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The Effect of Bracing Shape Variations (Z-Brace And X-Brace) on Energy Dissipation Due to Cyclic Loading in Cold-Formed Steel Frames

Wahyu Risky Nurpitasari, Nindyawati*, B. Sri Umniati
Department of Civil Engineering, Universitas Negeri Malang, Malang, Indonesia

e-mail: nindyawati@ft.um.ac.id

ABSTRACT
This study investigates the effect of bracing-shape variations—specifically Z-braces and X-braces—on the energy dissipation capacity of cold-formed steel (CFS) portal frames under cyclic loading. The research was conducted experimentally at the Structural Engineering Laboratory, Department of Civil Engineering, Universitas Negeri Malang, using hollow box CFS profiles (G550 grade, 40×40×0.3 mm). Three configurations were tested: non-braced (No-Brace), X-braced, and Z-braced frames. Cyclic static loading was applied in accordance with ASTM E2126-11 to evaluate lateral strength, energy dissipation, and failure mechanisms. The results show that adding bracing significantly increases lateral load capacity compared to the unbraced frame. The X-brace specimen demonstrated the highest lateral strength of 1.808 kN, nearly double that of the No-Brace configuration (0.898 kN), followed closely by the Z-brace (1.825 kN). In terms of energy dissipation, the X-brace achieved the highest value of 743.61 kN·mm, approximately 79.5% higher than No-Brace and 165.7% higher than Z-Brace, indicating superior hysteretic performance. Structural failures primarily occurred at screw joints due to cyclic shear and pull-out effects. Overall, the study concludes that X-brace configurations provide the most effective enhancement in both lateral stiffness and seismic energy dissipation capacity for cold-formed steel portal frames. At the same time, Z-braces exhibit better ductility but lower energy absorption efficiency. These findings are expected to contribute to the design of lightweight, earthquake-resistant cold-formed steel structures.

Keywords: *Cold-formed steel; Bracing configuration; X-brace, Z-brac; Cyclic loading; Energy dissipation; Structural performance.*

1. Introduction

Cold-formed steel (CFS) has become increasingly popular in modern construction due to its lightweight characteristics, high strength-to-weight ratio, ease of installation, and cost-effectiveness [1], [7]. In seismic regions, the lateral performance and energy dissipation capacity of CFS structures are critical aspects of structural safety and resilience against earthquake-induced forces [4], [5], [11]. Previous studies have demonstrated that incorporating bracing systems can significantly enhance the lateral resistance, stiffness, and cyclic performance of CFS structures [1], [2], [9]. Experimental investigations have further shown that braced cold-formed steel systems exhibit improved load-carrying capacity and more stable hysteretic behavior under cyclic loading conditions [3], [10].

Furthermore, the seismic behavior of CFS wall and frame systems is strongly influenced by the bracing configuration, connection details, and hysteretic response developed during cyclic loading [7], [10], [12]. Studies on innovative wall systems and connection mechanisms revealed that enhanced connection performance contributes significantly to energy dissipation and structural stability under repeated lateral loading [4], [5]. In addition, the implementation of supplemental energy-dissipation devices has been reported to improve seismic resilience and reduce structural damage during cyclic

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loading [6], [8].

Several researchers have reported that different bracing arrangements can lead to variations in stiffness, ductility, strength, and energy dissipation capacity, thereby affecting the overall seismic performance of the structure [13], [14]. The effectiveness of bracing systems depends not only on their geometry but also on the structural system's ability to develop stable plastic mechanisms and maintain energy dissipation throughout the loading history [6], [8], [14]. Moreover, performance-based seismic design approaches emphasize the importance of adequate deformation capacity and hysteretic energy dissipation in achieving reliable structural performance [11].

Although numerous studies have investigated the seismic performance of cold-formed steel systems, most of them focused on shear walls, strap-braced systems, or alternative bracing arrangements [1]–[4], [9]. Experimental comparisons between X-Brace and Z-Brace configurations in cold-formed steel portal frames subjected to cyclic loading remain limited, particularly with respect to their energy dissipation characteristics and failure mechanisms [15]. Therefore, this study aims to evaluate the influence of X-Brace and Z-Brace configurations on the energy dissipation capacity and structural performance of cold-formed steel portal frames subjected to cyclic loading. The findings are expected to contribute to the development of lightweight, efficient, and earthquake-resistant cold-formed steel structural systems.

