type grips to prevent slippage. The resulting engineering stress–strain curves for the tested materials are presented in Fig. 6. For identification purposes, the unstiffened Z-section specimens were designated with the letter “A” while the specimens incorporating a web stiffener were labeled with the letter “B”.

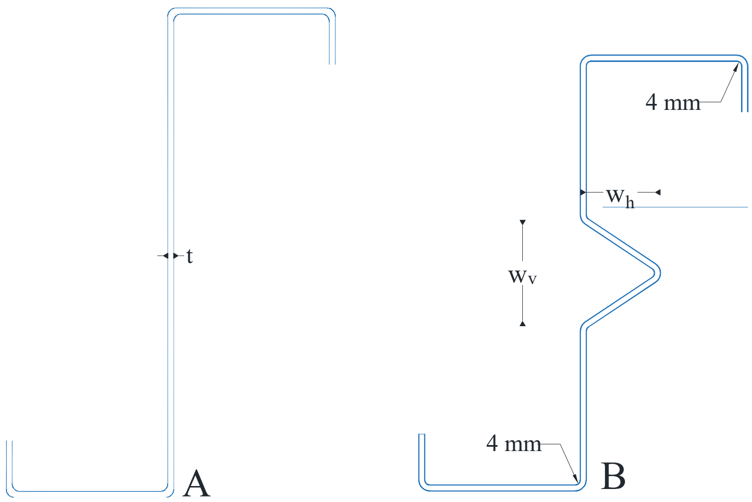


Figure 4. Geometry of cold-formed Z-section specimens with and without web stiffeners.

Table 1. Measured geometric dimensions of Z-section specimens with and without web stiffeners (mm).

Specimen	*h*	W_v	W_h	b_1	b_2	d_1	d_2	*t*
Z-A-1	181.5	-	-	61.8	62.1	21.6	21.8	2.72
Z-A-2	181.6	-	-	61.9	62	21.7	21.6	2.72
Z-B-1	159.2	42.1	21.8	61.03	60.18	22.96	22.24	2.85

Figure 5. Tensile test specimens and test setup.

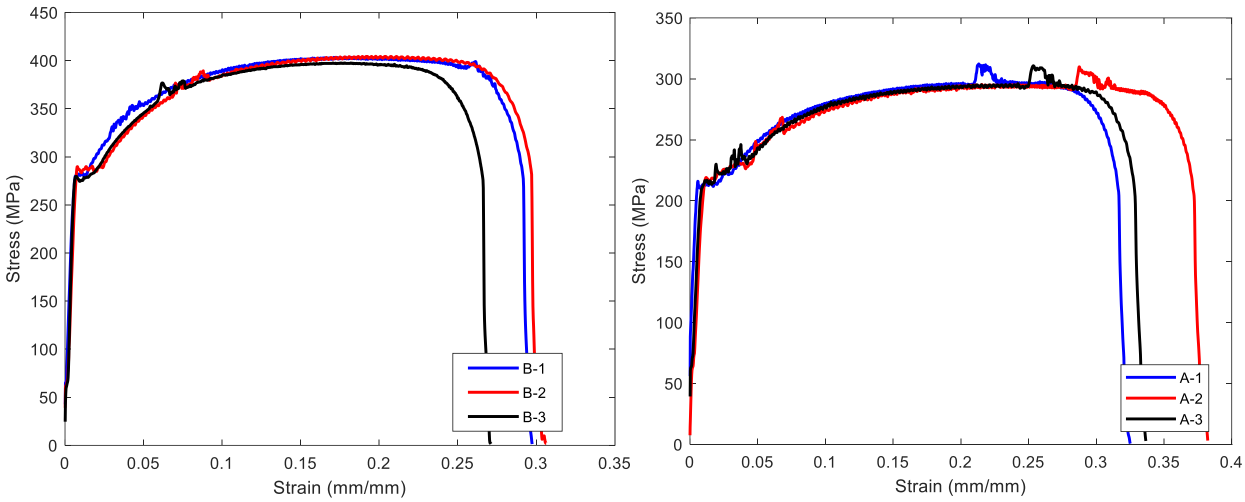


Figure 6. Measured stress–strain curves of cold-formed steel material.

