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# Behavior of Double Skin Composite Shear Wall with Different Faceplate Configuration towards Cyclic Loading

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**Abstract.** Double skin composite (DSC) shear wall is composed of two exterior steel faceplate connected to each other by connectors and infilled with concrete. In terms of axial and lateral strengths, stiffness, ductility, and energy dissipation capacity, DSC wall performs better than standard Reinforced Concrete (RC). There are two patterns DSC faceplate of DSC, namely flat and corrugated which offers significantly higher out-of-plane bending stiffness. Therefore, this study aimed to explore the effect of faceplate configuration on cyclic behavior of DSC shear wall. Comparison was made regarding the patterns of faceplate including trapezoidal, zig-zag, and curved profiles with flat. This was followed by finite element analysis with ANSYS software to investigate the response of DSC towards cyclic loading. The results showed that among the four profiles, trapezoidal profiles had better energy dissipation and ductility ratio. Trapezoidal pattern offered several advantages in the manufacturing field, including better contact between concrete and good aesthetic appearance. Energy dissipation of DSC wall with trapezoidal faceplate was found to be 37.57%, 23%, and 42.66% more than zigzag, curve, and flat, respectively. There was a reduction in stress by providing corrugated profiles, where the maximum of 54.3% was induced in DSC wall with flat faceplate compared to trapezoidal. This showed that optimizing faceplate configuration further increased the benefits of DSC wall, offering a robust option for seismic design.

*Keywords:* Cyclic loading; Energy dissipation; Double skin composite wall; Faceplate configuration; Finite element analysis

## 1. Introduction

Shear wall is often used in structures to resist lateral loads such as wind and earthquake (Annamdasu *et al.,* 2024; Mustafa *et al.,* 2023; Titiksh and Bhatt 2017). In lower stories of tall buildings, reinforced concrete (RC) are subjected to large axial forces that can be resisted by increasing RC thickness. However, increasing thickness consumes usable floor space, leading to higher self-weight of the building (Zhao, Li, and Tian, 2020; Alarcon, Hube, and De la Llera, 2014; Pecce *et al.,* 2014). This challenge can be addressed by

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developing double skin composite (DSC) for structures exposed to significant lateral forces, such as earthquakes and wind. The composite design combining steel faceplate with a concrete core enhances structural strength, stability, and load distribution, causing greater resilience against buckling and deformation. Absorbs seismic forces are also absorbed, causing improved energy dissipation by minimizing damage and enhancing safety. This wall reduced thickness, leading to lighter structural weight, material savings, and increased usable space. Additionally, steel plates in DSC wall provide extra ductility that allows larger deformations without sudden failure, serving as ideal option for seismic regions.

Because of insulating concrete core, DSC shear wall offers superior fire resistance capable of protecting the steel from high temperatures. Based on corrosion resistance, DSC walls are more durable, protecting the steel from environmental exposure. Prefabrication further simplifies construction, allowing faster and more controlled installation processes. It also offers a robust, efficient, and durable solution combining the benefits of steel and concrete to improve structural performance and longevity ( Qiao *et al.,* 2024; Senthilkumar, Karunakaran, and Chandru, 2023; Yang, Liu, and Fan, 2016). However, the complex design of DSC wall requires specialized analysis, expertise needs, and high costs. This is due to the use of steel faceplate, precision requirements, and the weight demands of strong foundations. In seismic areas, DSC wall adds design complexity to meet standards, balancing their benefits with practical constraints (Senthilkumar, Karunakaran and Chandru, 2023; Yan, Li, and Wang, 2018). DSC wall is composed of two exterior steel faceplates joined through connectors and filled with concrete. External faceplate acts as the main reinforcement for the concrete infill, enabling resistance in-plane shear and out-of-plane moment. It also acts as in-situ formwork to prevent spalling of concrete (Gharaei-Moghaddam, Meghdadian and Ghalehnovi, 2023; Ghodratian-Kashan and Maleki, 2021; Huang *et al.,* 2018; Varma *et al.,* 2014).

