Study of Capacity Calsium Board – Styrofoam Sandwich Panels on Wall Systems under Cyclic Lateral Force

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ABSTRACT

A new type of lightweight shear wall has been developed using composite panels, with styrofoam as the core layer and calcium board as the skin layer. This innovation aims to facilitate the rapid construction of housing in response to earthquake disasters. Physical testing of the material showed an increase in the compressive strength of the styrofoam core, from 2.14 MPa to 3.74 MPa in 75 mm thick sandwich panels. This study examines the use of precast panels with specific installation techniques involving pick-up beams (sloofs), connectors, and panel to panel connections to enhance wall strength against horizontal earthquake loads. The conducted cyclic loading test followed the ASTM E2126-18 (2018) standard loading cycle pattern test method. Lateral force experiments were conducted on full-scale shear walls with two different panel-frame connection modes. The test results revealed the behavior of Panel Lightweight Concrete (PLC) walls under cyclic lateral forces. Combined wall panels acted independently, and the use of PVAc adhesive and steel connectors resulted in a unified wall behavior system. The displacement behavior of the wall within the pinch system in the notch on the sloof demonstrated positive results. Quipanel walls can reduce building weight, mitigate earthquake forces, and provide a robust structure capable of withstanding long-term lateral forces. This development leads to the construction of simple, earthquake-resistant houses.

Keywords–prefabricated panels; lightweight concrete; shear wall; notch connection; connector

I. INTRODUCTION

The weight of conventional building constructions is one of the primary causes of severe damage when they are subjected to the horizontal forces of an earthquake. According to the Damage Avoidance Design (DAD) philosophy, structures must be capable of withstanding earthquake-induced displacements while minimizing structural damage [1]. Building walls are generally made of brick or concrete brick, but both materials have certain weaknesses, such as being heavy and brittle. The volumetric weights of conventional materials are: brick (15 kN/m³), lightweight concrete bricks (22 kN/m³), and solid concrete (24 kN/m³). Earthquake disaster management often faces problems in access to coverage of the affected locations; one of the problems is the transportation of heavy and difficult building materials. Transportation to far locations places an additional financial burden on disaster management [2]. This is problematic because the earthquake load increases linearly with the weight of the structure. Failures in brick masonry, both out-of-plane mechanisms and in-plane infills, are often caused by weak connections between walls [3]. Seismic studies of sliding walls indicate that poor conditions at concrete joints are the primary cause of severe earthquake damage [4]. The brittle nature of conventional building materials makes them susceptible to damage, such as cracking, even at relatively low rates of deformation. Infill walls have great contributions to building behavior under lateral loadings like earthquakes [5].

Over time, advancements in mineral and chemical admixtures, as well as improved particle strength of artificial aggregates, have enabled lightweight production. The characteristics of aggregate concrete, both mechanical and rheological, have been improved [6]. Industries and post-consumer products generate styrofoam waste. They are non-biodegradable but are usually disposed by burning or landfilling leading to environmental pollution and recycling solutions aim to decrease their negative effects on the environment. This problem can be solved by using waste styrofoam as a recycled material to produce sustainable Lightweight Concrete (LWC) [7]. Polystyrene sandwich panels, paired with two rigid sheets as outer layers, have the potential to form robust and lightweight wall panels. The additional rigidity provided by the outer layers enhances the elasticity of the panel. A comparative analysis of the results from axial load testing on a composite panel specimen revealed a higher elastic modulus compared to a single styrofoam concrete specimen. Therefore, it was concluded that the outer coating added rigidity to the composite panel material. Expanded Polystyrene (EPS) is made from plastic polystyrene particles, which are heated with small gas bubbles [8]. Utilizing styrofoam as filler in concrete in the form of cylinders can decrease both the weight and the volume of concrete, while also mitigating environmental pollution and reducing the utilization of natural resources such as grass or sand [4-8].

