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Structural Performance Evaluation of Cross Dapped Connection for Vertical Wall-to-Wall Connection of Precast Wall Panel

(Penilaian Prestasi Struktur Sambungan *Cross Dapped* untuk Sambungan Tegak Dinding-ke-Dinding Panel Dinding Pratuang)

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ABSTRACT

In the context of Industrialised Building Systems (IBS), precast concrete buildings are composed of multiple structural members that are interconnected through different techniques. The adoption of precast concrete wall panels has gained significant traction in contemporary construction methodologies. Nevertheless, the utilization of dapped connections specifically designed for non-load bearing applications in precast walls incorporating recycled concrete aggregate (RCA) remains largely unexplored and limited in practice. This research proposes a new wall-to-wall connection for precast wall panels to enhance the constructability of IBS for non-load bearing walls. The novel Cross Dapped (CD) design enables horizontal panel installation in confined areas with existing structural frames, while ensuring the connection's strength as a non-load bearing wall to prevent failure. Uniformly distributed loads are applied until sample failure, recording compressive load patterns, deflection, stress-strain patterns, and crack patterns on the wall surface. The CD connection demonstrates applicability for precast wall-to-wall connections, improving IBS constructability with its innovative design and locking system. Overall, this research explores and proposes an efficient and structurally sound wall-to-wall connection design for precast wall panels of non-load bearing system, facilitating the adoption of IBS methods, and improving the overall quality and constructability of building systems.

Keywords: Dapped connection; industrialised building system; precast wall panel; recycled concrete aggregate; uniform distributed load

INTRODUCTION

The implementation of Industrialised Building Systems (IBS) in Malaysia has been a topic of interest due to its potential benefits and challenges. The construction industry in Malaysia is transitioning from conventional methods to the systematic and mechanized IBS (Yunus et al. 2020). The government is taking the lead in convincing the construction industry to adopt a more systematic approach and methodology. It is a strategic shift in the construction industry that began in 1998. Aside from the goal of gradually reducing reliance on foreign labour and saving the country foreign exchange, IBS provides an opportunity for construction industry players to develop a new image of the construction industry to be on par with other manufacturing industries such as automotive and electronic industries (Abd Rahman & Omar 2006).

The Construction Industry Development Board (CIDB) has divided the IBS system into five categories which are precast concrete framed buildings, precast concrete wall buildings, reinforced concrete buildings with precast concrete slab, steel formwork system, steel framed buildings and roof trusses (CIDB Malaysia 2017). Precast concrete is the most used IBS system in Malaysia. Precast structures exceed conventional reinforced concrete (RC) structures in terms of quality, safety, economy, sustainability, and efficiency in construction. Precast structures are extremely effective at resisting gravity loads, but their ability to withstand lateral forces has been found to be lacking, as evidenced by past earthquakes (Singhal et al. 2021).

Over the last decade, the construction industry has witnessed the development of various wall-to-wall connections, including loop connections, wire loops, and U-shaped steel channels (Abdullah et al. 2019). A traditional method of transmitting weight between precast parts under tensile stresses is to use overlapping loop-shaped bent bars for connections (Sørensen et al. 2016).

The joints are classified into two types based on their orientation, which are horizontal joints and vertical joints (Inamdar 2018), and are categorized into were and dry joints. The joints must be properly designed and constructed to ensure structural integrity.

The distinction between wet joints and dry joints lies in their connection techniques. Dry joints utilize steel plates that are bolted or welded together, while wet joints involve cast-in-place concrete or grout poured between precast panels (Rossley et al. 2014). Despite their advantages, challenges arise during the transportation and installation of off-site cast precast members, owing to their substantial size and weight (Blismas & Wakefield 2009). Launching panels becomes a critical phase, prone to human error due to low tolerance in the connection interfaces (Jamil et al. 2012), leading to potential issues not only during immediate connection but also in the post-construction period, where problems like cracks and leaks may emerge due to incorrect connection procedures (Jabar et al. 2013). Moreover, the widespread use of natural aggregates in precast panels raises environmental concerns, depleting natural resources and subsequently increasing future costs (Hamid 2006; Shaban et al. 2019). Surprisingly, dapped connections are noticeably absent in the design and use of precast wall panels, with minimal research exploring their potential as vertical wall-to-wall connections—creating a noteworthy gap in the existing knowledge base. The primary objective of this study is to assess the structural performance of cross dapped precast wall panel connections through Uniformly Distributed Load (UDL) tests. Additionally, the research involves replacing natural aggregates in the concrete mortar mixture with 50% recycled concrete aggregate. To achieve these goals, the following objectives are delineated: to propose a novel vertical wall-to-wall connection for precast wall panels, aiming to enhance the overall quality of the Industrialized Building System (IBS) wall, and to evaluate the structural performance of the newly designed vertical wall-to-wall connection under a Uniformly Distributed Load (UDL).

