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Analyzing the Shear Performance of Dapped Wet Vertical Wall-to-Wall Connection

(Menganalisis Prestasi Ricih Sambungan Dinding-ke-Dinding Menegak Basah Dapped)

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ABSTRACT

The utilization of precast wall panels has gained prominence due to its potential for enhancing construction speed, quality, and sustainability. One critical aspect of precast construction is the connection between wall panels, where it is one of the proven to be the weakest link in the system. Rigidity of the connection between panels was also a point of concern. This research aims to investigate the mechanical performance of the dapped wet connection model in the vertical wall-to-wall connection in application for precast wall panels, particularly focusing on shear load considerations. The investigation includes experimental testing that includes three pair of specimens subjected to shear loading to evaluate their shear strength capacity, strain, and connection flexibility behaviour as well as the resulting crack propagation throughout the test. The test was verified through Acoustic Emission (AE) technique using Energy (eu) parameter. The proposed sample tested shows a significant improvement compared to the control sample with respect to maximum shear strength, however it displays a brittle behaviour by developing multiple cracks along the connection interface and having a significant shear failure at the end of the test. The findings of this study will contribute to a better understanding of the behavior of dapped wet connection and provide preliminary guidance for their design in precast concrete wall panels.

Keywords: Dapped connection; Industrialised Building System; Precast wall panel; Recycled concrete aggregate; Push-off shear test; Acoustic Emission technique

INTRODUCTION

Industrialised Building System (IBS) has been adopted in the construction industry in hope of enhancing the construction quality as well the productivity (Mohd Amin et al. 2017). Numerous countries around the world has adopted the system, with United Kingdom (UK) applying the Modern Methods of Construction (MMC) which involves technologies that includes prefabricated technologies, as well as off-site manufacturing and fabrication that offer an efficient approach to achieve increased production in less time (Vaghei et al. 2014a). This is no different in Malaysia, with IBS involves manufacturing structural elements in a controlled environment, transporting the said elements and assembling at the construction site (CIDB Malaysia 2017), with walls are the most common structural element casted and used in the construction of low to medium rise residential, commercial, as well as industrial buildings. Precast concrete walls are prized for their ease of manufacturing, efficiency, durability, and overall appeal (Vaghei et al. 2014a). Taking into accounts of the utilization of precast wall in the IBS, a crucial consideration in the connection between two wall panels need to be focused.

Nevertheless, the concerns surrounding wall-to-wall connections in precast wall panels have garnered significant attention, with recent studies indicating these connections as the system's weakest link, prompting a thorough examination of their performance (Kamar et al. 2012). Concurrently, challenges arise from excessively rigid panel connections, lacking flexibility for adjustments during construction or in the building's future lifecycle, thus hindering their effective implementation in the construction industry (Jabar et al. 2013).

Effectively addressing these challenges holds paramount importance, ensuring not only the structural integrity and performance of the entire system but also contributing to the development of durable and sustainable structures (Sritharan et al. 2015). These issues, along with others raised by previous researchers, pose significant problems that impact the constructability of construction projects. Ironically, most constructability attributes proposed by research point towards implementing Industrialised Building Systems (IBS) in construction, theoretically minimizing errors on-site and reducing material, time, and financial wastage. These attributes include simple detailing, flexibility, easy installation, encouragement of sustainable practices, safety considerations, maximized standardisation, and increased prefabrication.

Dry and wet connections are mostly used for the connections of wall-to-wall, as well as the combination of both. Wet connections are usually made of cast-in-situ concrete or other composite materials that are applied between precast concrete wall panels (Brzev & Guevara-perez, 2021). Usually, the wet connections works together with the geometrical shape of the connection provided on the connection side of the wall panel, or shear keys. Some of the wall-to-wall connections that are generally used nowadays are – but not limited to – loop connections, wire rope connections, as well as wet joint shear keys. Combination of other materials other than grouting are sometimes used for wet connections, such as the inclusion of steel fibres. However, the inclusion of such fibres increase the potential of premature crack development beside increasing the maximum shear load along the connection interface between each connected wall panels (Ahilan et al. 2016). Application of loop connections are more famous and suitable than bolted connections as they are easily installed on site without any need of professional services (Artemeva, 2018), as well as provided more flush finishes between each connected wall panels with any recesses or bumps as latter. Despite this, some connection such as dapped wet connection have seldom been considered for precast wall panel applications in IBS.