2. Materials and Methods

The dependent variables in this study are the load and displacement values obtained from the tests. The controlled variables include the material and weight of the cold-formed steel used as the test specimens. The quantitative experimental method was selected as the research approach, involving laboratory testing. This research was conducted at the Structural Laboratory, Department of Civil Engineering, Faculty of Engineering, Universitas Negeri Malang, located in Building D19 and Joint Lecture Building A20.

2.1. Research subject

This study used cold-formed steel hollow box sections with dimensions of 40 mm × 40 mm and a thickness of 0.3 mm as test specimens. The bracing configuration variations employed were X-Brace and Z-Brace. The frame was designed with a height of 100 cm and a width of 25 cm, and then fitted with bracing members as illustrated. The experimental testing was conducted to compare the load-carrying capacities of cold-formed steel portal frames with different bracing configurations. The test results consisted of the load (P) and displacement (Δ) recorded during each loading cycle. These data were subsequently analyzed using descriptive statistical methods to evaluate energy dissipation and failure patterns in the structural components.

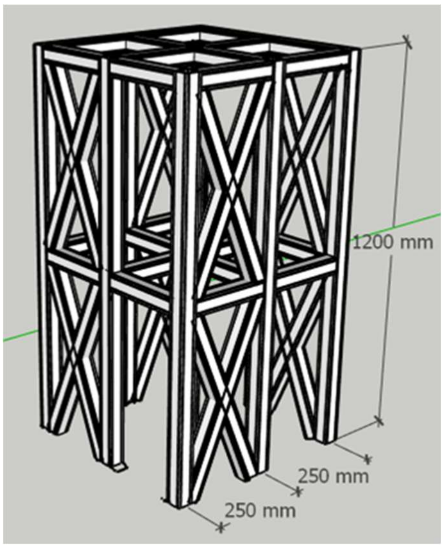

Figure 1. X-Brace specimen design

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Figure 1 illustrates the X-Brace configuration used in this study. The diagonal members intersect at the center of the frame, forming a triangulated structural system that improves lateral stiffness and enables efficient transfer of cyclic loads. The X-shaped arrangement allows both tension and compression forces to be distributed through the brace members, which is expected to enhance structural stability and energy dissipation performance during cyclic loading.

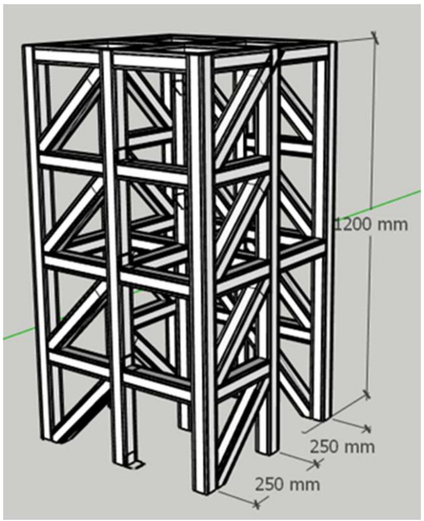

Figure 2. Z-Brace specimen design

Figure 2 presents the Z-Brace configuration employed in the experimental program. Unlike the X-Brace system, the diagonal members form a Z-shaped load path that provides lateral resistance while allowing greater deformation before reaching ultimate capacity. This configuration is expected to exhibit improved ductility under cyclic loading conditions, although the load distribution mechanism may be less efficient than that of the X-Brace system.

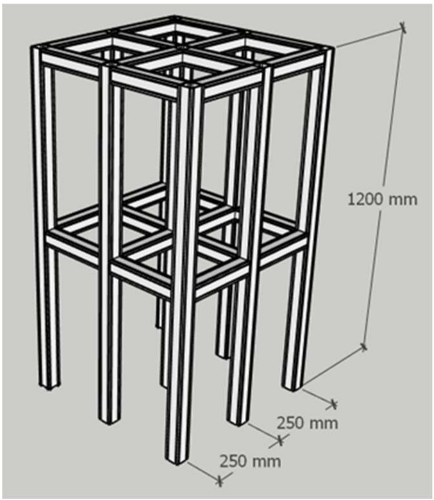

Figure 3. No-Brace specimen design

Figure 3 shows the control specimen without any bracing element (No-Brace). This specimen was designed to evaluate the contribution of bracing systems to the overall structural performance of cold-formed steel portal frames. The absence of bracing allows the frame behavior to be governed primarily by member bending and connection deformation under cyclic loading.

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2.2. Testing Procedure

In this study, testing was carried out by applying a cyclic load to a cold-formed steel portal specimen with rivet connections and stiffener plates at the top and bottom. The procedure for the lateral cyclic loading pattern used in this research refers to the applicable standard, ASTM E2126-11, specifically Test Method B (ISO-16670 Protocol). The detailed loading procedure is described as follows:

The loading/displacement protocol was controlled by applying cyclic loading with gradually increasing amplitudes.