The approaches to developing lateral force-resisting systems in North America and Europe presume that the lateral resistance of lightweight material walls primarily relies on the sliding resistance of all connectors at the base of the wall. The model emphasizes reinforcing the moment at building corners [11, 12] or by securing each wall corner [9, 10]. Three types of kinematic behavior can be distinguished: (1) Coupled wall behavior, where each segment of the rock wall behaves independently as an individual panel around its lower corner, (2) wall panels exhibit single-coupled wall behavior, functioning as partially fixed panels with semi-rigid screwed connections, and (3) combination of single system behavior panels with rigid screwed connections [14]. In the context of earthquake-resistant buildings, it is imperative to optimize the sliding capacity of walls to support lateral seismic behavior and mitigate earthquake loads [15, 16].

Two groups of connections were tested on composite panel walls: metal connectors and screw connections. During the cyclic wall test with metal bracket connectors connecting the wall to the foundation, failure occurred at the base of the wall around the anchor rod, resulting in a significant change in the connection [17]. The tested wall was connected to the floor and ceiling using metal bracket connectors, and a continuous bonding rod (16 mm in diameter) was positioned at both ends of the wall through the floors and ceilings to serve as rolling holder [18]. For H/B = 1, the shaking is predominantly influenced by the shaking component (4.72% of the total wall shake at 5% shake), whereas for H/B = 0.5, the primary contributor shifts to the sliding component (4.25% drift caused by sliding at 5% wall drift). This trend suggests that a lower ratio indicates that the sliding wall is less slender, making rotation more difficult, thereby resulting in a higher contribution from the sliding component.

The impact of using connector materials on previously conducted tests is as follows: (a) With BFRP connectors of all sizes, increased final load capacity and rigidity were observed across all angle model degrees (30, 45, 60). (b) When using steel connectors ranging from small to large diameters, improvements in final load capacity and rigidity were achieved. Specifically, employing diameters of 6 and 8 mm resulted in enhancements, whereas a reduction in capacity was observed with a smaller diameter of 4 mm. (c) There is a discernible change in failure mode with variations in connector size, transitioning from buckling of small-diameter connectors to crushing of larger diameter connectors [19]. As the diameter increases, the construction of the holder of the panel bonding decreases as the connectors take up a higher portion of the load applied. The variation in sliding connector distance produces a similar effect to changing the connector diameter. However, the failure mode of the connectors depends on diameter rather than quantity. Earthquake-resistant building technology, which is fast, inexpensive, and lightweight to install, is essential for areas situated in large earthquake zones. Experimental studies investigating precast concrete have shown that seismic performance in construction depends entirely on the design and durability of the connections [16-21]. The quipanel, as a precast material, consists of three physical layers: calcium board as the core and styrofoam as the skins. Its dimensions, 3000 × 600 × either 75 mm or 50 mm, are suitable for sliding walls weighing at least 650 kg/m³ and walls with a thickness of at least 13 mm [22] are displayed in Figure 1.

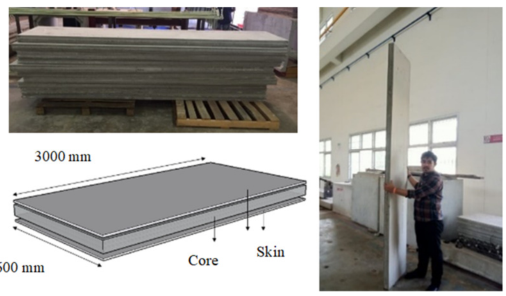


Fig. 1. Prefabricated sandwich panels.

The escalation of natural disasters and earthquakes presents challenges in accessing affected areas, limited availability of workforce, and the urgency for swift response. Precast materials offer a potential solution for effective disaster management. This study investigates the capacity of precast sandwich lightweight concrete panels, composed of styrofoam and composite calcium board (refer to Figure 1), to provide adaptive wall engineering capable of withstanding sliding and uplift modes under cyclical loads.