To assess a wall's performance, Ruslan et al. 2021 examined its characteristics related to compressive strength, ultimate load, deflection, and strain. Gu et al. (2019) and Pan et al. 2021 scrutinized the failure-induced cracking pattern of a wall subjected to horizontal cyclic loading. Their analysis encompassed parameters such as yield load, drift ratio, loop stiffness, and strain. The findings indicated that, for lower axial load values, there was a decrease in load-bearing capacity accompanied by increased deformability. Vaghei et al. (2014b) delved into the interaction dynamics between modelled concrete and precast concrete, as well as the interplay between reinforcement and concrete, focusing on nonlinear stress-strain behavior. Connection performance was assessed through stress, deformation, and absolute plastic strain. The authors observed that crack propagation in IBS walls and connections predominantly occurred at the bottom of the IBS wall and along the interface. In-plane lateral loads resulted in some cracks at the connection between IBS walls and the connection.

Shear test, however, remains the least test conducted in terms of wall-to-wall connection for precast wall panels. Rossley et al. (2014) has conducted a study on the behaviour of connection between interior and exterior wall panels with loop bar connection under shear loading. They found out that the connection performed well under shear loading condition and that the loop bar connection was suitable for the application which resulted in acceptable ductility behaviour before they fail. Vaghei et al. (2019) has also applied shear loading in their study in one of the degrees of freedom to identify the performance of loop connection as well as their proposed new type of connection that was used for vertical wall-to-wall connection between two panels. In summary, they found out that the proposed vertical wall-to-wall connection not only performed better in all suggested degree of freedom, but also excels in flexibility behaviour in all directions when compared to loop connection. Pramodh et al. (2018) has carried out their laboratory test to assess the performance of precast horizontal wall-to-wall connections by dowel action and shear friction under shear load. The test results were then compared and verified with theoretical values of ultimate shear resisting capacity calculated with Von Mises yield criteria, and ductile bending failure.

The examination indicated a restricted exploration into the performance of wall-to-wall connections, with limited incorporation of non-destructive testing methods, particularly the acoustic emission technique. Acoustic emission, commonly employed for assessing reinforced concrete beams (Mat Saliah & Md Nor 2022; Md Nor et al. 2022; Mat Saliah et al. 2021; Noorsuhada, 2016), verifying socket grouting compactness in shear walls (Li et al. 2021), detecting fatigue cracks in steel bridge eyebars (Megid et al. 2019), and monitoring concrete slab-to-wall connections (Reboul et al. 2020), has demonstrated efficacy in real-time material condition assessment prior to compromising load-bearing capacity. Ospitia et al. (2023) underscored its potential as a promising tool for continuous material assessment. Despite these applications, the review disclosed a scarcity in the use of acoustic emission to scrutinize the behavior and performance of concrete wall-to-wall connections. Consequently, this study aims to fill this gap by investigating the behavior and performance of dapped concrete wall-to-wall connections under shear load and is significant in terms of contributing to the exploration of wall-to-wall connection performance, which in turn will provide significant input in the construction engineering. The evaluation encompasses shear strength, connection flexibility, stress, strain, and crack development on the wall. Acoustic emission characteristics are employed to gauge the cracking behavior of the wall-to-wall connections.