In this context, Hitachi Ltd. had proposed DSC wall for coastal structures to withstand impact stresses induced by icebergs or waves Zhao *et al.,* (2020). This was followed by the development of DSC wall for use in nuclear safety-related facilities and infrastructures. During the development, different kinds of connectors were used, including headed studs (McKinley and Boswell 2002; Shanmugam, Kumar, and Thevendran, 2002), bi-Steel connectors (Clubley, Moy, and Xiao, 2003; McKinley and Boswell 2002), and J-hook connectors (Huang and Liew, 2016; Liew and Sohel, 2009). Studies have also been carried out using concrete-filled steel tubes (CFTs) as the boundary elements and faceplate connected by tie bolts, as lateral load-resisting system (Zhao, Li, and Tian, 2020; Ji *et al.,* 2017; Rassouli *et al.,* 2016).

Steel faceplate serves as a formwork for casting concrete to increase the efficiency of construction (Zhao, Li, and Tian, 2020; Yan, Wang, and Wang, 2018; Bruhl and Varma, 2017). Due to the demand for high lateral strength by high-rise buildings, the use of DSC wall is being promoted (Ma, Ma, and Liu, 2019; Ji *et al.,* 2017) to withstand axial load ratio of approximately 0.7 without significant reduction in ductility (Liu *et al.,* 2024; Zhao *et al.,* 2020). Ductility and energy dissipation capacity of RC shear wall are mostly affected by the axial force ratio and reinforcement ratio of wall (Zhang *et al.,* 2020).

According to (Bhardwaj and Varma, 2016), DSC wall consisted of flat faceplate which had tendency to develop deficiencies when transporting and assembling due to the pressure exerted by pouring concrete (Bhardwaj and Varma, 2016). For DSC wall with thin faceplate, there is significant reduction in capacity (Yang *et al.,* 2023; Yan, Li, and Wang, 2018). Flat faceplate is classified as slender or non-slender according to the width-to-thickness ratio (AISC 2010). Non-slender DSC wall may not have a substantial decrease in performance due to the out-of-plane deformations and defects. In comparison, slender

faceplate offers a significant reduction in capacity (Zhang *et al.,* 2019; Bhardwaj and Varma, 2016). A recent study reported that bond slip between flat steel plate and concrete of DSC wall easily occurred (Senthilkumar, Karunakaran and Chandru, 2023; Wang *et al.,* 2019b). Corrugated plate also has significantly superior out-of-plane flexural stiffness and better buckling resistance than flat plates (Alatoum and Musmar, 2022; Wang *et al.,* 2019a; Qiu *et al.,* 2018; Zhao *et al.,* 2017). Deformation and energy dissipation capacity can be enhanced by providing the boundary columns to DSC wall, thereby improving resistance to seismic loads (Miao *et al.,* 2022; Qian, Jiang, and Ji, 2012).

Based on the description, this study aimed to examine the impact of faceplate profile on cyclic behavior of DSC shear wall. The performance of trapezoidal, zig-zag, and curved profiles were compared with flat DSC shear wall. Cyclic behavior was evaluated in terms of energy dissipation, hysteretic response, deformation, ductility, damage, and failure patterns. The numerical investigation was performed using finite element software ANSYSProvide an adequate background, context of the problems based on the literature review. Subsequently, the study objectives were stated, and originality was emphasized (state of the art).

## 2. Methods

### *2.1. Numerical Study*

Finite Element (FE) Analysis is an efficient method for analyzing the mechanical behavior of complex structures to show important insights into performance under diverse loading conditions (Hamza *et al.,* 2023; Kholil *et al.,* 2023). This method uses ANSYS to execute the numerical study. FE model comprised the steel faceplate, shear studs, concrete wall, and concrete-filled steel tube. The concrete was used as the infill between the steel faceplate and tubes. The infilled concrete was of compressive strength 29.2GPa and Poisson's ratio 0.15.

#### 2.1.1. Finite element modeling

DSC wall having corrugated faceplate with three different profiles such as trapezoidal, zigzag, and curved were considered for analysis, and a comparison was made with flat faceplate. The thickness of faceplate and wall were fixed for flexural rigidity of $1.28 \times 10^{14}$ N/mm$^2$ to be the same for all the four models considered. A bilinear kinematic hardening property with 1% strain hardening was adopted. Shear connectors were used to connect the steel faceplate to the infill concrete. Plates were joined using an equal number of 8 mm diameter high-strength bolts for all models. For trapezoidal plate profile, studs were provided at a spacing of 140 mm in horizontal and 150 mm in vertical directions, respectively.

Concrete-filled steel (CFS) tubes were provided on the two boundaries to resist the induced bending moment. The columns functioned as anchors for the steel plate's tension field and bearing supports for the compression diagonals in the concrete wall. The steel tubes were 150 mm x100 mm in size with 4 mm thickness and were placed at both ends of the shear wall. The material properties of steel faceplate, shear studs, and CFS are shown in Table 1.

