Trapezoidal corrugated plate behavior on Steel Plate Shear Wall

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Abstract. Corrugated Steel Plate Shear Wall (CoSPSW) is a corrugated steel plate used in steel frame structures with shear walls instead of flat plates. Corrugated steel plates are reported to have greater strength than using flat steel plates. This study's specimen model is a one-story steel frame with shear walls using trapezium corrugated plates at an angle of 45°. The analysis was carried out with a finite element analysis using Patran and MSC Nastran software. Structural loading in the form of a monotonic static load with displacement control. The thickness of the corrugated steel plate is varied to analyze the effect of the depth of the corrugated plate on the behavior of the structure. The analysis results of the specimen model indicate that the value of strength, stiffness, and ductility will increase along with the thickness of the corrugated plate. The CoSPSW structure begins to behave in ductile when the corrugated plate's depth is \( \geq 2/3 \) of the cross-section web thickness.

1. Introduction
According to SNI 03-1729-2015 codes, the moment frame is a frame system that provides resistance to lateral loads and provides structural system stability, mainly through shear and bending of the frame structure components and their connections [1]. The moment frame is the most common form of a structure consisting of beams and columns. It works together in a unified whole to withstand the load. Efforts to increase the steel frame's strength can be added stiffeners (bracing) or shear walls.

Shear wall is one element to hold lateral loads and serves to increase structural stiffness. Using a shear wall is one solution that can be used to improve the rigidity of a structure in the horizontal direction to resist lateral forces.

Steel Plate Shear Wall (SPSW) is a lateral load retaining system on a steel frame consisting of vertical steel plates connected to the surrounding beams and columns. It is installed in one or various spans at the structure's full height to form a wall [2]. SPSW provides several benefits such as adequate lateral stiffness and strength, acceptable energy dissipation, and good post-buckling conditions. But there are some weaknesses primarily related to the sudden decrease in stiffness and strength in the post-buckling phase [3]. The shear buckling behavior of steel plates is a significant concern in shear walls of thin steel plates. Initially, to prevent buckling, SPSW was designed with a very rigid filler plate. However, several experimental and analytic studies using quasi-static and dynamic loading show that post-buckling's strength and ductility from thin plate SPSWs become very large.

SPSW in this study uses corrugated plates as shear walls. Corrugated shear walls (CoSPSW) have greater strength than flat plate shear walls. The use of corrugated plates has been proposed as an
alternative to steel shear walls to avoid several lack of flat plates and improve structural and seismic performance. Shear walls of corrugated steel plates have a unique buckling mode. Corrugated steel plates produce geometrical behavior in which axial and out-plane stiffness parallel to the wave increases tremendously, while stiffness in the direction perpendicular to wave decreases significantly, known as the Accordion Effect [4]. As a result, corrugated steel plates are capable of being in a pure shear and do not experience gravity loads if placed horizontally on the shear wall plates. The corrugated shear wall thickness can affect the capacity and rigidity of a structure [5].

The purpose of this study is to increase understanding of the influence of static monotonic loading on a steel frame by using a horizontal corrugated shear wall against structural behavior. Structural behavior is reviewed in the form of ultimate load, structure ductility, and stress distribution. The analysis also varied the depth of the corrugated shear wall thickness.

2. Analysis

2.1. Geometric properties

The analysis is carried out on the steel frame structure with width and height from centerline to centerline is 1500 × 1000 (mm.). The beams and columns use steel sections of WF 250.125.6.9. (mm.). The image can be seen in Figure 1. The steel frame structure is given a corrugated plate with a wave pattern in the horizontal direction (horizontal corrugated) between the two columns and the beam.

Figure 1. Geometric properties of steel frame

Figure 2 shows the corrugated plate pattern used, a plate with a trapezoid pattern with an angle of 45°. The thickness of the horizontal corrugated plate (t_{hc}) will be varied, with the maximum depth equal to the web thickness of the cross-section (t_{w}), which is 6 mm.

2.2. Material properties

The steel material is using BJ-370 steel with ultimate stress (f_u) 370 MPa, and yield stress (f_y) 240 MPa. The elastic modulus is 2×10^5 MPa and the Poisson ratio 0.3. Material is modeled as a function of bilinear material.