II. MATERIALS AND METHODS

A. Physical Material

The composite panel in this study adheres to the design principle of a sandwich structure, featuring two rigid layers serving as the skin and a lightweight core layer acting as the web. The core layer possesses greater thickness compared to the overall layers of the lightweight composite panels, thereby producing composites with a higher strength-to-weight ratio and rigidity-to-weight ratio [20, 21] as well as economical and energy-efficient values [25]. In this study, 2 test specimens were studied. This prefabricated material was produced in two thickness types, 50 mm and 75 mm, both with the same dimensions (3000 × 600 mm). Several physical tests were conducted on the base material, including tests for weight, compressive strength, sliding, and direct sliding. The test documentation is exhibited in Figure 2. The results of the material's physical tests are summarized in Table I.

TABLE I. SUMMARY OF PHYSICAL TEST RESULTS

Specimen core thickness (mm)	Compressive strength (MPa)	Elasticity module	Flexural strength (MPa)	Weight (kg)
50	2.14	89.82	0.88	
75	3.47	98.05	2.00	97.217

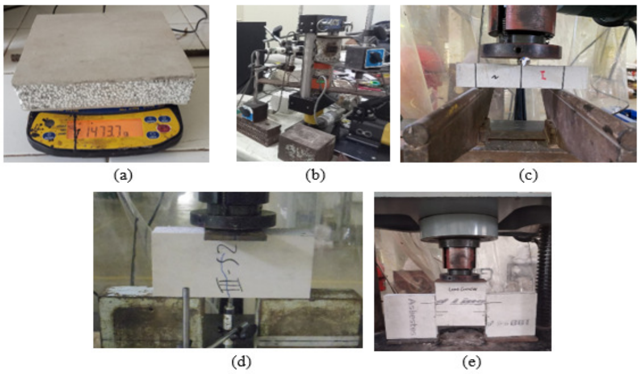


Fig. 2. Physical test series of precast panel materials (a) volume weigth, (b) compressive strength, (c) and (d) bending strength, (e) direct strength.

TABLE II. PLC SPECIMEN MATRIX

Test configuration	Connection type	Panel dimensions (mm)		
		Height	Width	Thickness
PLC 1	Normal	3000	1800	75
PLC 2	Ø 10 mm stainless steel connector + PVAc glue	3000	1800	75

The cyclical tests conducted in this study utilized full-scale panels assembled into specimen walls. There are three prefabricated panels the dimensions of which are specified in Table II.

B. Full-scale Wall Test Setups

The cyclic force was applied in the form of displacement at the top end of the wall, following Method B (amplitudes of the reversed cycles) of [26]. The magnitude of the provided deformation as well as the number of cycles were adjusted to match the load pattern depicted in Figure 3. The documentation set up for the full-scale wall test is evidenced in Figure 4.

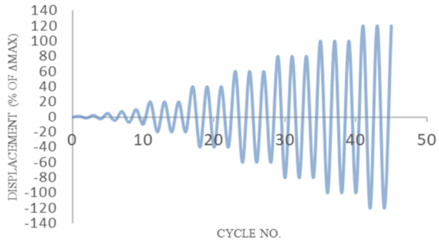


Fig. 3. Cyclic displacement schedule.

For the structural performance assessment of the vertical element under the category of moderate target damage safety, the first displacement pattern consists of five entirely reversible cycles with displacements of 1.25%, 2.5%, 5%, 7.5%, and 10% of the specified maximum displacement, set at 2% of the total building height [27]. The Earthquake Planning Guidelines [28] for this building category have a return period of 2500 years, indicating that the second displacement pattern comprises phases, each consisting of three similar reversed amplitude cycles, with displacements of 20%, 40%, 60%, 80%, 100%, and 120% of the maximum.