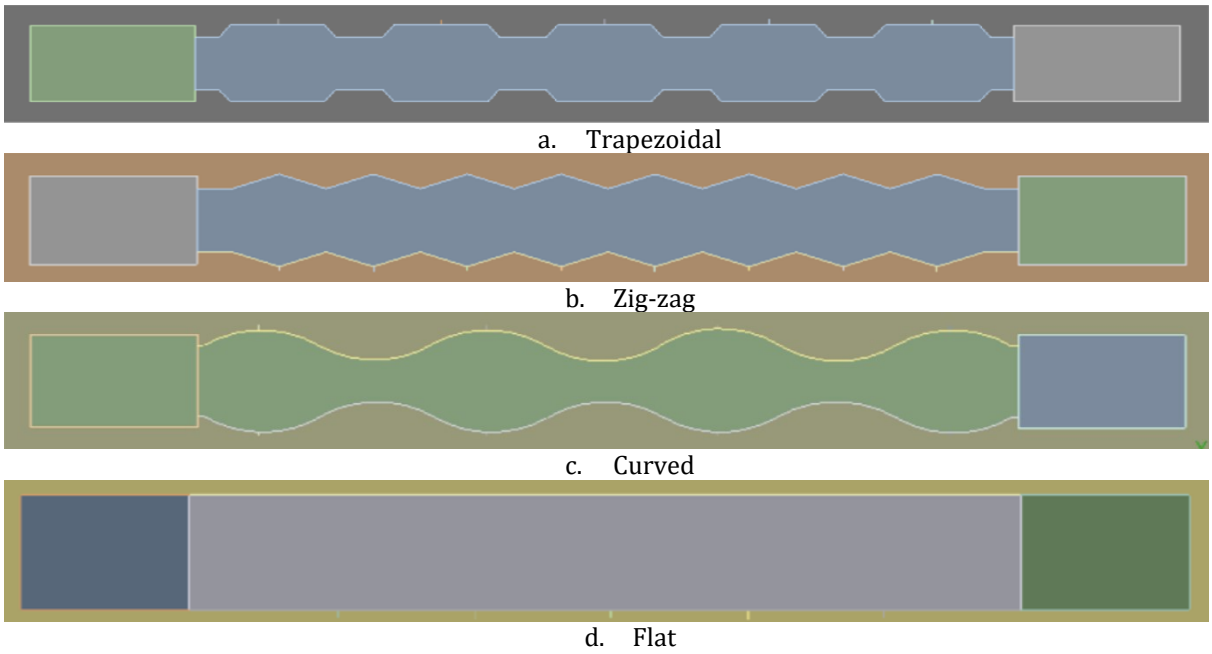
**Table 1** Mechanical Properties of Steel faceplate, CFS tube, and Bolt (Luo *et al.,* 2021)

| | Yield strength (MPa) | Ultimate Strength (MPa) |
|---|---|---|
| Steel plate | 307 | 445 |
| CFS tube | 328 | 386 |
| Bolt | 640 | 800 |

The geometric properties of CFS wall with different faceplate profiles are shown in Table 2. Figure 1 shows the cross-section of the models developed in ANSYS software and Figure 2 represents FE model of DSC wall with trapezoidal faceplate.

**Table 2** Geometrical properties of DSC wall with different faceplate profile

| Description | Faceplate profile | | | |
|---|---|---|---|---|
| | Trapezoidal | Zig zag | Curved | Flat |
| Wall Width (mm) | 1000 | 1000 | 1000 | 1000 |
| Web Width (mm) | 700 | 700 | 700 | 700 |
| Wall thickness (mm) | 100 | 80 | 85 | 80 |
| Height (mm) | 2000 | 2000 | 2000 | 2000 |
| Faceplate thickness (mm) | 3 | 4 | 4 | 4 |