The applied loading consisted of two patterns, namely:

- The first loading pattern consisted of five complete single loading cycles (one full cycle) with input amplitudes of 0.0125Δm, 0.025Δm, 0.05Δm, 0.075Δm, and 0.1Δm.
- The second loading pattern consisted of several phases, each containing three loading cycles with the same amplitudes: 0.2Δm, 0.4Δm, 0.6Δm, 0.8Δm, 1Δm, and 1.2Δm.

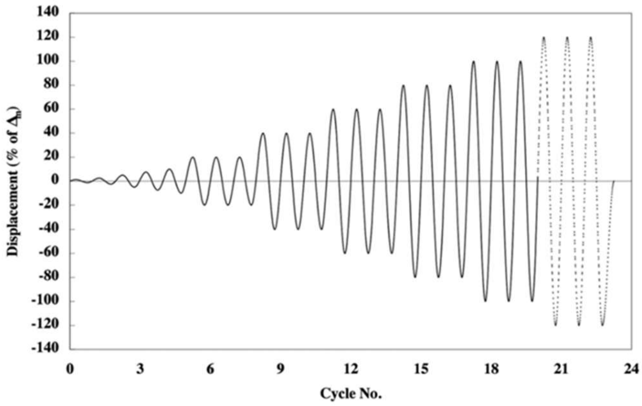

Figure 4. Loading Pattern of Test Method B

3. Results and Discussions

3.1. Maximum Lateral Load

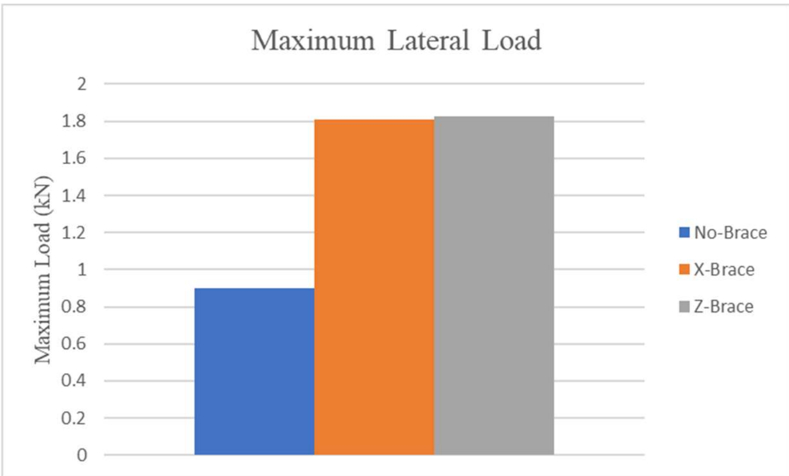

Figure 5. Maximum Lateral Load

From the cyclic loading test results, a diagram was generated based on the average lateral push and pull loads for each specimen. In the unbraced structure, the lateral load was 0.89828 kN. When X-type bracing was applied, the lateral load capacity increased significantly to 1.80822 kN. This increase indicates that the X-Brace enhanced structural strength by approximately 2 times compared to the unbraced structure. Similarly, the use of Z-type bracing yielded results comparable to or slightly higher,

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with a maximum lateral load of 1.82508 kN.

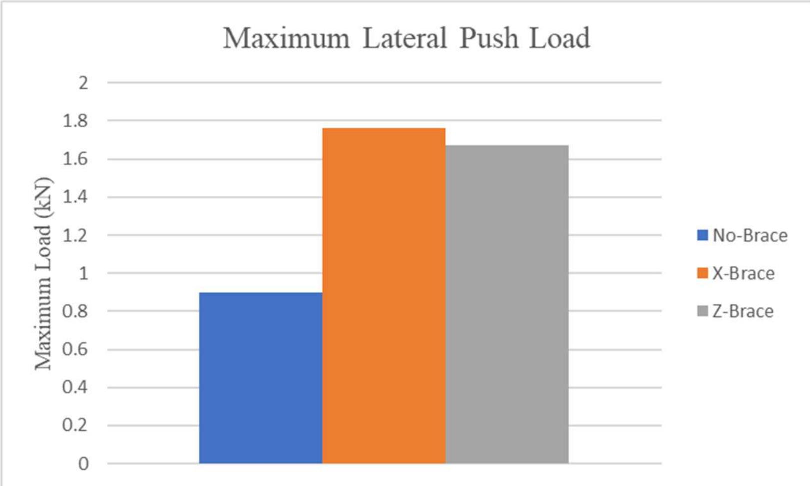

Figure 6. Maximum Lateral Push Load

Figure 6 shows the maximum push load achieved by the three specimens, namely No-Brace, X-Brace, and Z-Brace. The specimen without bracing exhibited a maximum push load of 0.89855 kN, which increased significantly—nearly twice as high—to 1.76015 kN in the specimen with X-type bracing. The Z-Brace specimen also showed a twofold increase in maximum push load compared to the unbraced specimen, although it was slightly lower than the X-Brace specimen, with a value of 1.67392 kN.