METHODOLOGY

MATERIAL AND SPECIMEN PREPARATION

1. Recycled Concrete Aggregate (RCA)

The recycled crushed aggregates (RCA) were obtained by crushing the concrete or mortar waste from construction and demolition (C&D) waste. The crushing was done by hand using a hammer and hacker. After that, RCA will go through the sieve process. The RCA sizes used in the mixture are those that pass through a 5mm sieve and were used as natural sand replacement material, replacing 50% natural fine aggregate of the mortar.

2. Sand

Fine aggregate was one of the materials that is important in the production of mortar. Fine aggregates were obtained from the Structural Heavy Laboratory, Faculty of Civil Engineering, UiTM Pulau Pinang. Fine aggregates were sieved with the size of 4.75mm. The fine aggregates were air-dried at room temperature for 24 hours at room temperature to achieve saturated surface dry condition in order to not give off any moisture or add any moisture to the mixed mortar. 1.5324 kg of sand were used for 12 numbers of sample cubes, and 183.858 kg of sand for six numbers of wall panels for proposed CD connection.

3. Ordinary Portland Cement (OPC)

The main material used in this study is OPC as a binder. OPC percentages used in the sample's constant according to the mix design. For this study, 0.5746 kg of cement were used for 12 sample cubes and 68.947 kg for 6 sample walls.

4. Water

Water was added into a combination of fine aggregate and cement for making a strong and workable cement mortar. Water was the main material that was needed in production of mortar to bind the fine aggregate together. It can cause hydration process when the water is added into the mortar mixture. Hydrations are a process of chemical reaction in which the chemical component in cement cause reacts with the water particles to become hydration product. The type of water used was tap water in the heavy laboratory, UiTM Penang. The temperature of the water was at room temperature, in the range of 23-to-25-degree Celsius. In this study, the water-cement ratio was 0.75, so 0.431 kg of water was used for 12 sample cubes and 52.71 kg for 6 sample walls.

5. Superplastisizer

The last material used in this study was Superplasticizers. Superplasticizers were high- range water reducers used in the production of high-strength concrete. It has the capacity to reduce water content by up to 30% while preserving workability. In this laboratory experiment, Sika® ViscoCrete®-2192 were employed. The superplasticizer used in this study is 1% of the cement weight, with 5.746× 10-3 kg used for 12 sample cubes and 0.6894 kg used for 6 sample walls.

6. Mortar Mix Design

Mortar mix design was a preparation procedure in which a combination of materials creates the required strength and durability for mortar construction. In the ratio of 2:2:1 by weight, the mortar mix contains sand, RCA as fine aggregate replacement and OPC.

7. Mixing of Mortar

The components, including RCA, sand, cement, and water, were thoroughly blended to achieve a homogeneous mortar mixture. The meticulous mixing ensured a comprehensive combination, aiming to enhance the strength of the mortar upon hardening. In this study, all materials were poured into the mixer until the mortar completely mixed. The fresh mortar was used to test for setting time and flow table to analyse the workability of the mortar.

8. Casting of Cube and Wall Samples

A total of 12 cube samples were prepared (50 mm x 50 mm x 50 mm) for cube test and six wall samples with CD connection were cast to form three pairs of connected as shown in Figure 1. The dimensions of the proposed CD connection were shown in Figure 3. A control sample with normal dapped without RCA replacement was also cast in the same way. The moulds were cleaned and covered with oil using the brush before pouring the mortar into the cube sample and wall. The oil function prevents the sample from becoming difficult to remove once the mortar hardens. The concrete was filled in moulds in layers approximately 5 cm thick. Each layer was compacted using a vibrator machine to avoid the presence of air voids. The top surface was levelled and smoothened with a trowel.