a. Trapezoidal

b. Zig-zag

c. Curved

d. Flat

**Figure 1** Cross sections of DSC shear wall.

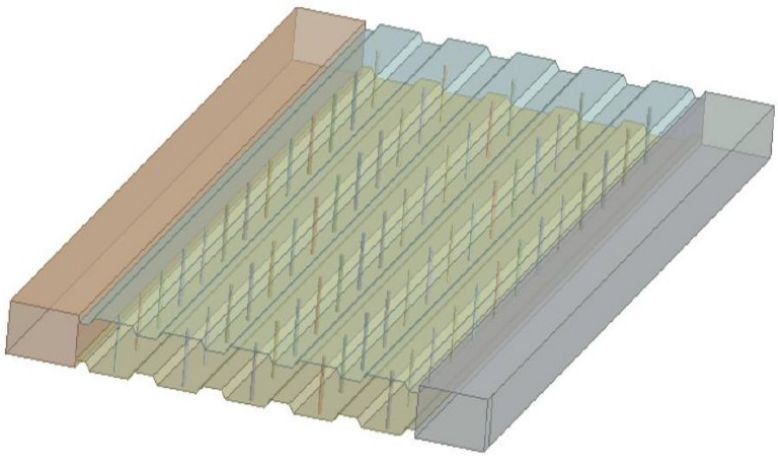


**Figure 2** FE model of DSC wall with trapezoidal faceplate

The concrete is modeled using Solid 186 element available in ANSYS element library. Solid 186 is a 3D 20-node element with 3 degrees of freedom (translation in x, y, and z directions). Faceplate is modeled using shell 181element, which is a 3D 4-node element

with 6 DOF (translations in x,y,z direction and rotations about x,y,z direction). Beam 188, 3D 2-node element with 6 DOF is used for the modeling of shear studs.

2.1.2. Loading and Boundary Conditions

Cyclic loading in the horizontal direction in Figure 3 is applied at the top of wall. The drift ratio and the corresponding displacement value for the model of 2000 mm height are shown in Table 3. Fixed support is provided at the base of the foundation with all degrees of freedom restricted.

**Table 3** Displacement corresponding to the drift ratio

| Drift Ratio (%) | 0.13 | 0.25 | 0.38 | 0.50 | 0.75 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Displacement (mm) | 2.6 | 5 | 7.6 | 10 | 15 | 20 | 30 | 40 | 50 | 60 | 70 |

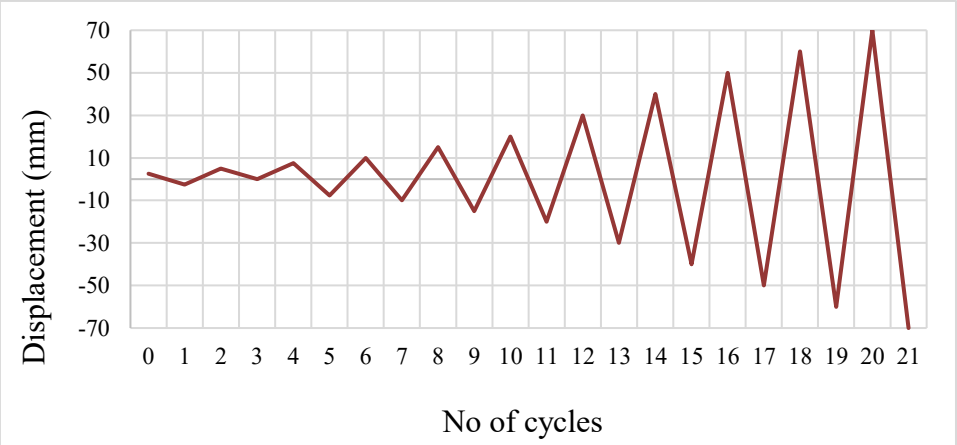



**Figure 3** Cyclic loading protocol.

*2.2. Validation of Models*

In this study, the numerical investigation carried out by Zhao, Li, and Tian (2020) was used for the verification of FE model of DSC wall with trapezoidal faceplate profile, as shown in Figure 2. The geometric details of the model are given in Table 2. DSC wall with trapezoidal profile was analyzed and energy dissipation was found to be $1.21 \times 10^7$ J. For the drift ratio of 1.5% and the corresponding displacement of 30 mm, the load value obtained in the present study was 640 kN. Meanwhile, through the numerical analysis conducted by Zhao, Li, and Tian (2020), the maximum load was 624kN. The load-displacement curve was plotted, as shown in Figure 4.