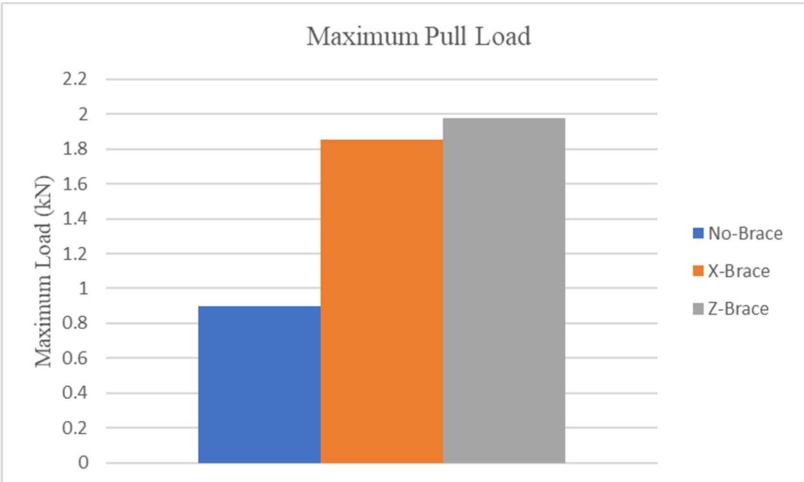

Figure 7. Maximum Pull Load

Figure 7 shows the maximum tensile load diagram, with a value of 0.89801 kN for the specimen without bracing. The load increased more than twofold for the specimen with X-type bracing, reaching 1.8533 kN, and further increased to 1.97624 kN for the specimen with Z-type bracing. Based on the load-versus-drift-ratio graph for each configuration, it can be observed that the lateral load increases with increasing drift ratio, reaches a peak, and then decreases. This behavior occurs due to material yielding or structural stiffness degradation after the maximum capacity point is reached.

In the No-Brace structure, the peak value occurs at a 180% drift ratio, indicating that although the structure can withstand large deformations without bracing, its strength remains relatively low. In the X-Brace structure, the maximum value is reached at a 40% drift ratio, demonstrating high initial stiffness that decreases after exceeding the elastic limit. Meanwhile, in the Z-Brace structure, the maximum value occurs at a 100% drift ratio, suggesting that this type of bracing can maintain lateral strength under

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larger deformations compared to the X-Brace configuration.

The results of this study are consistent with those of Lu et al. [1] and Zhang et al. [2], who observed that the addition of bracing systems significantly improved the lateral resistance of cold-formed steel structures subjected to cyclic loading. Similar to their findings, both X-Brace and Z-Brace configurations in the present study increased the maximum lateral load capacity by approximately two times compared to the unbraced frame.

Kassem et al. [13] reported that different bracing arrangements yield varying levels of stiffness and strength due to differences in the mechanisms of force distribution. The current experimental results support this observation, as the X-Brace and Z-Brace specimens exhibited distinct load-displacement responses despite having similar material properties and geometric dimensions.

Furthermore, Wang and Tian [12] demonstrated that braced cold-formed steel systems generally exhibit improved lateral stiffness and delayed structural degradation under cyclic loading. A similar trend was observed in this research, where both braced specimens maintained higher load capacities than the No-Brace specimen throughout the loading history.

3.2. Dissipated Energy

In this cold-formed steel portal test, a cyclic loading system was applied, in which the load is repeatedly applied in the positive direction and then reversed to the negative direction.