2.3. Supports and Loading

The test supports were fabricated from 8 mm-thick steel plates using a laser-cutting machine. Each support assembly consisted of two 200 × 200 mm steel plates and two triangular stiffeners cut at an angle of 101°, as illustrated in Fig. 7. This angle was selected to simulate a roof slope of 20% (approximately 11°). The support plates were welded to a 10 mm-thick steel base plate, forming a rigid support. Each assembly was anchored to the laboratory floor using a solid steel block to ensure rigidity. The bottom plate of each support was fastened to the block with four 22 mm-diameter bolts. A 150 mm-high steel block was placed beneath the supports to elevate them above the floor, providing sufficient clearance for installing linear variable displacement transducers (LVDTs) beneath the specimen (Fig. 8a).

To connect the Z-section purlins to the support plates, 14 mm drill bits were used to create bolt holes, and 12 mm bolts were employed for fastening (Fig. 8b). For the stiffened specimen, a nut was inserted as a spacer between the web and the support plate to compensate for the offset introduced by the web stiffener (Figure 8c).

Two 6 mm-thick laser-cut steel plates were employed as loading plates, each cut to match the angle and dimensions of the Z-section specimens (Fig. 9). A hole was drilled at the shear center of the section on the loading plate to ensure biaxial bending during test. The center of this hole, the shear center of the purlin, and the axis of the hydraulic jack were carefully aligned. The loading plate was positioned at midspan (1500 mm from each support) and secured in its location with aquarium sealant to prevent unintended slippage (Fig. 10a). The plate was connected to the hydraulic jack through two U-shaped clamps and chains.

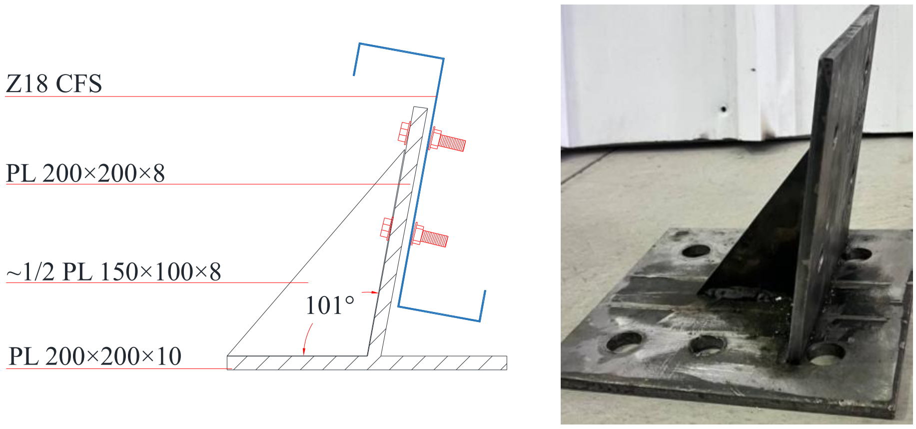
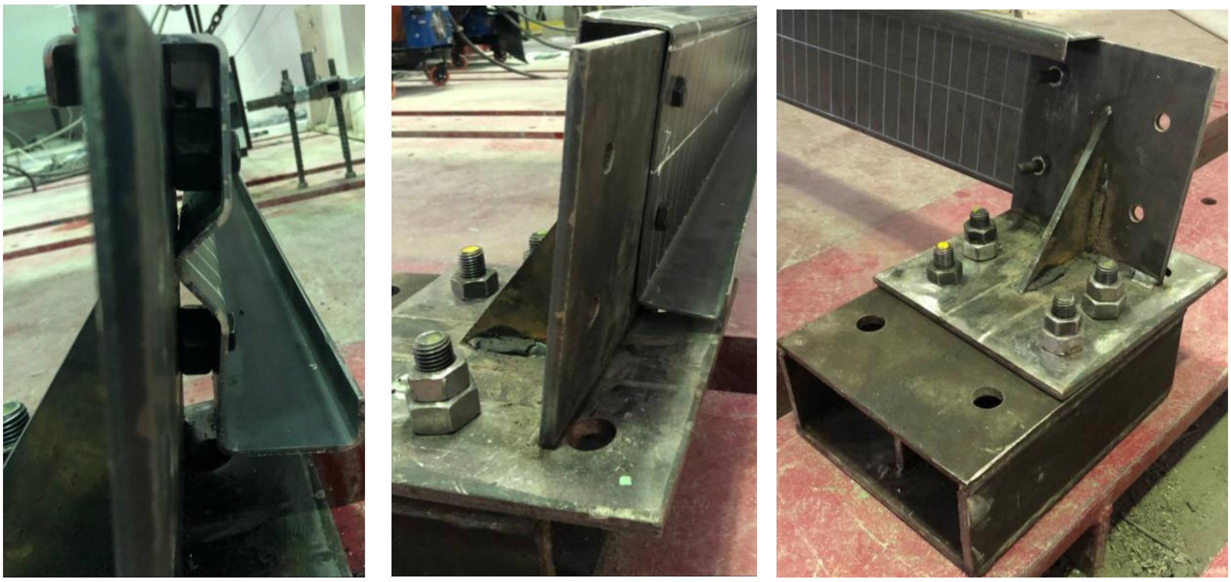


Figure 7. Configuration of sloped support assemblies.