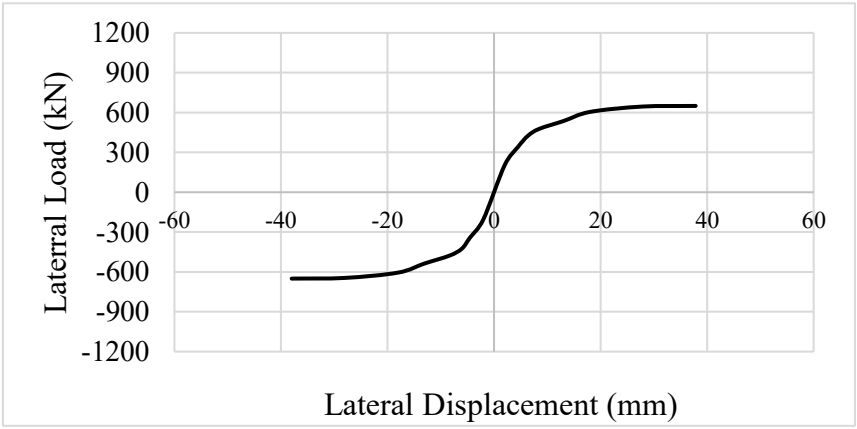



**Figure 4** Load Displacement curve for DSC wall trapezoidal faceplate profile.

## 3. Results and Discussion

Behavior of composite shear wall with different faceplate configurations was evaluated under displacement-controlled cyclic load. The examination was carried out regarding the response parameters