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Seismic Resilience of Braced Corrugated Steel Shear Panels: Finite Element Investigation and Parametric Analysis

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Abstract. This study proposes a novel braced corrugated shear panel (BCSP) system aimed at enhancing the seismic resilience of steel structures. In contrast to conventional flat shear panels, the BCSP incorporates stiffening ribs and corrugated geometry to improve deformability, delay local and global buckling, and increase lateral load-carrying capacity under cyclic loading. Metal shear panels are widely recognized for their stable hysteretic behavior, particularly in high seismic regions; nevertheless, their performance can be further improved through optimized geometry. This research examines the influence of corrugation orientation and angle on the behavior of BCSPs subjected to cyclic loading, demonstrating that replacing traditional thin ductile shear panels with a corrugated configuration significantly enhances structural response. The results show that horizontal corrugation provides superior strength, stiffness, and ductility compared to vertical or inclined corrugation, while the combined effect of bracing and corrugation increases lateral load-resisting capacity and facilitates easier post-earthquake replacement. Overall, BCSPs with horizontal corrugation exhibit optimal performance and high structural resilience in earthquake-prone regions, offering a promising advancement for future steel structure design.

Introduction

The demand for seismic-resilient structural systems has grown substantially as modern buildings are increasingly expected not only to resist collapse but also to maintain functionality after major earthquakes. Advances in materials and structural configurations have focused on improving energy dissipation, delaying buckling, and enhancing post-event reparability. Within this context, steel shear panels have emerged as highly effective components due to their stable hysteretic behavior and ability to dissipate energy under cyclic loading.

Significant progress has been made in the development of corrugated steel panels and bracing systems aimed at improving lateral resistance. Corrugated profiles have demonstrated increased shear strength, stiffness, and buckling resistance compared to traditional flat panels, while bracing systems such as buckling-restrained braces (BRBs) and eccentrically braced frames (EBFs) have shown notable improvements in ductility and cyclic performance. Recent innovations-including hybrid braced-panel systems, demountable metallic shear walls, and partially connected or perforated steel plate systems-highlight how these technologies enhance stability, energy dissipation, and ease of post-earthquake repair. These developments collectively underscore the potential of integrating corrugated geometries with advanced bracing mechanisms to create robust and resilient seismic systems.

Despite these advancements, few studies have systematically compared how different corrugation orientations and angles influence the cyclic performance of braced corrugated panels, leaving a significant gap in identifying the most effective geometric configuration for seismic applications. Corrugation geometry plays a crucial role in controlling buckling behavior, stiffness distribution, and the overall energy dissipation capacity of steel panels; therefore, understanding its influence in the presence of bracing systems is essential for optimizing performance. Addressing this research gap, the present study conducts a detailed investigation into the cyclic behavior, post-buckling response, and overall seismic resilience of braced corrugated shear panels (BCSPs). The analysis focuses on how variations in corrugation orientation-such as horizontal, vertical, and inclined profiles and corrugation angles alter key structural responses including strength, stiffness degradation, ductility, and hysteretic energy dissipation. By examining these parameters, the study aims to determine the corrugation configuration that offers the most favorable balance between stability, deformability, and repairability. Ultimately, the outcomes of this research are intended to contribute to the development of more efficient, resilient, and easily replaceable seismic force-resisting systems, advancing the design of steel structures in earthquake-prone regions and supporting rapid post-event recovery.

II. Methodology

The research employed Finite Element Analysis (FEA) to investigate the cyclic behavior of braced corrugated shear panels (BCSPs). Numerical simulations were conducted using **ANSYS Workbench 2022 R2**. The research procedure comprised the following steps.

2.1 Modeling Approach: Three-dimensional finite element models of both braced ductile shear panels (BDSPs) and the proposed braced corrugated shear panels (BCSPs) were developed. Thin steel plates were modelled using **SHELL181** elements, whereas **SOLID185** elements were used for boundary frames and bracing components.Adaptive meshing ensured a balance between computational efficiency and result accuracy, particularly in regions prone to high stress concentration and local buckling.

2.2 Boundary Conditions and Loading Protocol: The bottom nodes of the lower beam were fully restrained in all translational and rotational degrees of freedom. Lateral displacement was applied to the top interface to induce in-plane shear deformation.The cyclic loading protocol recommended by **FEMA** was adopted to capture stiffness degradation, strength deterioration, and hysteretic response under repeated loading cycles.