TABLE. 1 Types of wall-to-wall connections

Types of connection	Specimens	Size (mm) / pair
Type 1: Dapped Wet	T1S2	1000 mm x 535 mm x 100 mm
	T1C1	

METHODOLOGY

INTRODUCTION

Figure 3 shows the process flowchart of evaluating the performance of dapped wet vertical wall-to-wall connections in this study. Materials needed were all prepared, with control sample did not incorporate any recycled concrete aggregate (RCA). Other materials prepared includes ordinary Portland cement (OPC), natural sand, expanded perlite (EPA), superplasticiser, as well as clean water. All the materials were mixed properly and the workability of the fresh mortar were evaluated using flow table test. Wall panels of dimensions 1000 mm high, 300 mm wide, and 100 mm thick were casted on custom formwork with the geometry of the proposed dapped wet connection were formed using Styrofoam inside the formwork. Two individual panels were casted each for both sample and control respectively. The panels will then cure using wet gunny sacks placed on top of each panels. As for the cube samples for compression test, nine samples were casted using standard plastic moulds of dimension 50 mm x 50 mm x 50 mm, which were cured in the water. On day 14th of curing, the individual panels were then connected in pair using commercially available concrete grout. Each hardened wall were tested on the 28th day of curing with push-off method to apply the shear load, and cracks were monitored using both visual inspection with help of photography and videography, as well as acoustic emission technique. The ultimate shear load and its strength, connection flexibility behaviour, stress, strain and acoustic emission energy were then obtained. Thus, the mechanical performance of the proposed connection could be determined. Control sample without RCA was casted to compare with the sample that was casted with RCA. The cube samples were tested on 3rd, 7th, and 28th day of curing to evaluate the compressive strength of the casted mortar.

MATERIAL AND SPECIMEN PREPARATION

In this investigation, 40% of the natural fine aggregate in the mortar mix for sample casting was replaced with RCA. The RCA was derived from tested concrete cubes at a Penang batching plant, crushed into fine aggregates that passed through a 5 mm sieve using a jaw crusher. No RCA was utilized for the control casting. The mortar mix employed OPC, impurity-free water, and natural fine aggregates that passed through a 5 mm sieve. A 1:4:4:2 ratio of cement: RCA: natural fine aggregate: expanded perlite was used to cast nine mortar cubes measuring 50 mm x 50 mm x 50 mm. To enhance workability, 5.905 ml of superplasticizer (Sika ViscoCrete 2192) was added to the mortar mix based on the manufacturer's recommendation. Compressive strength was determined for all cubes at 3, 7, and 28 days. The composition of the materials used in this study were based on the study by Md Nor et al. (2024).

Four formworks measuring 1000 mm high x 300 mm wide x 100 mm thick were created for wall panel preparation, with each pair for the proposed connection with RCA and the control sample without RCA. The formworks facilitated pouring the wall panels, and the proposed connection shape and dimension were formed using the Styrofoam method at one end of the formwork. Fresh mortar, mixed in a concrete mixer, was poured into the prepared formwork in three layers and compacted with a vibrator. The entire mixture was evenly distributed and well compacted to prevent subsequent honeycombing. The test specimens were cured in a laboratory with wet gunny sacks placed on them as in Figure 4.

After a 14-day curing period, the wall panels were connected vertically using a concrete grout (SikaGrout 215) as the bonding agent between pairs of panels. The proposed connection, specifically Type 1 for dapped wet, was prepared. One test specimen of Type 1 (Dapped wet) and one control specimen were formed. Thus, two specimens were produced, designated as T1S2 for the type of wall-to-wall connection with RCA, and T1C1 for the control sample without RCA, as shown in Table 1.

The cement grout used was SikaGrout-215, which has a compressive strength of more than 45 MPa after seven days of casting with mortar in castable form, according to ASTM C109/C109M-02 (2020). The bonded wall panels continued to be cured for the remaining 14 days. On the 28th day, testing was conducted to determine the mechanical performance of the wall-to-wall connections with respect to shear load. The damage to each specimen was also assessed using the AE technique.

Figure 1 and Figure 4 show the schematic diagram of the proposed vertical wall-to-wall connection when connected between two panels, all units are in millimeters. Figure 2 shows the prepared wall panels before the joining process.