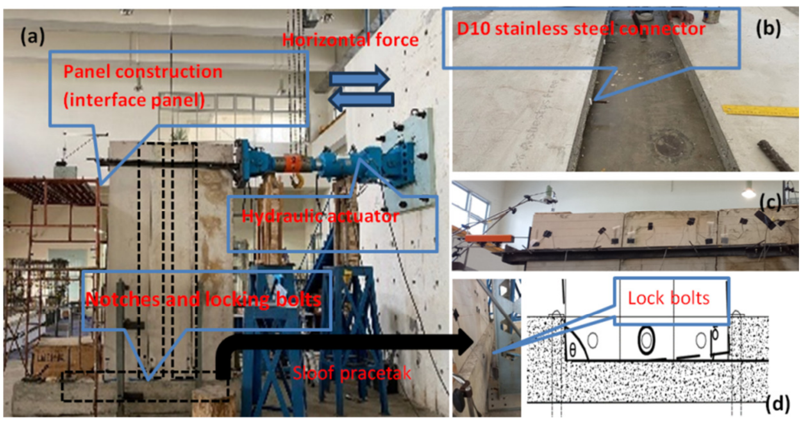


Fig. 4. (a) Setup for cyclic test model, (b) installation of interface panel connectors, (c) displacement reading position details with LVDT, and (d) locking bolts.

III. RESULTS AND DISCUSSION

A. Lateral Force and Displacement Relationships

Figure 5 summarizes the force transfer connection observed in the group of cyclic test specimens, highlighting the influence of different sizes and interface panel connectivity models. The lateral force and displacement curves reveal that LWC composite walls, enhanced with steel connectors on the precast sill beams, exhibit improved rigidity and accommodate greater displacements. Bolts effectively limit the excessive uplift and displacement of the walls. However, the addition of steel connectors at the panel connections further enhances the wall's strength. All curves demonstrated the pinching effect, as noted in [29]. During the initial loading phase, when the drift ratio is less than 0.7%, the hysteretic loops are narrow and gradually become slimmer. The number of cycles applied to all specimens was almost identical. The pinching effect of PLC 1 is less pronounced than in the other specimens, exhibiting a larger hysteretic curve area and a pronounced ducktail shape. When applying a lateral force to PLC 1 and PLC 2, the elastic rigidity of these two types of specimens is nearly identical, however, they display different behaviors under plastic conditions until they reach strength and experience accelerated displacement. Panels that are 75 mm thick and the PLC 1 series of normal panels, which lack connectors or adhesives, showcase the strongest push forces (Fp = 4.245 kN). In fact, the pulling strength began to deteriorate once the panel was no longer fully elastic, resulting in a 45% reduction in maximum pulling capacity compared to that of the pushing capacity. PLC 2, which includes a 10 mm-diameter steel connector and PVAc adhesive, achieves a maximum strength of 5.280 kN in the push direction, with a degradation of 8.5% in the pull direction.

PLC 1 is a typical paired panel without joints. The rocking mechanism of all the typical test conditions in the laboratory and the hysteresis curve of the cyclic lateral load test results were observed. The PLC 1 hysteresis curve showed inelastic deformation range behavior, giving residual displacement at a Fp = 0. Test observations disclose that the behavior of the panel is deformed following the direction of the pushing or pulling force. This condition occurs because each series of panels is rocking individually [30, 31]. Each panel is free to rocking, center on its respective bolt ties in the sloof notches, attains larger ultimate displacements, and increases the durability of the wall which is very important in earthquake design.

PLC 2 is a typical paired panel with steel joints and PVAc glue. The PLC 2 hysteresis curve showed the rocking mechanism of phase. The elastic - plastic - peak of rocking is stable by returning to its initial vertical position at pushed or pulled force of zero because the paired panels are able to fully rock as a single wall due to the contribution of the steel and PVAc glue connector. Observations of the condition of the joints between panels when failure occurred at the panel legs were found to remain intact. The displacement behavior at the joints between panels can be seen in the hysteresis curves in Figures 5. The influence of the three bolts on the wall legs in the sloof notches can limit the rocking mechanism as a single wall.