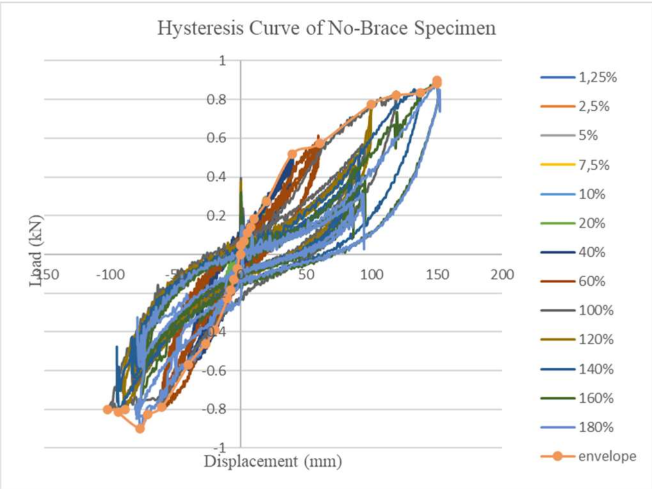

Figure 8. Hysteresis Curve of No-Brace Specimen

Figure 8 shows the hysteresis response of the No-Brace specimen**.** The relatively narrow hysteresis loops indicate limited energy dissipation capacity and significant stiffness degradation during repeated loading cycles. The pinched shape of the hysteresis loops suggests that deformation was concentrated mainly in the connections and frame members, resulting in inefficient energy absorption.

Figure 9 presents the hysteresis behavior of the X-Brace specimen**.** Compared with the No-Brace configuration, the hysteresis loops are wider and more stable, indicating improved energy dissipation capability. The larger enclosed area demonstrates that the X-Brace system absorbed and dissipated more seismic energy through repeated inelastic deformation.

Figure 10 illustrates the hysteresis response of the Z-Brace specimen. The specimen exhibited a relatively stable response at moderate drift levels, maintaining its load-carrying capacity over a wider deformation range. Although the total dissipated energy was lower than that of the X-Brace specimen, the Z-Brace configuration demonstrated good ductility characteristics.

The dissipated energy is defined as the area under the envelope curve obtained from the processed experimental test data. The calculation of the area under the envelope curve can be performed using AutoCAD software to determine the area more quickly and accurately. As the number of cycles increases, the resulting curve becomes more gradual. For example, in the specimen with the Z-Brace variation, the lateral load of each specimen increases with the drift ratio up to a certain point, after which

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it gradually decreases. The summary of the dissipated energy-area results is shown in **Figure 11**.