such as energy dissipation, maximum stress, total deformation, yield load, ultimate load, yield displacement, ultimate displacement, and ductility ratio. Energy dissipation was obtained from the hysteresis loop given in Figure 5 for DSC wall of different profiles.

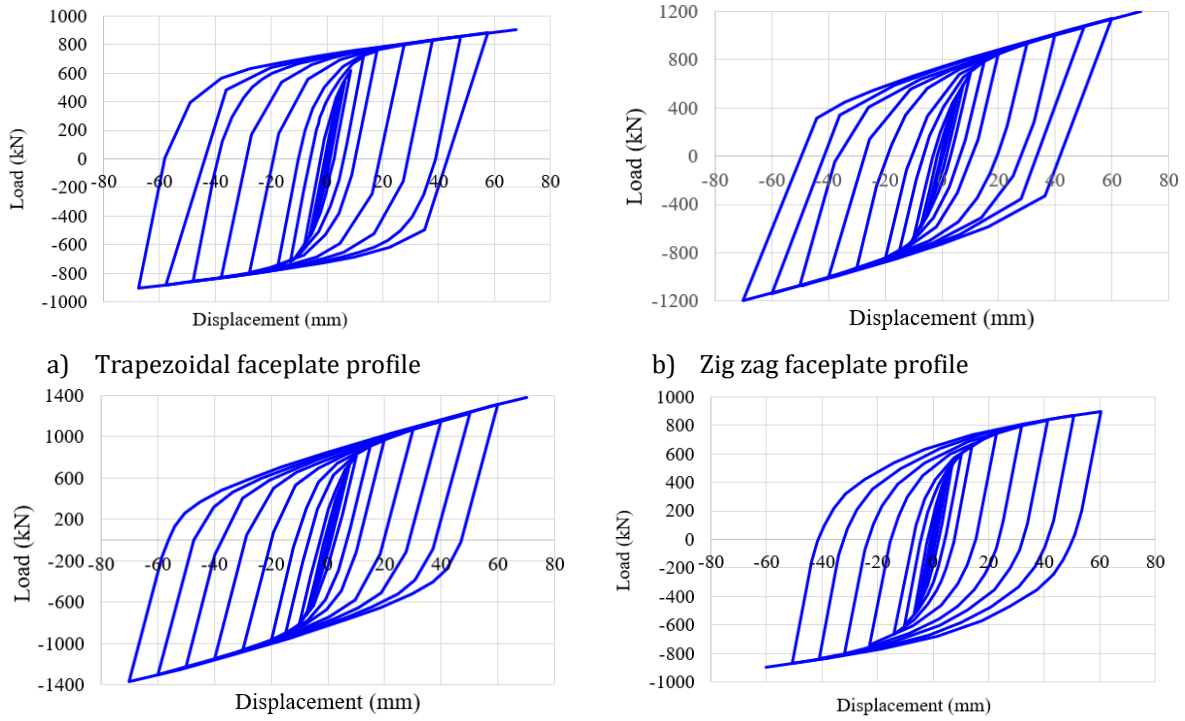
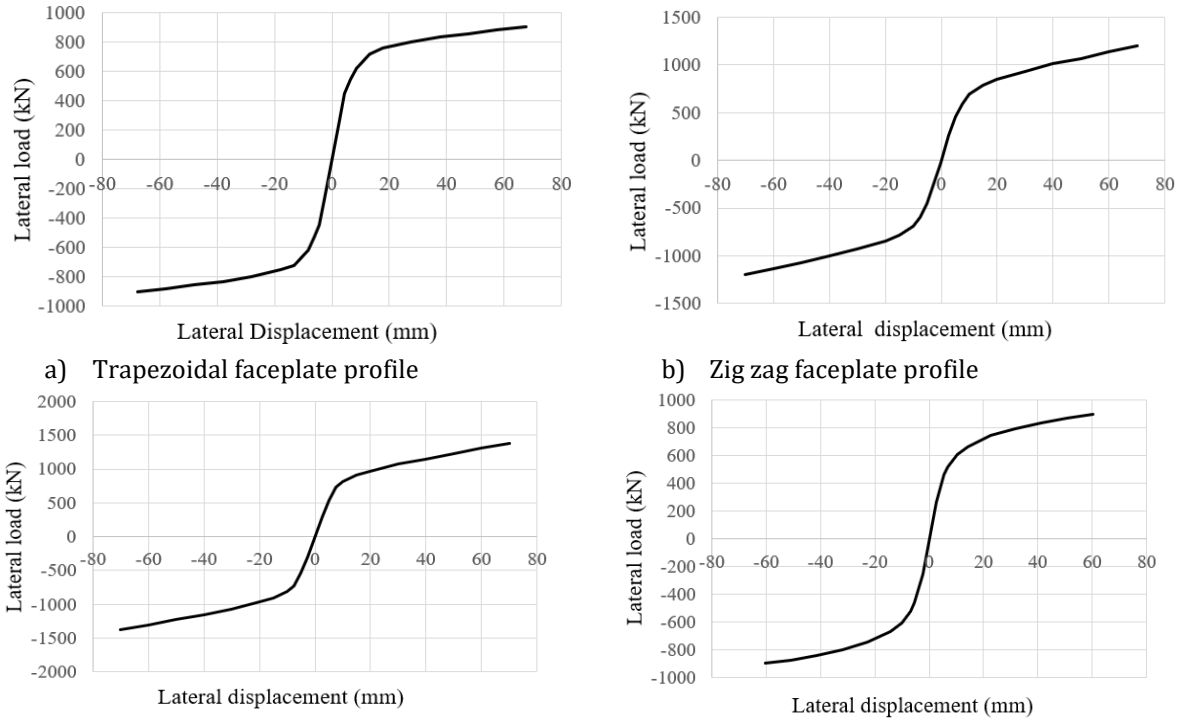