FIGURE 1. Casting of Wall Samples

9. Curing Process

Curing was carried out after the mortar completely hardened in the mould for 24 hours. Curing of hardened mortar was done to prevent the samples from moisture loss and to keep them in a reasonable temperature range. Before preparing for the compression test of the test cube, the hardened cube was placed in a water tank for curing for 3, 7, 14, and 28 days. While, for the wall sample were left outside and rinsed with water daily as shown in Figure 2.

FIGURE 2. Curing of Wall Samples

TESTING SETUP AND PREPARATAION

1. Flow Table Test

The flow table test was one of the methods to determine the workability of fresh mortar and it also used to observe the moisture limit of the mortar. After the mortar mixing process is completed, the workability of the mortar must be checked before it can be poured into the mould. The test started by wetting the flow table and the mould on the plate. Then, the mould was filled with mortar mixed in three layers, and each layer was tamped 10 times using a tamp rod. The mould was carefully lifted vertically after done with the tamping allowing the mortar to flow. The table then was raised up to 40mm and dropped 25 times causing the mortar to flow. The diameter of the spread mortar mix and record the data was taken (ASTM 2001).

2. Cube Compressive Strength Test

Compressive strength test was the mechanical test that usually used to estimate the maximum strength of the mortar or concrete until failure. The test was used to determine certain characteristics such as the sort of items utilised and the mortar's quality. At 3, 7, 14 and 28 days after curing, these samples were evaluated with a compression machine. This testing was identified by using the 50 mm cubes as per ASTM [4] which was the Standard Test Method to determine the compressive strength by using the testing machine. To avoid errors, the samples were removed from the tank and allowed to dry before being tested. The test was repeat for 3 times to get an average reading.

3. Wall-to-Wall Connection Test with Uniformly Distributed Load (UDL)

Before the test was performed, the wall surface should be smooth by using grinder. The one side of the wall surface should also be painted, and grid lines was made to ensure the effects of the cracks are easier to be seen.

As shown in Figure 5, the load was supplied to the wall and the data was recorded using the data collection system that was connected to the load cell. The reaction frame machine transfers force to a wall panel via hydraulic actuators and allows multiple actuators to apply load simultaneously. The reaction frame was adjusted to the height of the wall panel prior to the test. To transfer the wall from the wooden palette to the reaction frame, the wall panel was lifted by crane and held in place by a belt. The wall was then placed in the centre of the reaction frame. To prevent the wall from moving when the load was applied, the bottom of each wall panel was clamped as a fixed support as in Figure 5. The testing machine had been calibrated and was being used in deflection control mode at 0.1 mm/min constant deflection rates. Linear variable deflection transformers (LVDT) and strain gauges measuring force or strain were attached to the specimen at 240 mm (LV1) and 490 mm (LV2), as well as Strain Gauge labeled as SG1 and SG2 at 250 mm and 500 mm respectively from the top of the wall surfaces as shown in Figure 5. Lastly, the crack propagation which resulted from the test were observed and recorded.

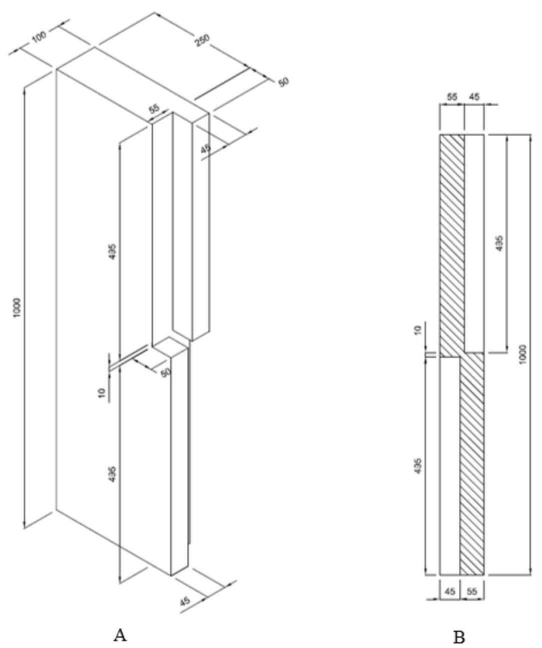

FIGURE 3. CD Connection Design. (A) Isometric view, (B) Side view.

RESULTS AND DISCUSSION

COMPRESSIVE STRENGTH AGAINST AGE (DAYS)

Using the compression machine provided at the heavy lab, 12 cubes are tested using mortar for 3, 7, 14, and 28 days. Mortar strength was found to be 14.39 MPa as shown in Figure 4 on day 28 of sample age.