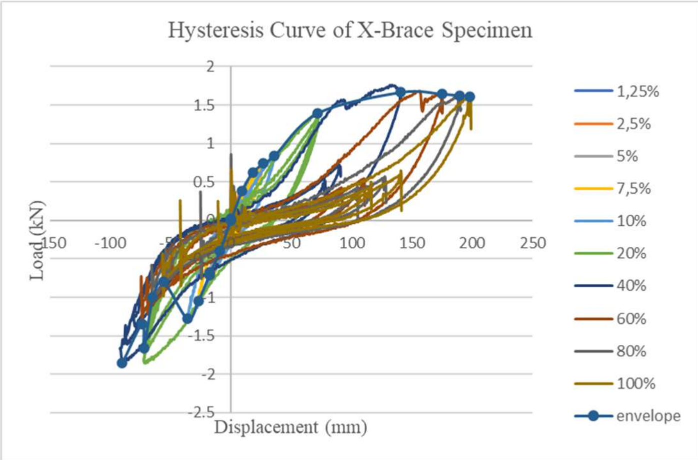

Figure 9. Hysteresis Curve of X-Brace Specimen

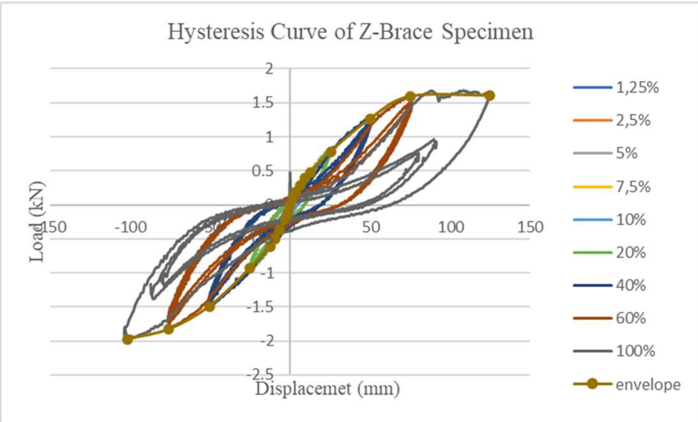

Figure 10. Hysteresis Curve of Z-Brace Specimen

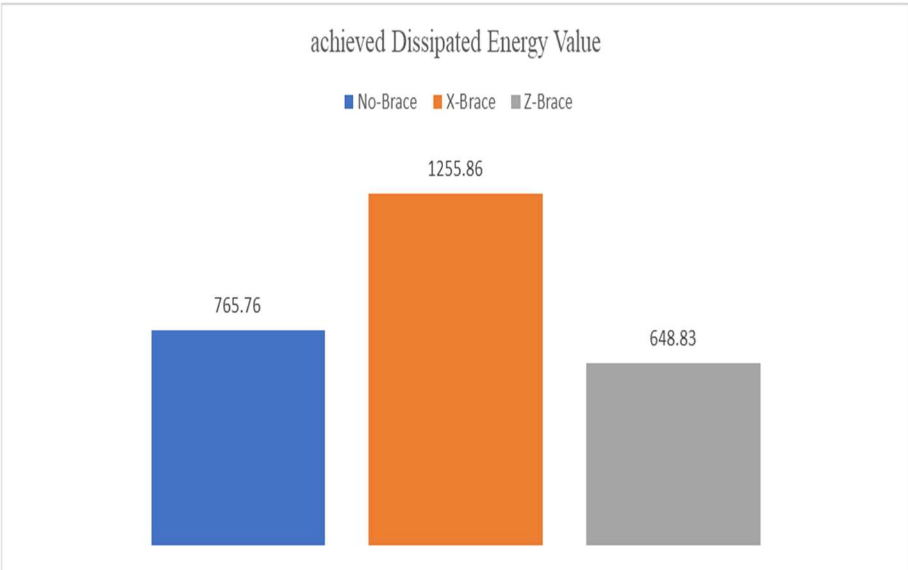

Figure 11. Achieved Dissipated Energy Value

Based on cyclic loading test results and energy dissipation calculations, it can be concluded that

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the bracing system configuration significantly influences the ability of cold-formed steel portal frames to absorb and dissipate energy under repeated lateral loading. Energy dissipation was calculated from the area enclosed by the force–displacement hysteresis curves at each drift ratio level and subsequently summed to obtain the total energy dissipation for each test specimen.

The unbraced specimen (No-Brace) produced a total energy dissipation of 765.76 kN·mm. The energy dissipation in this configuration primarily resulted from deformation of the portal frame and the screw connections. Although the No-Brace specimen exhibited large deformations and high drift ratios, the energy dissipation mechanism was relatively inefficient, leading to significant stiffness degradation and suboptimal energy absorption.

The specimen with the X-Brace configuration exhibited the best energy dissipation, with a total of 1,255.86 kN·mm, the highest among the three variations. This indicates that the X-Brace system developed a more stable, sustained plastic mechanism across a range of drift ratios. The combination of increased stiffness, ductility, and more uniform lateral force distribution makes the X-Brace configuration the most effective in absorbing and dissipating energy under cyclic loading.

Meanwhile, the specimen with the Z-Brace configuration exhibited a total energy dissipation of 648.83 kN·mm, which was lower than that of the No-Brace and X-Brace configurations. However, when compared at the same drift ratio, particularly at 100%, the Z-Brace configuration exhibited the highest energy dissipation. This indicates that the Z-Brace has good energy-dissipation efficiency at large deformations, although limitations in global ductility and premature failure led to lower total dissipated energy.

Overall, this study's results demonstrate that energy dissipation is influenced not only by the magnitude of deformation but also by the stability of the plastic mechanism and the structure's ductility. The X-Brace configuration offers the most balanced performance in terms of stiffness, ductility, and energy dissipation. It can therefore be recommended as the most effective strengthening system for cold-formed steel portal frames subjected to repeated lateral loading.

Chen et al. [14] concluded that energy dissipation in cold-formed steel structures is strongly influenced by the stability of the load-resisting mechanism and the ductility of structural components. Similar behavior was observed in the present study, where the X-Brace configuration exhibited the highest cumulative energy dissipation due to its stable force transfer mechanism.

Mahdavian et al. [15] also reported that improved hysteretic performance is commonly associated with increased structural stiffness and better load redistribution. The current experimental results support this conclusion, as the X-Brace specimen demonstrated the most balanced performance across strength, stiffness, and energy dissipation capacity.

3.3. Structural Failure of the Specimen

3.3.1 Failure at the Connection

A connection failure occurred at the screw joints on the panel. The observed failures were pull-out and tilting (prying) failures of the screws. This failure occurred when the screws were lifted out of the cold-formed steel panel. This occurs because the screws attempt to resist the shear mechanism induced by the applied load. In the specimens with various bracing configurations—No-Brace, X-Brace, and Z-Brace—tilting failure occurred, leading to the pull-out of the screws at the connections. This type of connection failure resulted in a significant reduction in the load-carrying capacity of the specimens.