2.3. Finite Element Model

CoSPSW is modeled using Patran software; then, specimens are analyzed using MSC Nastran. The relationship between corrugated plates, beams, and columns is modeled with perfectly connected. The support in the column, the underside of the corrugated plate is modeled as fixed support. It will lock the direction of displacement and rotation in all directions. Besides, four nodes at the beam-column joint were also restrained.

The lateral load is given to the structure in the form of static monotonic displacement. Loads which are displacement controls, are delivered gradually until the structure reaches the ultimate condition.
3. Analysis and Result

3.1. Load-displacement relationship
The output obtained from the analysis using MSC Nastran software. The results of testing the CoSPSW steel frame with a static monotonic load produce a load vs. displacement curve (figure 4). This curve shows the value of the capacity required to push the steel frame according to displacement control.

Figure 4. Horizontal Corrugated- SPSW load-displacement relationship in a variety of thicknesses.

The load vs. displacement curves above are then analyzed to obtain the yield and ultimate values for each specimen model. The ultimate displacement value ($d_u$) is directly obtained based on the maximum load value. The yield displacement ($d_y$) is calculated in a tangential way. The intersection point between the tangential line and the ultimate load value is expressed as the yield displacement (figure 5).
Figure 5. Horizontal Corrugated-SPSW load-displacement relationship, $t_{hc} = 3$ mm.

Furthermore, the value of stiffness, ductility, and drift ratio can be calculated and given in Table 1 as follows:

| Model | Shear wall type | $t_{hc}$ (mm) | $P_{ult}$ (kN) | $d_{ult}$ (mm) | $d_y$ (mm) | Stiffness (kN/mm) | $\mu$ | Drift ratio |
|-------|-----------------|---------------|----------------|----------------|-------------|-------------------|------|-------------|
| HC2.5 | Corrugated      | 2.5           | 581.023        | 3.222          | 2.904       | 198.72           | 1.110| 0.003       |
| HC3   | Corrugated      | 3             | 678.566        | 3.887          | 3.130       | 214.29           | 1.242| 0.003       |
| HC4   | Corrugated      | 4             | 842.757        | 9.062          | 3.467       | 237.98           | 2.614| 0.008       |
| HC5   | Corrugated      | 5             | 939.412        | 13.750         | 3.377       | 275.23           | 4.072| 0.012       |
| HC6   | Corrugated      | 6             | 905.819        | 15.625         | 3.236       | 275.36           | 4.828| 0.014       |

From the table above, it can be seen that the thickness of the corrugated plate affects the increase in ultimate load, ductility, and structural stiffness.

3.2. Stress distribution

Based on the corrugated plate's load vs. displacement curve with $t_{hc} = 2.5$ mm dan $t_{hc} = 3$ mm (figure 6), the structure tends to be brittle. The structure experiences a sudden decrease in strength right after reaching the ultimate load. Based on the specimen's stress distribution, it can be seen that there is a high-stress concentration in the support area. It can cause the lower left column of the web cross-section to bend. The observation of the corrugated plate condition shows that all parts of the plate have yielded.
Corrugated plates with \( t_{hc} = 4 \) mm (figure 7), the structure behavior is more ductile. Ductility value increases up to 1.36 times compared to corrugated plates with thickness \( t_{hc} = 2.5 \) mm. The decrease in strength occurs gradually after the structure reaches the ultimate load. In the ultimate displacement condition, the stress concentration in the left column is concentrated in the support area and distributed to the half-height of the column. It can delay the buckling in this section. Based on the stress distribution, it can be seen that all parts of the corrugated plate have also yielded.

For corrugated plates with \( t_{hc} = 5 \) mm dan \( t_{hc} = 6 \) mm (figure 8), the ductility specimen value can increase up to 3.35 times compared to corrugated plates \( t_{hc} = 2.5 \) mm. In this condition, the stress concentration on the left column support will decrease. Corrugated plates have not yet reached the yield stress limit under ultimate displacement conditions.
4. Conclusion

Strength, stiffness, and ductility values will increase as the thickness of the corrugated plate is used. The increase in ultimate load is 62%, stiffness by 39%, and reached a 335% increase in ductility. The CoSPSW structure starts to behave in ductile when the plate thickness used is ≥ 2/3 \( t_w \) cross-section. At thickness, \( t_{hc} = 2/3 t_w \), the condition of all plates has reached the yield stress limit. If depth \( t_{hc} > 2/3 t_w \) is used, this will reduce the stress concentration in the left column support, the structure is more ductile, but no part of the corrugated shear wall plate reaches the yield stress limit.

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