2.3 Parametric Study:A detailed parametric study was performed by substituting the BDSP configuration with the BCSP system. The parameters investigated included:

2.3.1 Corrugation orientation: horizontal, vertical, and inclined

2.3.2 Corrugation angle: 30°, 60°, 45° and 90°

These variations were examined to evaluate their effects on panel strength, stiffness, ductility, and energy dissipation capacity.

III. Parametric Study

To validate the accuracy of the developed Finite Element Analysis (FEA) models, the cyclic behavior of corrugated braced shear panels was examined. The influence of corrugation angle and orientation on the overall structural performance was investigated. The modelling approach and material properties proposed by Guohua Sun et al. (2021) were adopted; however, the thin ductile shear panel used in the reference study was replaced with a corrugated shear panel for the present analysis.

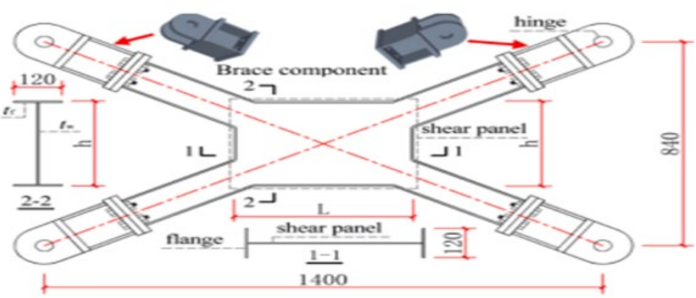

Fig. 1. Moment-resisting steel frame with innovative ductile thin shear panels.

- **Specimen Details:** The experimental specimens comprised a thin rectangular ductile shear panel with concentric X-braces and stiffening ribs. The dimensions of the shear panel and the material properties used in the FEA models were derived from the experimental study (Table I).

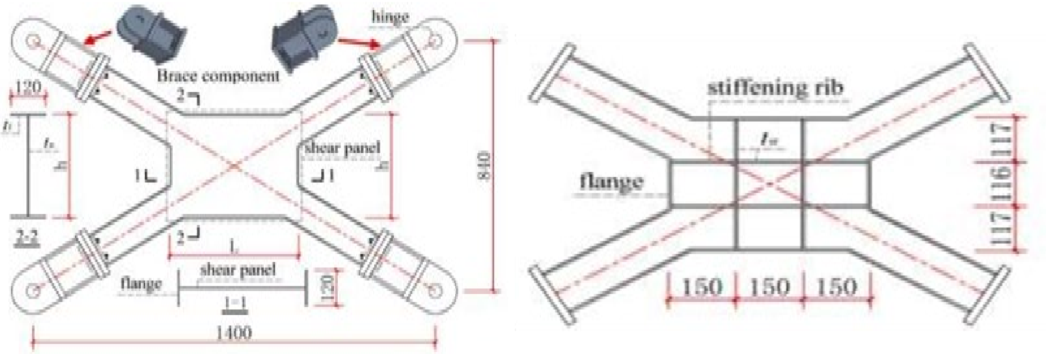

Fig. 2. Test specimen details.

Table 3.1. Details of specimen for validated Model with Guohua Sun. et.al. [2021].

Specimen	Dimension of the shear panel, $h \times l$ (mm)	Thickness of shear panel, tw (mm)	Height- to the thickness of the shear panel, λ	Thickness of flange, tf (mm)	Thickness of stiffening rib, tsr (mm)	Spacing of stiffening rib, Dh/D_v (mm)
BDSP 3	450 × 350	3	117	6	3	------
BDSP 5	450 × 350	3	36.3	6	3	145/110

- **Material Properties:** Table 3.2 presents the mechanical properties of Q235B steel used in the validation study. The yield stress, ultimate tensile strength, and elastic modulus were consistent with the experimental data.

Table 3.2. Material properties of the validated model with Guohua Sun. et.al. [2021].

Steel component	Actual steel plate thickness(mm)	Yield stress, fy (mm)	Ultimate stress, fu (MPa)	Elastic modulus, $E/10^5$(MPa)	Elongation at rupture, εu (%)
3mm thick plate	2.66	331.22	471.00	2.04	25

- **Loading Conditions:** The same FEMA cyclic loading protocol was applied in both the FEA and experimental tests, with boundary conditions involving full restraint at the bottom interface and lateral displacement applied to the top interface (illustrated in Fig. 1).