**Figure 5** Hysteresis loop of DSC wall

Load-deflection curve in Figure 6 was used to compute energy dissipations, with the results shown in Table 4. Energy dissipation was found to be the maximum of $1.65 \times 10^7$ J for DSC wall with trapezoidal faceplate profile. Meanwhile, zig zag, curved, and flat profiles had $1.03 \times 10^7$J, $1.27 \times 10^7$J, and $9.45 \times 10^6$J, respectively. Energy dissipation of trapezoidal faceplate was 37.57%, 23%, and 42.66% more than zig-zag, curved, and flat faceplate profiles, respectively.

The maximum stress in faceplate was 429.66 MPa, 435.71 MPa, 411.79MPa and 663.45 MPa for DSC wall with trapezoidal, zig zag, curved, and flat faceplate profiles, respectively, as shown in Figure 7. By providing corrugated profiles for faceplate, the stresses induced can be considerably reduced. The maximum stress developed in the steel tubes of boundary elements of DSC wall with trapezoidal, zig zag, curved, and flat faceplate profiles were 402.34 MPa, 388.48 MPa, 365.32MPa, and 346.58 MPa, respectively. The stress distribution along faceplate and steel tube was found to be more uniform in DSC wall with trapezoidal profile.




a) Trapezoidal faceplate profile

b) Zig zag faceplate profile

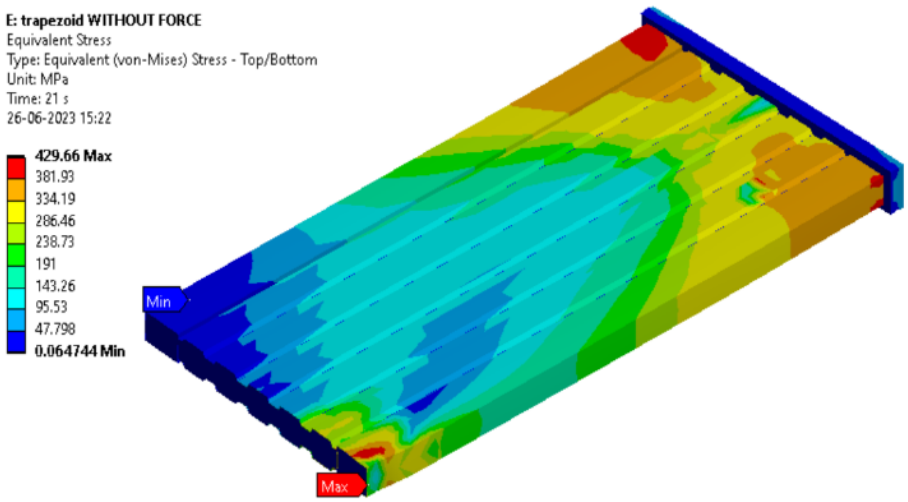
c) Curved faceplate profile

d) Flat faceplate profile

**Figure 6** Load deformation plot of DSC wall

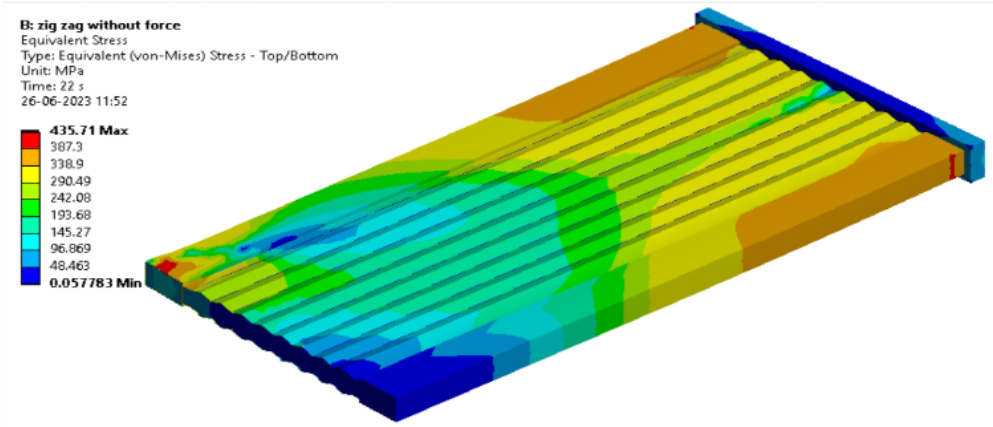
**Table 4** Response of the specimens to cyclic loading

| | Trapezoidal | Zig-zag | Curved | Flat |
|---|---|---|---|---|
| Yield load (N) | 6.21 x $10^5$ | 6.89 x$10^5$ | 8.14 x$10^5$ | 6.06 x $10^5$ |
| Yield displacement (mm) | 8.44 | 10 | 9.97 | 10.3 |
| Ultimate load (N) | 9.04 x $10^5$ | 1.2 x $10^6$ | 1.38 x $10^6$ | 8.96 x$10^5$ |
| Ultimate displacement (mm) | 67.58 | 70 | 69.9 | 60.35 |
| Ductility ratio | 8 | 7 | 7 | 5.83 |