Figure 12 shows the connection failures observed in the tested specimens. Pull-out and tilting failures of the screws were identified as the dominant failure modes. These failures occurred due to repeated cyclic loading, which progressively weakened the connection regions and reduced the screws' ability to transfer shear forces effectively.

3.3.2 Tearing Failure on the Panel at the Connection Area

Tearing failure of the cold-formed steel panel occurred due to the continuous increase in applied load, which eventually caused a fracture at the connection area.

Figure 13 illustrates tearing failures that developed around the connection zones of the braced specimens. The tearing damage resulted from stress concentration near the screw connections combined

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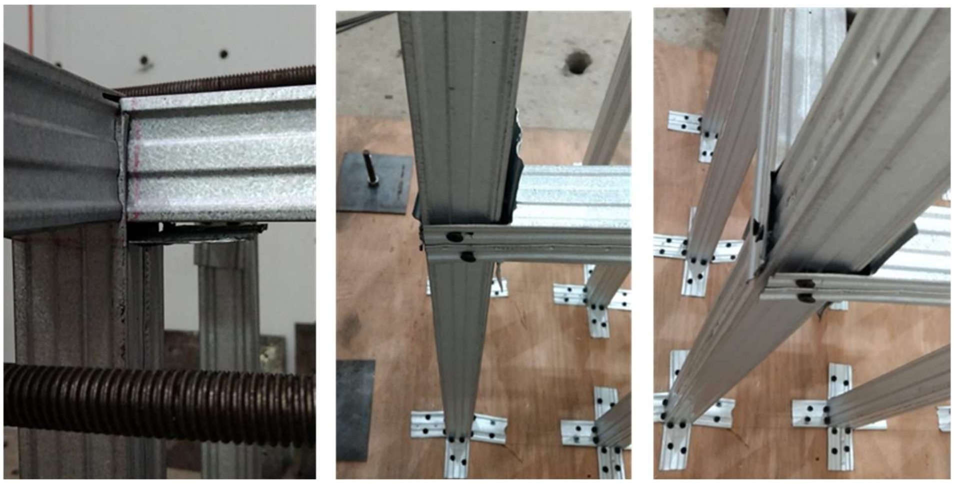
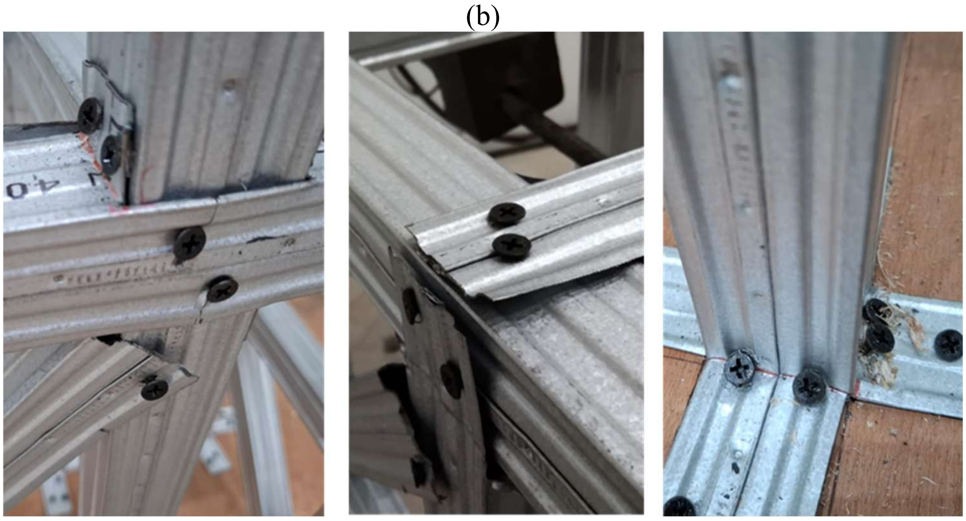
with repeated cyclic deformation. Once tearing initiated, local stiffness decreased rapidly, reducing the frame's overall load-carrying capacity.