Table 3.3. Loading condition with Guohua Sun. et.al. [2021].

FEMA PROTOCOL			
LENGTH	DRIFT RADIAN	DRIFT PER	DRIFT DISPLACEMENT (mm)
0.84	0.00375	0.375	3.15
0.84	0.005	0.5000	4.20
0.84	0.0075	0.7500	6.30
0.84	0.01	1.0000	8.40
0.84	0.015	1.5000	12.61
0.84	0.02	2.0000	16.81

The study was conducted to evaluate the influence of corrugation orientation and corrugation angle on the performance of Braced Corrugated Shear Panels (BCSP). The parametric analysis was performed on BCSP models with varying orientations and corrugation angles to assess their effect on load-bearing capacity, ductility, and lateral stiffness.

A. Effect of Corrugation Orientation

The corrugation orientation plays a significant role in the structural performance of BCSPs under cyclic loading. Three different corrugation orientations were considered: horizontal, vertical, and inclined (45°). The key results obtained from the analysis are compiled and presented in Table I.

- **Horizontal Corrugation**: Panels with horizontal corrugation demonstrated superior performance, showing a 6% higher load-bearing capacity compared to vertical corrugation and a 13% improvement over inclined corrugation.
- **Vertical Corrugation**: Vertical orientation showed intermediate performance, providing moderate ductility and stiffness.
- **Inclined Corrugation**: Inclined panels exhibited the lowest load-carrying capacity but still demonstrated sufficient ductility for seismic applications.

Table 3.4. Comparison of Load-Bearing Capacity for Different Corrugation Orientations.

Orientation	Maximum Load (kN)	Maximum Displacement (mm)
Horizontal	412.68	8.41
Vertical	389.10	8.39
Inclined	359.38	8.42

As illustrated in Figure 3, the hysteretic curves for horizontally oriented BCSPs showed the fullest loops, indicating better energy dissipation and improved ductility.

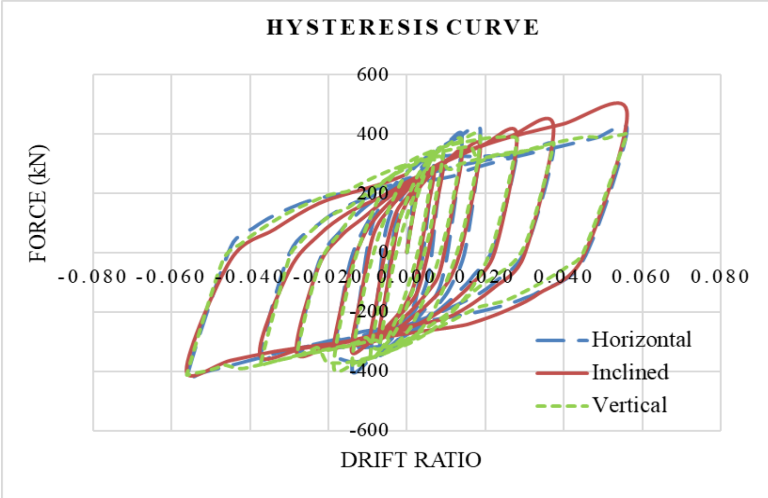

Fig. 3. Hysteretic Curve of braced corrugated shear panel with different orientation.

The skeleton curves for BCSPs with various corrugation orientations (horizontal, vertical, and inclined) are illustrated in Figure 4. Based on the analysis, the following observations can be made:

- **Horizontal Orientation**: This configuration displayed the highest peak loads at each drift level, with the maximum load-bearing capacity reaching 412.68 kN at a drift ratio of 2%. This indicates superior lateral stiffness and energy dissipation compared to the other orientations.
- **Vertical and Inclined Orientations**: The vertical orientation showed moderate load-bearing capacity, while the inclined configuration demonstrated the lowest peak loads, indicating reduced lateral stiffness. However, both configurations still provided sufficient load-carrying capacity for moderate seismic applications.