(a) (b) (c)

Figure 8. Details of connections between specimen, support assembly, and steel block (a) Web stiffened specimen, (b) Web unstiffened specimen, (c) support-to-block interface.

The purlins were loaded at a displacement rate of 2 mm/min using the hydraulic jack. Displacement measurements were obtained using LVDT transducers: one measuring vertical deflection and the other horizontal lateral displacement. Because of the sloped configuration of the specimens, direct attachment of the LVDTs to the flanges or web could introduce measurement errors. To avoid this, two wooden guide plates (vertical and horizontal) were fixed to the edges of the loading plate, and the LVDTs were mounted at their midpoints (Fig. 10b). In addition, the built-in displacement transducer of the hydraulic jack was used to monitor actuator movement. Thus, three displacement readings were collected for each purlin test. The same procedure was applied to both stiffened and unstiffened specimens.

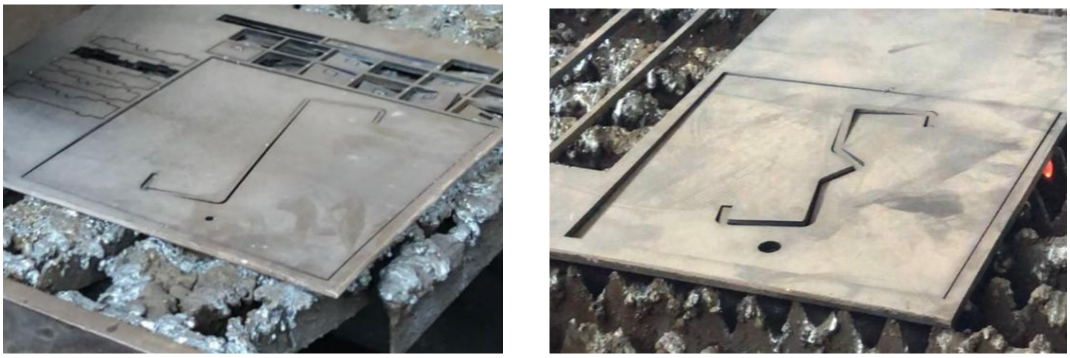
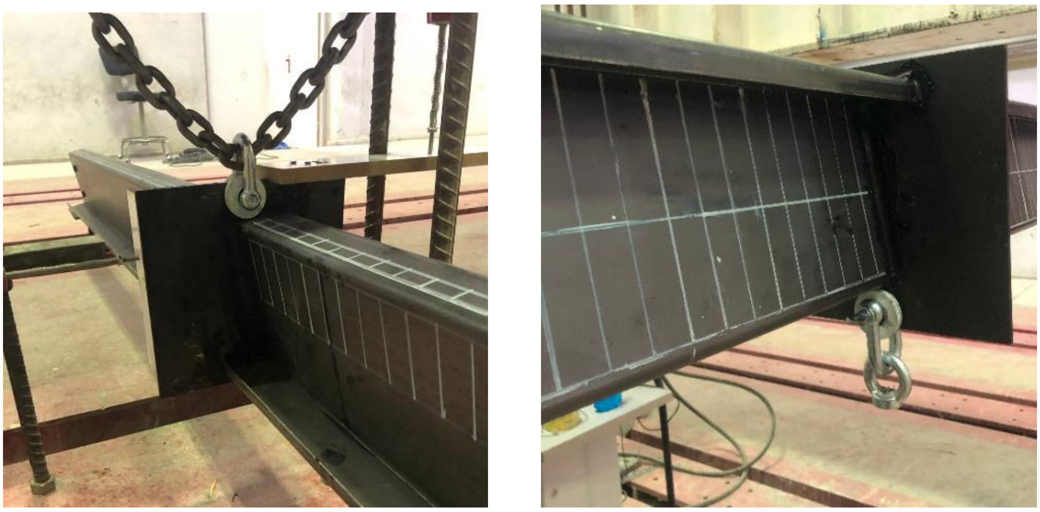


Figure 9. Laser-cut loading plate designed for Z-section specimens (11° inclination angle).