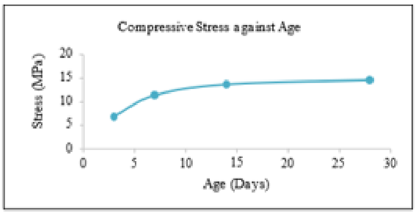

FIGURE 4. Compression Test Result

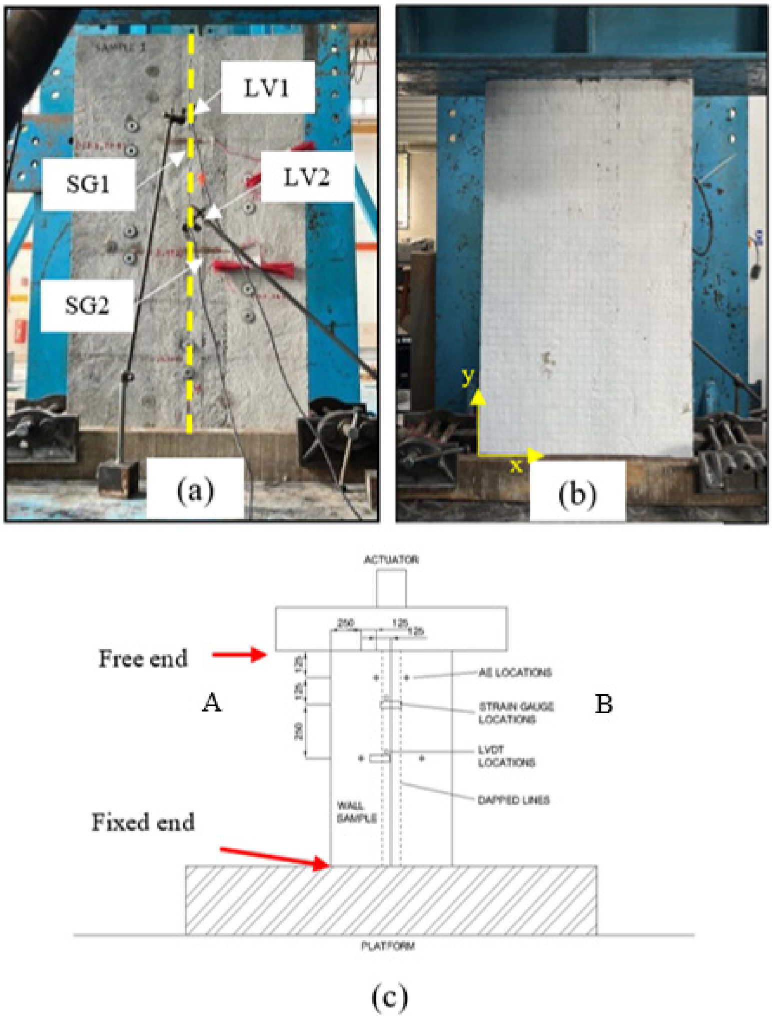

FIGURE 5. CD Connection Design. (A) Isometric view, (B) Side view.

STRESS VS. HORIZONTAL DEFLECTION ANALYSIS

Stress vs. horizontal deflection analysis of both proposed wall connection as well as control sample were shown in Figure 6 and Figure 7 respectively. Average maximum stress of CD samples is much higher than those in controls, which was 5.084 MPa and 3.9 MPa respectively. Both controls and samples exhibit higher horizontal deflection near the top of the wall, which was shown by LVDT1 that has been placed at 240 mm from the top, compared to LVDT2 (490 mm) near the middle of the wall. CD samples recorded an average of 2.614 mm of horizontal deflection for LVDT2 and up to 3.772 mm for LVDT1, which were lower than recorded values for controls, with 8.768 mm for LVDT2, and 10.263 mm for LVDT1. This shows that the proposed CD connection can resist horizontal deflection more than control from the vertical uniformly distributed loading on the top of the wall samples. This is due to the CD design which formed a good interlocking behaviour mechanically compared to normal straight dapped in the control samples in their connection interfaces.