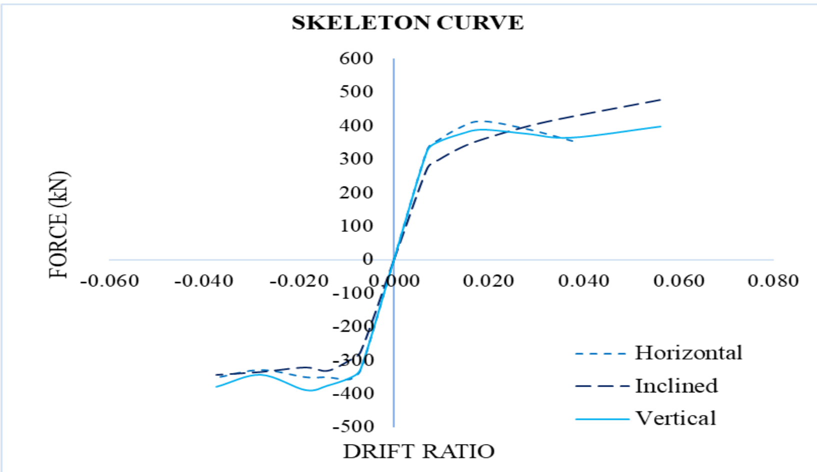

Fig. 4. Skeleton Curves for Different Corrugation Orientations".

B. Effect of Corrugation Angle

To examine the influence of corrugation angle, horizontal BCSP specimens with corrugation angles of 30°, 60°, and 90° were analyzed. As summarized in Table II, an increase in corrugation angle resulted in enhanced load-bearing capacity and stiffness of the panels.

- **90° Corrugation Angle**: The panel with a 90° corrugation angle exhibited the highest load-carrying capacity, with a 7.6% improvement over the panel with a 60° angle and a 26.4% improvement over the panel with a 30° angle.
- **60° Corrugation Angle**: This angle provided balanced performance between strength and ductility, showing substantial load-bearing capacity with moderate deformation.
- **30° Corrugation Angle**: The panel with the lowest angle had the least stiffness and strength but still performed adequately for low-to-medium seismic conditions.

Table 3.5

Corrugation Angle	Maximum Load (kN)	Maximum Displacement (mm)
30°	314.49	8.41
60°	423.60	8.41
90°	427.12	8.41

Table 3.5 indicates that panels incorporating a 90° corrugation angle exhibit superior resistance to lateral deformation and buckling compared to the other configurations.The hysteresis curves for the various corrugation angles are illustrated in Figure 3, depicting the cyclic response of the panels under incrementally applied lateral displacements.

1) 30° Corrugation Angle: The BCSP with a 30° corrugation angle displayed a relatively narrow hysteresis loop, indicating lower energy dissipation and reduced ductility. The maximum load at 2% drift was recorded as 314.49 kN. The narrow loops also suggest less capacity to absorb and dissipate energy under cyclic loading, which is less desirable for structures in seismic regions.

2) 60° Corrugation Angle: The hysteresis curve for the 60° corrugation angle exhibited a wider loop compared to the 30° panel, showing enhanced energy dissipation and greater ductility. The peak load reached 423.60 kN, with minimal pinching of the hysteresis loop, indicating better stability and performance under cyclic loads.

3) 90° Corrugation Angle: The BCSP with a 90° corrugation angle provided the widest hysteresis loops, which is indicative of superior energy dissipation and ductility. The maximum load reached 427.12 kN at a 2% drift, with the loops showing minimal pinching and a stable cyclic response. The performance of the 90° corrugated panel suggests that it is the most suitable configuration for applications requiring high lateral stiffness and energy absorption, such as in earthquake-resistant structures.

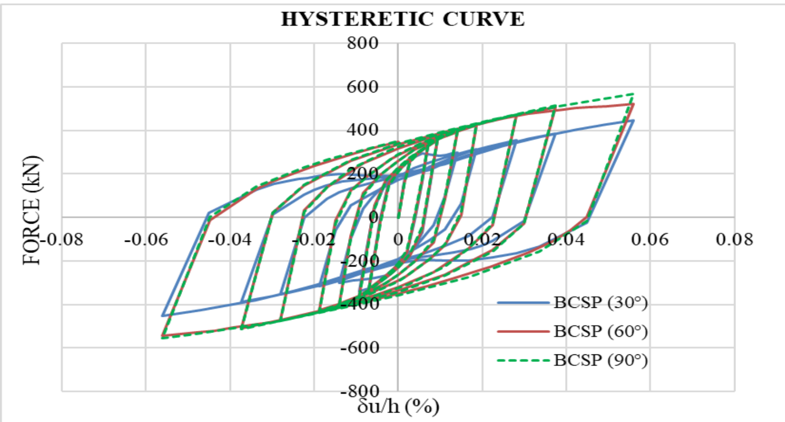

Fig. 5. Hysteresis Curves for BCSPs with 30°, 60°, and 90° Corrugation Angles.