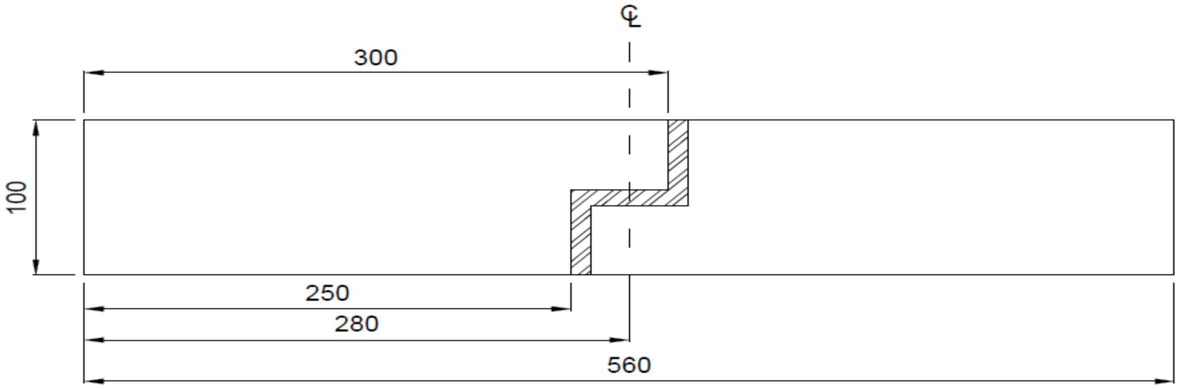

FIGURE 1. Typical dimensions from plan view of connected panels

FIGURE 2. Curing process of wall panels

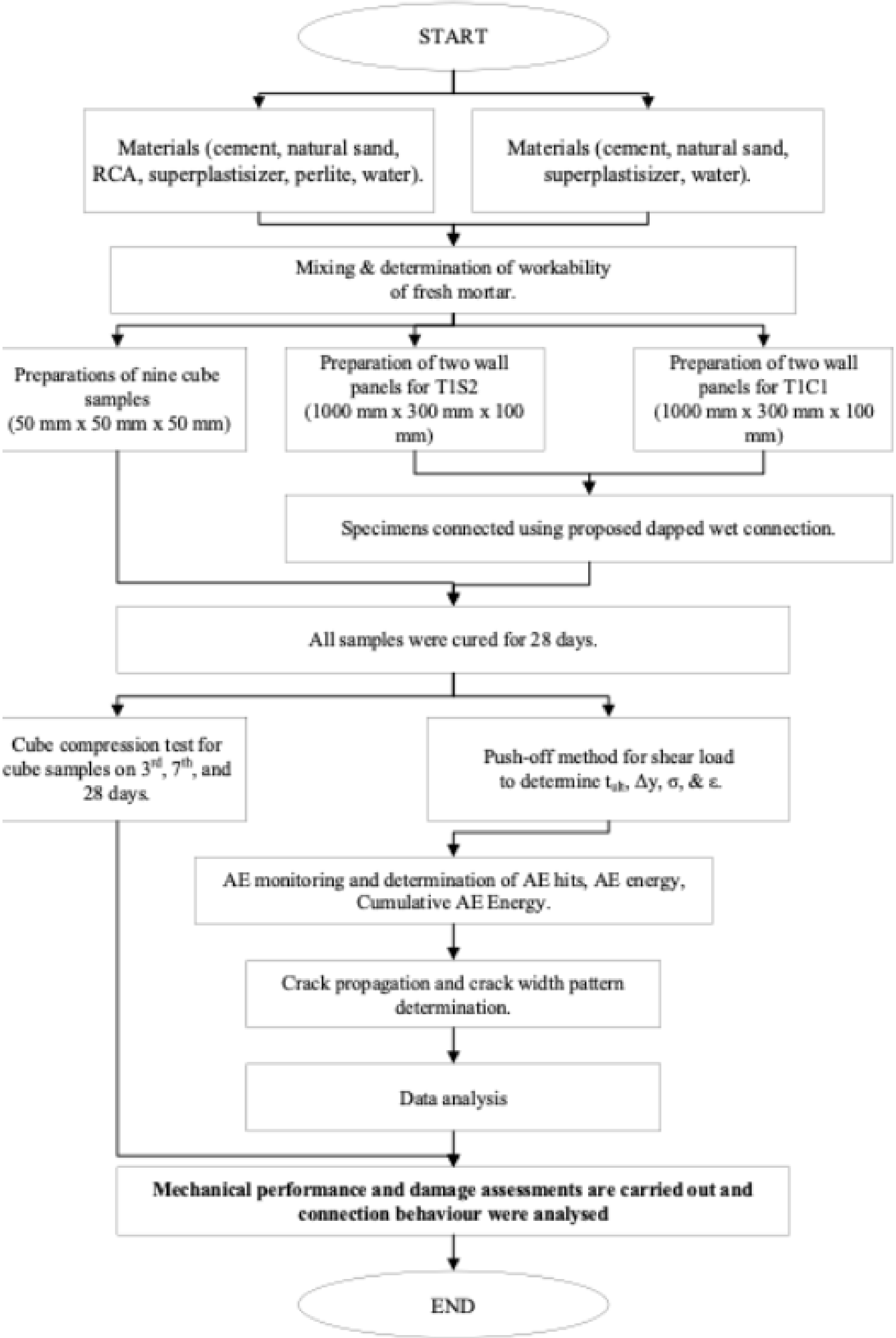

FIGURE 3. Process flow for the determination of the mechanical performance and damage assessments of Type 1 (dapped wet) connection

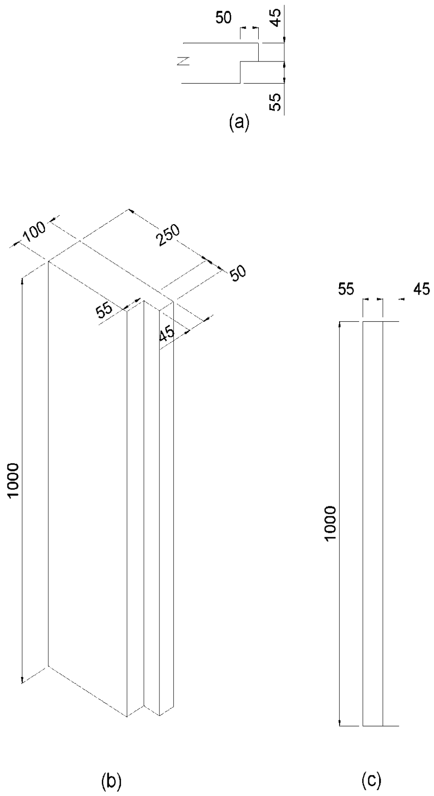

FIGURE 4. Schematic diagrams for Type 1 connection; (a) Plan view, (b) Isometric view, and (c) Side view

TEST SETUP

Figure 5 shows the schematic diagram of the test setup of the wall-to-wall connection and illustrates the arrangements made for other measurements, such as linear vertical displacement transducers (LVDTs), strain gauges and acoustic emission sensors. The LVDTs were used to measure the displacement of each wall panels which will then be used to calculate the connection flexibility in the analysis part. Location of LVDT L1 and L2, as well as L3 and L4 were positioned 100 mm from the centre line of the connected sample. The strain gauges were located at each segment of 250 mm along the horizontal length of the sample as indicated in the Figure 5, with each S1, S3, S4, S6, S7, and S9 lying across the connection interface of the connected sample, which will be used to measure the strain exhibit on the connection interface. S2, S5, and S8 were located along the centre line of the connected sample as shown in Figure 5, which was used to capture the strain that occurred in the dapped region along the centre line. Finally, S10 and S11 strain gauges were used to measure the strain on each panel due to the shear loading and the resistance of the connection that results in resisting the load, if any. However, for the scope of the study presented in this article, only data of S4, S5, and S6 were discussed.

Due to spatial limitations and constraints in the equipment utilized for the push-off test method in shear load assessment, the samples were horizontally positioned. A steel frame platform, constructed from an I-beam and securely bolted to the laboratory floor, served as the foundation for placing the samples. While one panel was firmly fixed in place, the other panel was permitted to move freely along the established Y-axis. An actuator applied a uniformly distributed load (UDL) along the edge of the movable panel, as illustrated in the Figure 5. To minimize friction between the panel and the struts at the contact points, the entire sample was stabilized using struts equipped with Teflon plates. This configuration was devised to prevent sample overturning caused by the movement of the actuator applying the UDL.