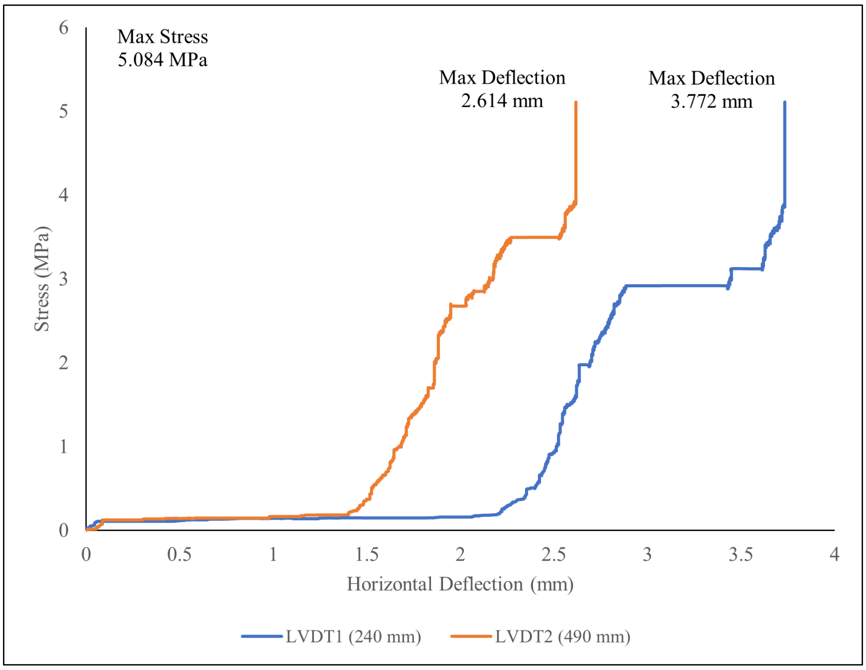

FIGURE 6. Graph of Stress Against Horizontal Deflection for Wall Connection CD.

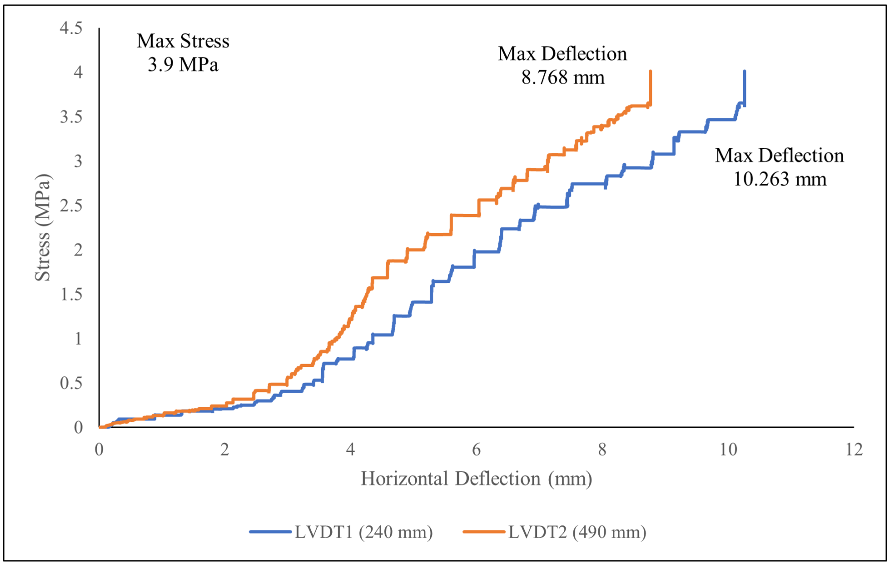

FIGURE 7. Graph of Stress Against Horizontal Deflection for Control Wall Connection.

STRESS VS. VERTICAL DEFLECTION ANALYSIS

Figure 8 shows the stress vs. vertical deflection of both proposed CD connection and control sample. From the graphs, it shows that plastic behaviour developed earlier in control sample (Point A) compared to proposed connection (Point B) from the yield points shown. Considering the utilization of conventional mortar materials, comprising a mixture of water, sand, and cement, and featuring a standard straight dapped connection throughout the wall height, it was anticipated that the control wall sample would exhibit relatively quicker failure. In contrast, the wall connection CD sample incorporated a cross dapped configuration, wherein the dapped formation was inverted on the opposite side (as illustrated in Figure 3). This design served to establish a mechanical interlock between connected panels at their connection interface, thereby reinforcing the dapped area along the X-axis of the panel. Consequently, the compressive stress capacity of the wall connection CD sample proved to be significantly higher than that of the control wall sample.