(a) (b)

Figure 10. Loading setup and measurement instrumentation.

3. RESULTS AND DISCUSSION

The vertical load–deflection responses of the three tested specimens are shown in Fig. 11. The specimen with a web stiffener exhibited a more ductile flexural behavior compared with the unstiffened specimens. The presence of the stiffener enabled the section to sustain larger deflections after yielding, thereby demonstrating improved energy absorption capacity. Because of the displacement limitation of the hydraulic jack (130 mm), the ultimate load of the stiffened specimen could not be fully recorded. Nevertheless, the stiffened purlin (Z-B-1) achieved a load-carrying capacity at least equal to, and likely greater than, that of the unstiffened specimens (Z-A-1 and Z-A-2).

The lateral displacement histories of specimens Z-A-2 and Z-B-1 are presented in Fig. 12. Owing to the incorrect positioning of the LVDT in specimen Z-A-1, its lateral deflection data could not be obtained. Comparison of the remaining two specimens indicates that the stiffened Z-section (Z-B-1) exhibited larger lateral deflections than the unstiffened specimen (Z-A-2), suggesting that the web stiffener enhanced rotational flexibility and delayed the onset of local buckling.

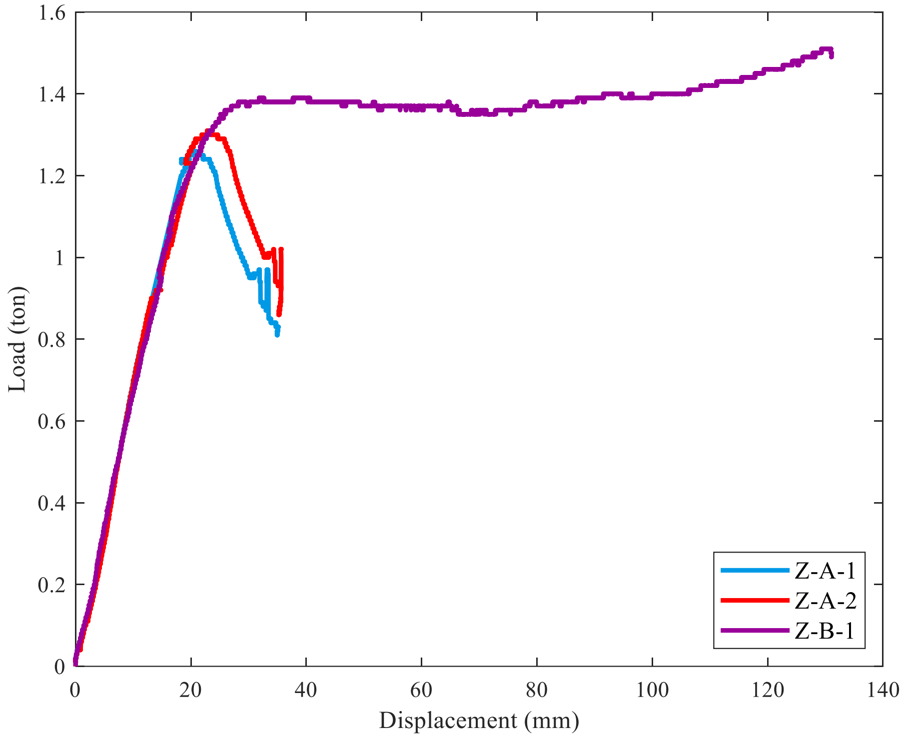


Figure 11. Load–deflection curves of tested Z-sections.

delayed the onset of local buckling, enhanced global stability, and promoted a more uniform stress distribution along the span. At ultimate failure, the stiffened section exhibited incipient local buckling within the overall lateral–torsional deformation mode, indicating an interaction between local and global buckling mechanisms.

Overall, the experimental results demonstrate that incorporating a V-shaped web stiffener significantly improves the stability, ductility, and load-bearing capacity of cold-formed Z-section purlins subjected to biaxial bending.