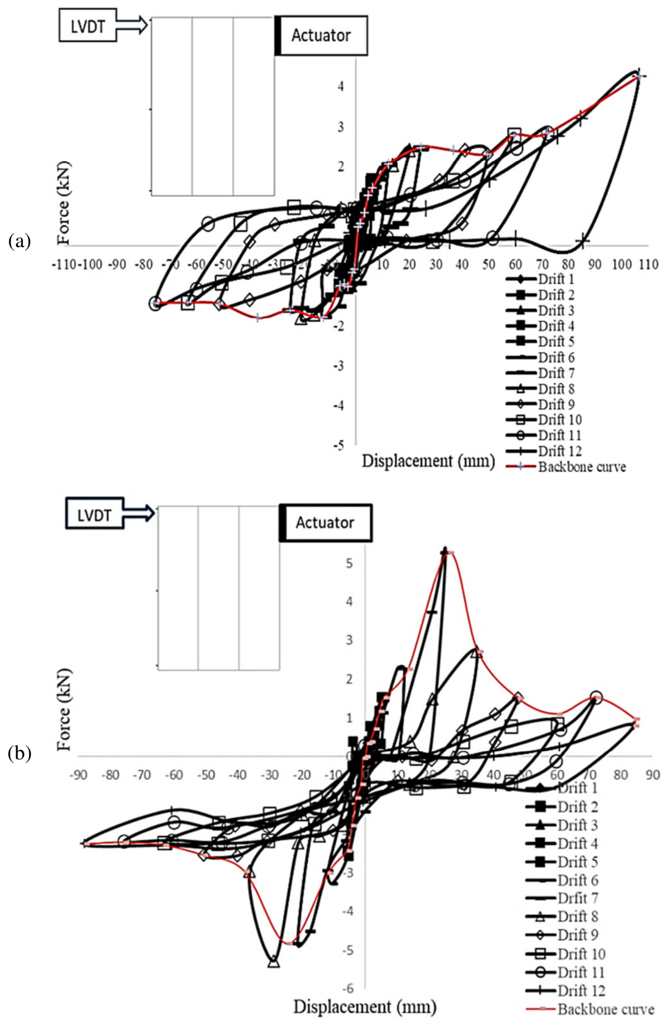
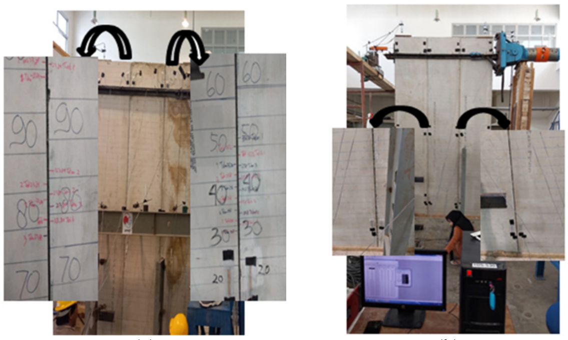


Fig. 5. Hysteresis curve of walls (a) PLC 1, (b) PLC 2.

PLC 1 and PLC 2 exhibit lower pulling force branches compared to their pushing force branches. However, the maximum strength ratios differ: 2.32 for PLC 1, 1.09 for PLC 2. Figure 5 illustrates the hysteresis curve observed during the test. Under cyclic loading, PLC 1 can displace up to 120% of its original position, with a displacement range reaching 106.28 mm in the pressure direction. The deviation in the diversion curve from the pull direction primarily arises from the test specimen's capacity to withstand lateral force. The displacement behavior of PLC 1 is distinct, and there is a change in the wall connection system with the precast sloof. The previously fixed system transitions to semi-pinned system due to modifications in the bolt-hole area. Additionally, the wall displacement becomes more dynamic without causing fractures to the wall surface, maintaining perfect stability.