STRESS-STRAIN DIAGRAM OF SAMPLES

Strain gauges were affixed to the specimen, positioned at distances of 250 mm and 500 mm from the top of the wall surfaces to quantify strain. The load-carrying capacity of the walls exhibited an increase both at the initiation of the first crack and at the point of failure. Notably, SG 1, located 250 mm from the top of the wall samples, recorded a higher strain value compared to SG 2. This outcome was expected, given that SG 1 measured strain in the grouting area connecting the two wall panels. Specifically, the maximum strain value for SG 1 in the wall connection CD sample was 2070, whereas SG 2 recorded a maximum strain value of 83. In contrast, for the control wall panel, the maximum strain value for SG 1 was 181, and for SG 2, as depicted in Figure 9 and Figure 10, respectively.

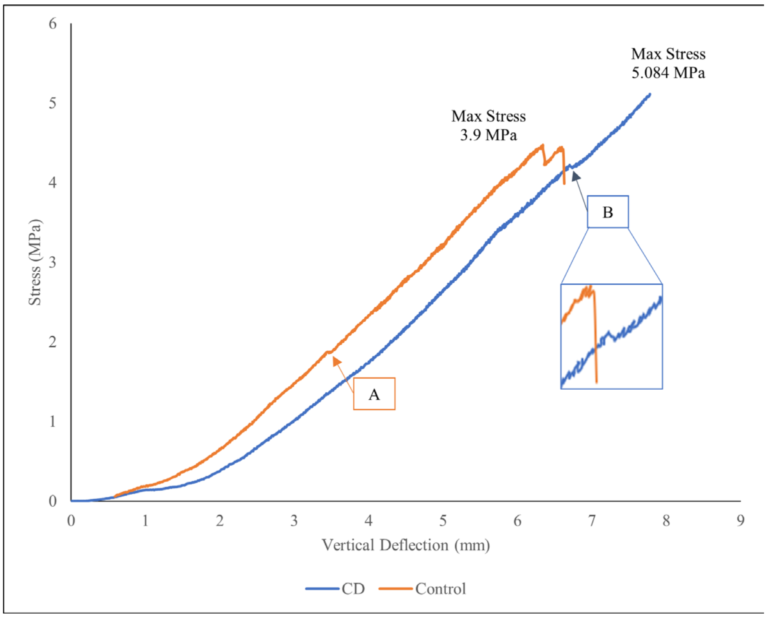

FIGURE 8. Graph of Stress Against Vertical Deflection for Wall Connection CD and Control

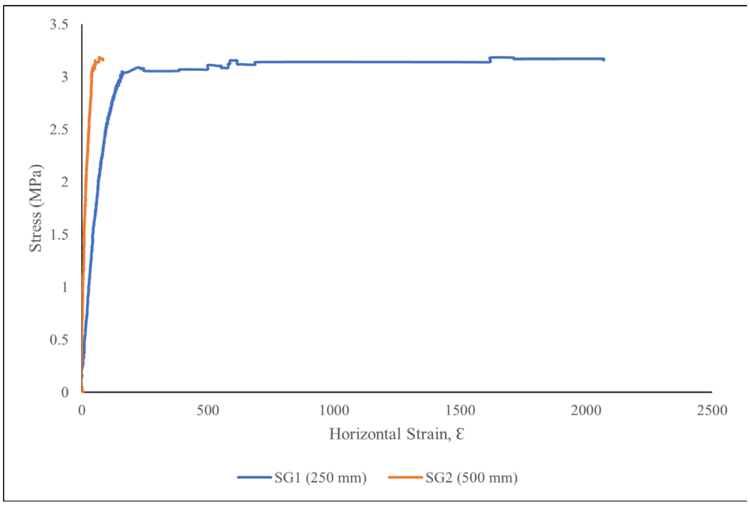

FIGURE 9. Graph of Stress-Strain of Wall Connection CD.

The interlocking system for CD connections is also superior because cement grout is used to bond the wall without any gaps as demonstrated by the higher maximum stress obtained compared with the control sample. The connection has a better shape and locking system that can help in improving the load capacity of the precast wall. Consequently, CD connections have a high potential for improving structural performance and overall wall quality.

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DECLARATION OF COMPETING INTEREST

None.

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