Six acoustic emission (AE) sensors were fixed at selected locations and designated as AE1, AE2, AE3, AE4, AE5, and CH4, as shown in Figure 6 at the other side of the sample. The wall-to-wall connections were statically loaded to failure and the crack pattern of each sample were also investigated with visual inspection, assisted by video capture peripherals, as well as crack ruler to determine the crack width occurred.

ACOUSTIC EMISSION MONITORING

AE was used to monitor the crack propagation in each specimen when loaded to failure. As AE is defined as elastic wave propagation due to localised internal energy release, this allows the identification of microfractures in elastic materials that cannot be determined visually, such as hairline cracks (Md Nor, 2018). Hence, the crack propagation in the concrete was captured and displayed on the AE display. Meanwhile, AE would be able to capture the formation of any micro and macro cracks occurring both in the mortar matrix and on its surface.

Six VS75-V sensors were placed on one side of each sample (see Figure 6). The coordinates of the sensors are shown in Table 2, with the x and y positions indicated, while the x and y positions can be seen in Figure 6.

Before the monitoring process, the AE hardware was set in the system, as were the threshold level, wave velocity, rearm time, sampling rate, duration and discrimination time, pre-trigger and digital setting. The settings used were 45 dB, 4000 m/s, 1.62 ms, 10 MHz, 400 µs, 200 and 25 kHz to 850 kHz, respectively. In this study however, only sample T1S2 and T1S3 uses AE monitoring due to the unavailability of the said sensors for sample T1S1.

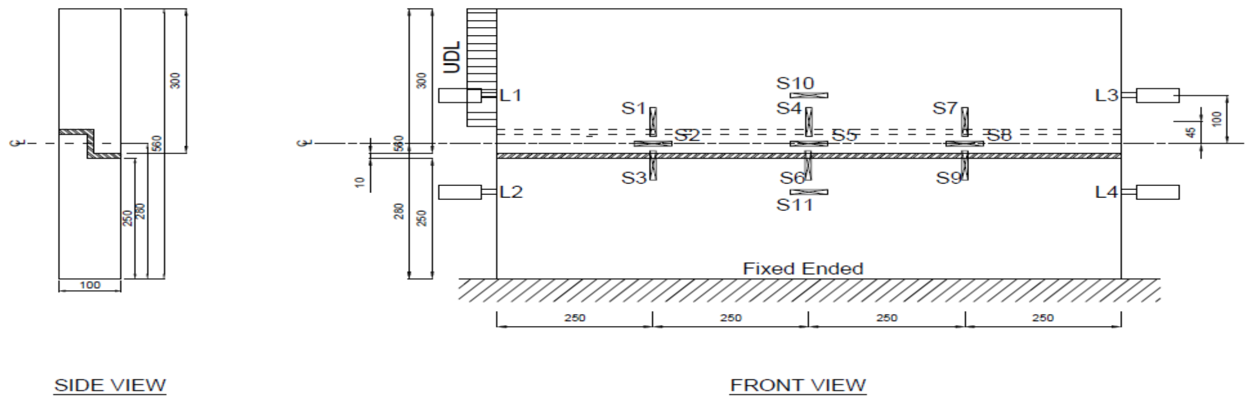

FIGURE 5. Schematic diagram for push-off method test on connected samples (strain gauges side)