The hysteresis curves indicate that when the actuator returns to its normal position, a gap is left at the base of the raised panel. Furthermore, the direction of the panel's displacement follows that of the actuator in the push displacement direction, with the magnitude of the force continuing to increase. However, the force in the pull direction does not increase correspondingly. While Figure 6 manifests a hysteresis curve, the relationship between force and displacement behaves linearly until reaching maximum force. At maximum strength, PLC 2 exhibits a displacement of 26.12 mm in the push direction and 24.38 mm in the pull direction are displayed in Figure 6. The kinematic behavior of the wall system under lateral force is characterized by rigidity and lateral support, which depend on: (1) the nail slip between the panels, (2) the shear distortion of the panel, (3) the flexural deformation of the frame, and (4) the rigid rocking of the panel due to squashing in compression and stretching of the hold-down in tension [15]. Individual panel movement responses were observed in PLC 1, where each wall segment was displaced independently at its lower corner, consistent with test results from previous research [17, 30].



(a) (b)

Fig. 6. Control marking vertical directional displacement: (a) PLC 1 (b) PLC 2.

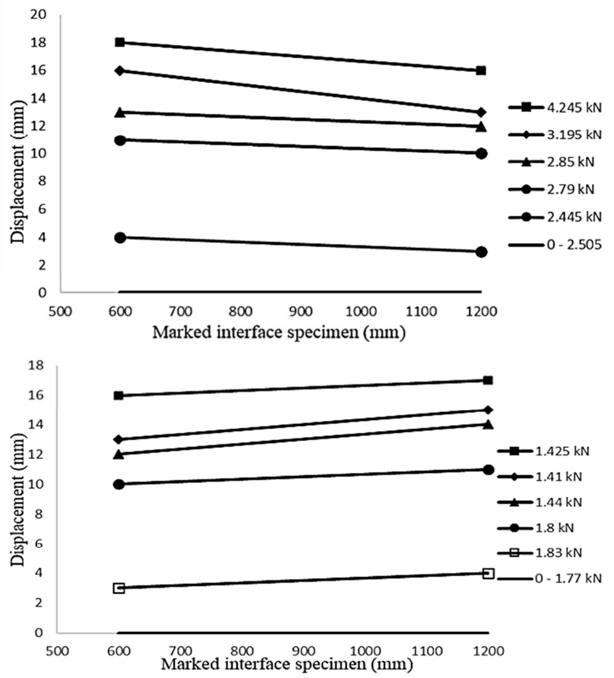


Fig. 7. Vertical displacement of PLC 1: (a) push directions, (b) pull directions.

Figure 7 portrays the displacement behavior observed at each cycle, measured manually by recording the displacement distance of each marker between adjacent panels. Figure 7(a) depicts the graphical data for vertical displacement on the PLC 1 side, with 18 mm in the push direction and 17 mm in the pull direction between panels. With the addition of steel connectors and PVAc adhesives, Figure 7(b) for PLC 2 demonstrates the vertical directional friction behavior and rigidity in a single wall system, preventing panel displacement due to the concentrated lateral load on the handles and screw connections, as previously evidenced in the tests [15].

IV. CONCLUSIONS

The sandwich material made from styrofoam composite calcium board is classified as lightweight concrete. Typical wall panel joint configurations were investigated through cyclic tests according to ASTM E1216 standard. The novelty of this research is the the anchor system with a wall configuration that includes a notch connection on the precast sloof and a bracing system with bolt clamps on each leg of the panel to which it is attached. The test results show that the movement of the pair of walls without joints appears to be free with a continuously increasing horizontal force capacity utilizing a rocking mechanism centered on the bolt holes obtained in PLC 1. On the other hand, in PLC 2, the increase in horizontal force results in damage to the resistance of the wall legs due to the stiffness of a single wall with greater deformation, so that the maximum stress at the 3 bolt points causes damage to the panel surface. When constructing earthquake-resistant buildings, it is important to consider the displacement reactions of walls with minimum defects.

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