The influence of corrugation angle on the skeleton curves was analyzed, as illustrated in Figure 6. Three corrugation angles—30°, 60°, and 90°—were examined, and the results reveal a pronounced effect of corrugation angle on the structural performance of BCSPs.

- **90° Corrugation Angle**: This configuration exhibited the highest peak load, reaching 427.12 kN at a 2% drift ratio. The higher angle provided greater resistance to lateral deformation, enhancing the overall buckling resistance and load-carrying capacity.
- **60° and 30° Angles**: The 60° angle performed slightly better than the 30° configuration, with a maximum load of 423.60 kN, while the 30° angle exhibited the lowest peak loads. This suggests that increasing the corrugation angle improves both the stiffness and strength of the BCSP.

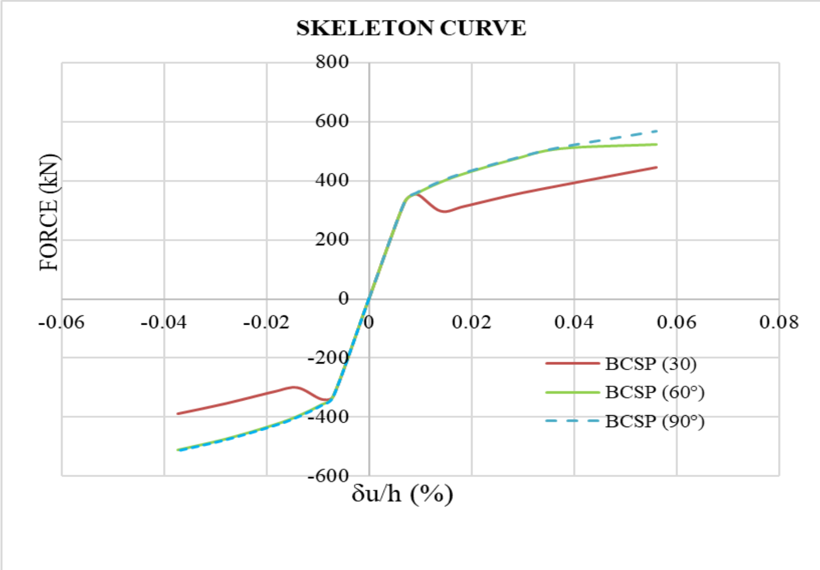

Fig. 6. Skeleton Curves for Different Corrugation Angles.

C. Discussion

The parametric study results indicate that corrugation orientation and angle significantly influence the load-bearing capacity and overall performance of BCSPs. Horizontal corrugation with a 90° angle provided the best performance, demonstrating superior lateral stiffness, load-carrying capacity, and energy dissipation compared to other configurations. These findings suggest that BCSPs with horizontal corrugation and a high corrugation angle are optimal for structures in high seismic regions.

D. Results & Discussion

The parametric study revealed significant differences in the performance of braced corrugated shear panels based on corrugation orientation and angle.

- **Effect of Corrugation Orientation:** Horizontal corrugation provided the highest load-carrying capacity, with a 6% improvement over vertical orientation and a 13% improvement over inclined corrugation (Figure 3). Horizontal corrugation also demonstrated higher stiffness and ductility under cyclic loading.
- **Effect of Corrugation Angle:** As the corrugation angle increased from 30° to 90°, the in-plane stiffness and load-carrying capacity of the BCSP increased. The panel with a 90° corrugation angle exhibited the highest ultimate strength, as shown in Table I. This was attributed to enhanced buckling resistance provided by the increased corrugation angle.

The FEA analysis also indicated that horizontal corrugated panels at 90° provide superior seismic performance, with significant improvements in energy dissipation and lateral stiffness compared to other configurations.

The hysteresis curves clearly show that increasing the corrugation angle from 30° to 90° significantly enhances the performance of BCSPs in terms of ductility, energy dissipation, and cyclic stability. Panels with higher corrugation angles exhibited wider loops with minimal pinching, indicating a better ability to sustain cyclic deformations and absorb seismic energy.

- **Energy Dissipation**: The 90° corrugation angle showed the greatest ability to dissipate energy, making it ideal for structures subjected to seismic loading.
- **Ductility**: The wider loops in the 90° angle configuration demonstrated superior ductility, allowing the panel to undergo greater deformation without losing stability.
- **Stiffness and Strength**: The 90° BCSP maintained the highest stiffness and strength under cyclic loading, as evidenced by the peak loads in the hysteresis curves.