(a)

(b)



(c)

Figure 12. Connection Failure in No-Brace (a), Connection Failure in X-Brace (b), and Connection Failure in Z-Brace ©

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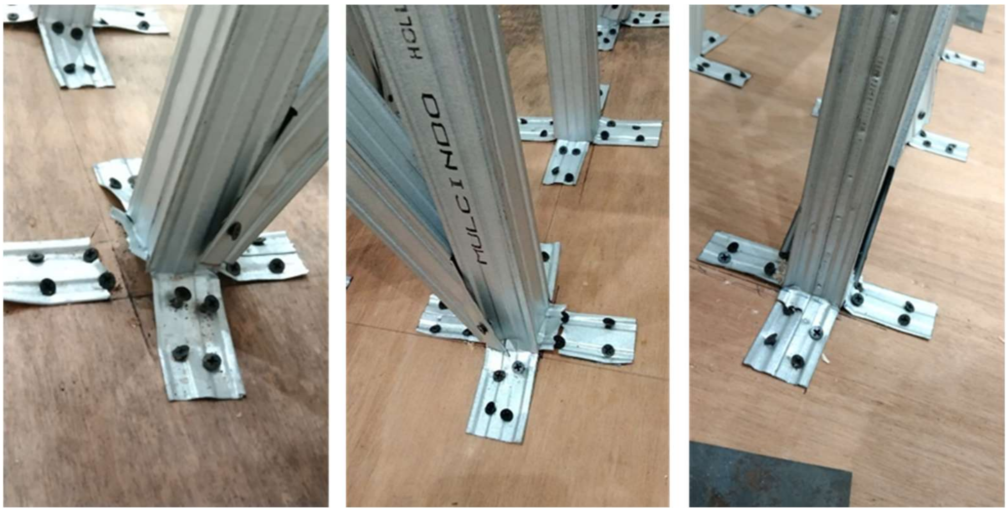
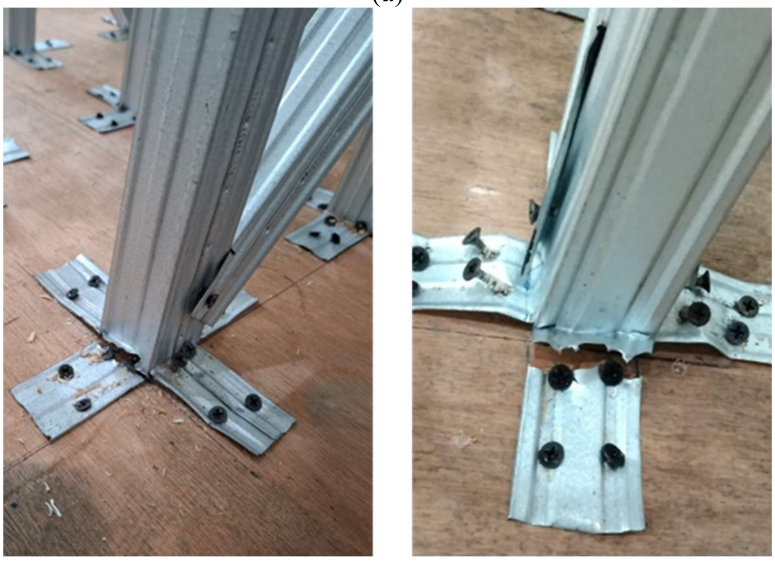


(a)



(b)

Figure 13. Tearing Failure at the X-Brace Connection (a), Tearing Failure at the Z-Brace Connection (b)

The observed failure mechanisms are consistent with previous experimental studies on cold-formed steel structures. Wang and Tian [12] reported that connection failures frequently govern the seismic response of cold-formed steel systems due to the relatively thin steel sections and localized stress concentrations around fasteners.

Similarly, Li et al. [4] found that screw pull-out and local tearing failures commonly occur in cold-formed steel structures subjected to cyclic loading. The present study confirmed these observations, as connection failure and panel tearing were the dominant failure modes in all tested specimens.

According to Ye et al. [7], connection detailing remains one of the most critical factors affecting the seismic performance of cold-formed steel structures. The current results further emphasize the importance of improving connection design to achieve greater energy dissipation capacity and structural reliability under earthquake loading.

4. Conclusions

The X-Brace and Z-Brace specimens in the laboratory cyclic loading test experienced damage or the formation of plastic hinges earlier than those predicted by the SAP2000 analysis under monotonic (one-directional) loading. Conversely, the No-Brace specimen experienced damage or plastic hinge

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formation later than the results obtained from the SAP2000 monotonic load analysis. The addition of bracing can significantly improve lateral stiffness and structural strength, as well as enable a more uniform distribution of lateral forces. This is evidenced by the maximum lateral load increasing by up to two times in the X-Brace and Z-Brace specimens compared to the No-Brace specimen. The energy dissipation results indicate that the specimen with X-shaped bracing exhibited the highest dissipated energy, while the specimen with Z-shaped bracing showed the lowest energy dissipation capacity. The cyclic loading test results revealed several types of structural failures, including connection failures and tearing of wall panels near the connection base area.

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