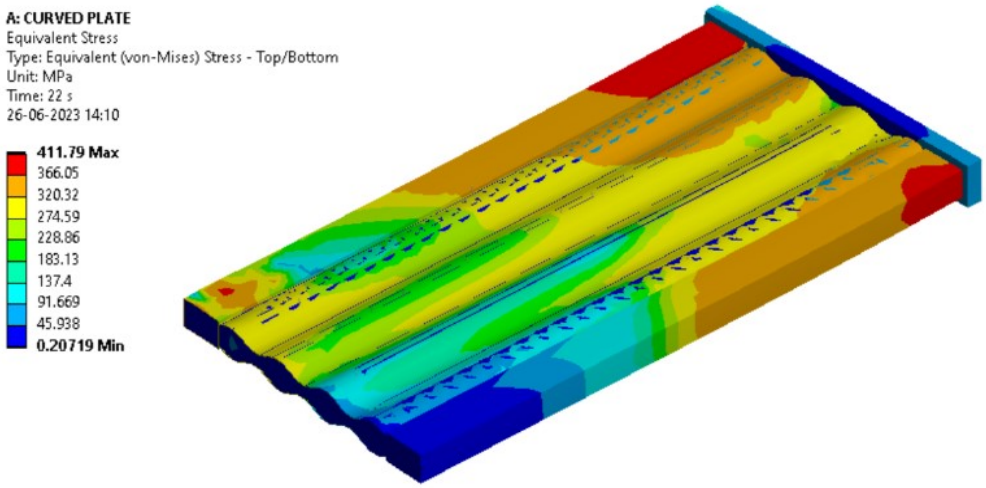



a. Trapezoidal faceplate profile

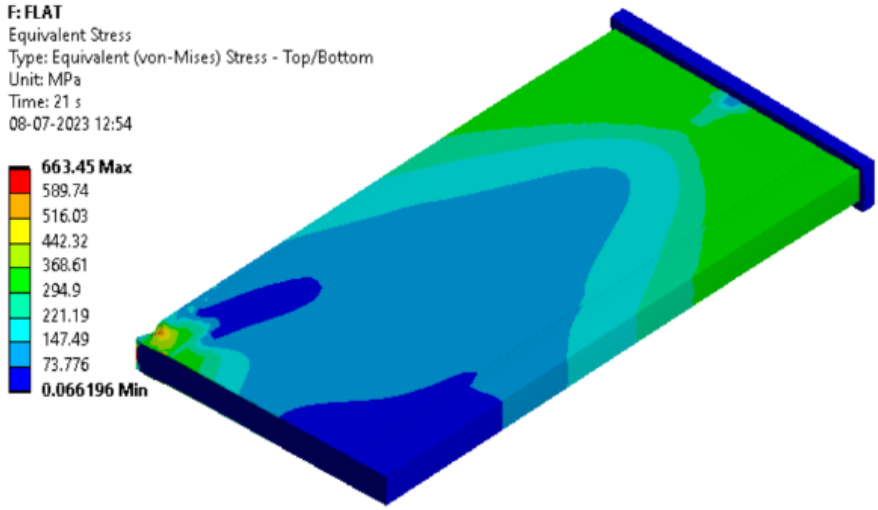
**Figure 7** Stress distribution of DSC wall




b. Zig-zag faceplate profile




c. Curved faceplate profile




d. Flat faceplate profile

**Figure 7** Stress distribution of DSC wall (cont.)

The results showed that trapezoidal provided additional points of plastic deformation, allowing the formation of multiple hinges to absorb and dissipate more energy (Ma, Chai, and Chen, 2022). In composite shear wall, plastic deformation significantly contributed to energy dissipation capacity. Compared to curved or zig-zag, trapezoidal profiles showed a

higher out-of-plane stiffness, which prevented unwanted deformations and enhanced energy dissipation capacity. Although trapezoidal profiles showed good energy dissipation, their response to seismic forces varied based on load patterns and cyclic loading. Trapezoidal shape could lead to uneven stress distribution along the profile, potentially creating stress concentration points capable of reducing the structure's efficiency or causing premature failure. Furthermore, trapezoidal profiles are more complex to manufacture than flat or curved, requiring precise formation processes and specialized equipment to create trapezoidal folds leading to higher production costs.

## 4. Conclusions

In conclusion, this study analyzed cyclic behavior of DSC shear wall using ANSYS software based on trapezoidal, zigzag, curved, and flat faceplate profiles. To identify the best configuration, cyclic analysis was performed by examining energy dissipation, load-carrying capacity, and ductility parameters. The results showed that DSC shear wall with corrugated faceplate under horizontal cyclic loading performed better than flat type. Among the four profiles, trapezoidal faceplate showed superior energy dissipation and ductility, indicating 37.57%, 23%, and 42.66% higher energy dissipation than the zigzag, curved, and flat profiles, respectively. Furthermore, trapezoidal faceplate showed a higher ductility ratio, providing greater stability against lateral loads, with ductility ratios of 8, 7, 7, and 5.83 for trapezoidal, zigzag, curved, and flat faceplate, respectively. The load-carrying capacity was also higher for wall with corrugated profiles, and the stresses induced in trapezoidal were significantly lower, with the flat faceplate experiencing 54.3% more stress. Considering these response parameters, trapezoidal profile was found to be the most effective, offering additional benefits such as improved concrete contact and aesthetic appeal. Therefore, DSC wall with trapezoidal faceplate were recommended as the superior option among composite shear wall.

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## Conflict of Interest

The authors declare no conflicts of interest.

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