Thus, the BCSP with a 90° corrugation angle provides the best performance in terms of both load-bearing capacity and seismic resilience, making it an optimal choice for earthquake-prone regions.

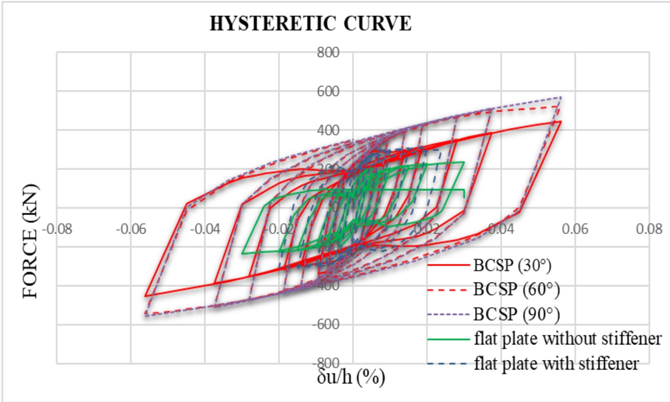

Fig. 7. Hysteretic curve of horizontally corrugated BCSP with & BDSP with and without stiffener.

The skeleton curves clearly illustrate the superior performance of horizontally corrugated BCSPs with a higher corrugation angle. The 90° horizontal corrugation not only increased the load-bearing capacity but also provided enhanced ductility and energy dissipation, making it an ideal configuration for high seismic applications. Both orientation and angle significantly affect the cyclic performance of BCSPs. Horizontal corrugation with a higher angle (e.g., 90°) optimizes the strength and stiffness of the panel, allowing it to absorb and dissipate more seismic energy. The skeleton curves further validate the results obtained from the parametric study, confirming that these configurations are optimal for improving structural resilience under lateral loads.

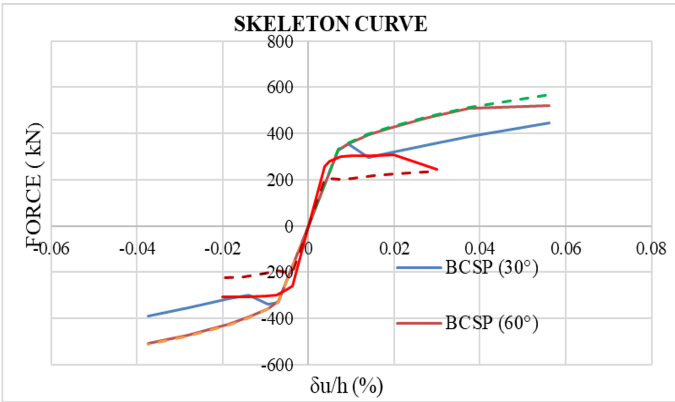

Fig. 8. Skeleton curve of horizontally corrugated BCSP with & BDSP with and without stiffener.

V. Conclusion

This study demonstrates that horizontally corrugated Braced Corrugated Shear Panels (BCSPs) provide superior seismic performance compared to Braced Ductile Shear Panels (BDSPs), both with and without stiffeners. The key findings are as follows:

1. **Horizontal corrugation at 90° significantly enhances structural performance**, yielding the highest load-carrying capacity, stiffness, and buckling resistance. A 90° BCSP exhibits a **38% increase in ultimate load capacity** compared to stiffened braced thin ductile shear panels.
2. **BCSPs achieve better deformation control**, exhibiting a **50% reduction in maximum lateral displacement** relative to stiffened BDSPs, thus improving stability under cyclic loading.
3. **Corrugation angle strongly influences capacity:** Increasing the angle from 30° to 60° and 90° progressively improves load-carrying capacity, while having no significant effect on maximum displacement.
4. **Finite Element Analysis (FEA) validation confirms consistency with experimental trends**, indicating that stiffened BDSPs benefit from added load resistance; however, BCSPs-

particularly those with 90° horizontal corrugation-demonstrate superior strength, stiffness, and cyclic stability.

Overall, **horizontally corrugated BCSPs with 90° corrugation offer the most effective configuration for seismic load resistance**, combining enhanced stiffness, strength, energy dissipation, and reduced lateral deformation. These characteristics confirm their potential as a practical and resilient solution for earthquake-resistant steel structures.

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