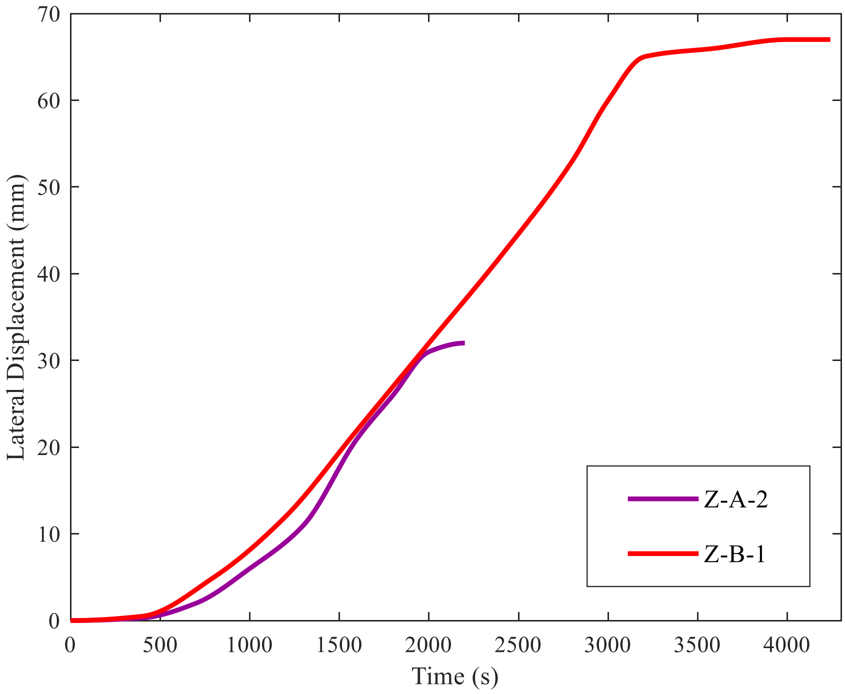


Figure 12. Lateral displacement–time curves of tested Z-sections.

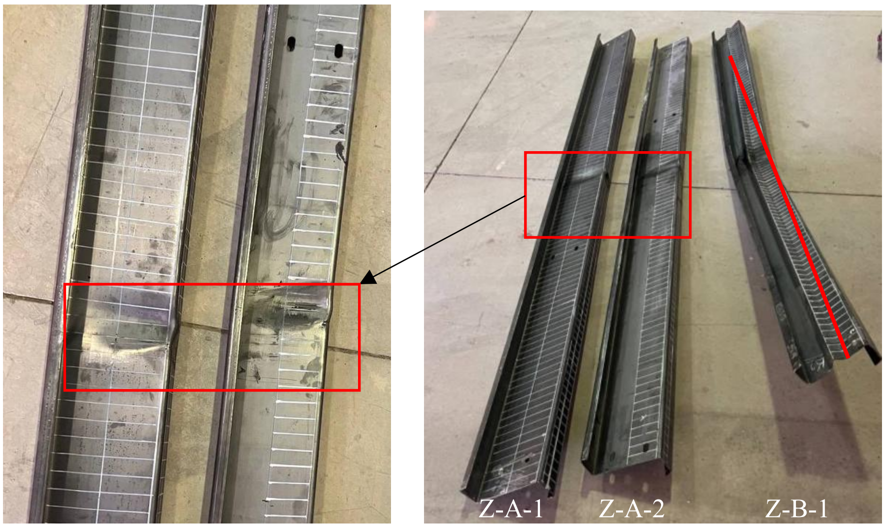


Figure 13. Failure modes of Z-section specimens

4. CONCLUSION

In this study, the effect of a web stiffener on the biaxial flexural behavior of cold-formed Z-shaped steel purlins was investigated experimentally. Three single-span specimens—two without a stiffener and one with a longitudinal web stiffener—were tested to evaluate the influence of the stiffener on load-carrying capacity and failure mechanisms. Based on the experimental results and observations, the following conclusions can be drawn:

- Ductility enhancement: Z-sections with web stiffeners exhibited greater ductility than their unstiffened counterparts. The addition of the stiffener enabled the specimens to sustain larger deformations before failure, demonstrating improved post-yield behavior.
- Failure mechanism transformation: The ultimate failure mode of unstiffened Z-sections under biaxial bending was governed by local web buckling at midspan. In contrast, the introduction of a web stiffener shifted the dominant failure mechanism to global lateral–torsional buckling, with only minor local buckling observed at the ultimate stage. This indicates that the stiffener effectively altered the instability mode from local to global.
- Stability improvement: The inclusion of a V-shaped web stiffener delayed the onset of local buckling at midspan, thereby enhancing the overall stability of the Z-shaped purlins. The stiffened specimens exhibited a more stable load–deflection response and maintained structural integrity over a longer portion of the loading process.

Overall, the experimental findings demonstrate that incorporating web stiffeners in cold-formed Z-sections enhances both stability and ductility, making them more suitable for roof systems subjected to biaxial bending and other complex loading conditions.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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