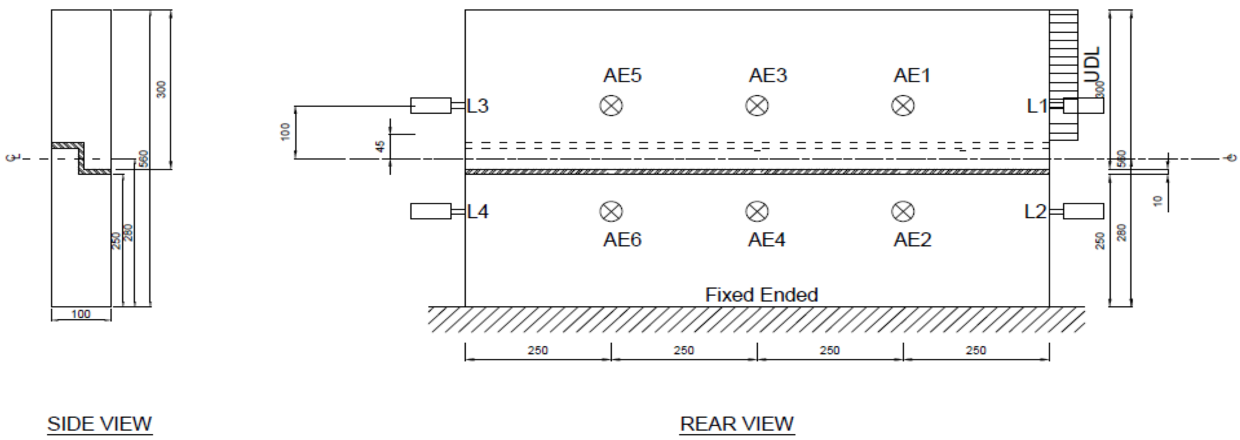

FIGURE 6. Schematic diagram for push-off test of connected samples (AE sensors side)

TABLE 2. Location of the sensors with the x and y coordinates on the specimen

Designation of sensor	Coordinates	
	Y (mm)	X (mm)
Sensor 1, AE1	750	380
Sensor 2, AE2	750	180
Sensor 3, AE3	500	380
Sensor 4, AE3	500	180
Sensor 5, AE3	250	380
Sensor 6, AE4	250	180

RESULTS AND DISCUSSION

COMPRESSIVE STRENGTH OF CUBE SAMPLES

A compressive strength test was performed for the 50 mm x 50 mm x 50 mm cube samples that have been cast and cured for 28 days. The compressive strength at 28 days was recorded at 20.31 MPa in average. The detailed compressive strength records for 3, 7, and 28 days were shown in Table 3.

TABLE 3. Compressive strength of cube samples

Curing day	Compressive Strength, MPa
3rd	14.12
7th	17.70
28th	20.31

RELATIONSHIP BETWEEN LOAD AND DISPLACEMENT OF CONNECTED SAMPLES

From the push-off shear test method, maximum shear strength as well as displacement along established Y-axis were determined for each connected samples with proposed dapped wet wall-to-wall connection. The ultimate shear load as well as maximum shear strength of each sample were shown in Table 4.

TABLE 4. Ultimate shear load and maximum shear strength of dapped wet vertical wall-to-wall connection

Sample name	Ultimate shear load (kN)	Maximum shear strength (kN/m2)
T1S2	51.27	341.8
T1C1	47.26	315.1

In Figure 7, the control sample T1C1 achieved a maximum load of 47.26 kN. LVDT1 recorded a horizontal displacement of only 2.4 mm before the sample broke at the maximum load of 47.46 kN, representing the yield point. The region preceding this yield point is known as the elastic region, where the material deforms proportionally to the applied load and returns to its original shape upon load removal. Beyond the yield point, the displacement increases to 15.25 mm, with some resistance from the connection interface causing a rebound from 10.19 kN to 34.07 kN. The recorded displacement reaches 31.25 mm, corresponding to the plastic region, before the sample experiences total failure, known as the point of failure.

A similar load-displacement relationship pattern was observed for sample number T1S2, with a maximum load of 51.27 kN and a recorded displacement of only 1.38 mm, which is less than that recorded in the control sample. Beyond this point, the displacement continues to increase until it reaches 30.13 mm before the sample fails, which can be seen in Figure 8.

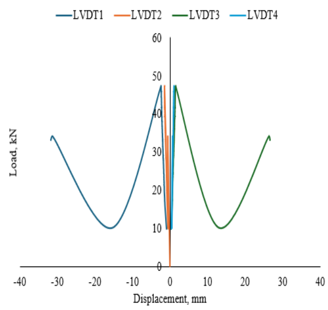

FIGURE 7. The relationship between load (kN) and displacement (mm) for control proposed model of wall-to-wall connection for dapped wet T1C1

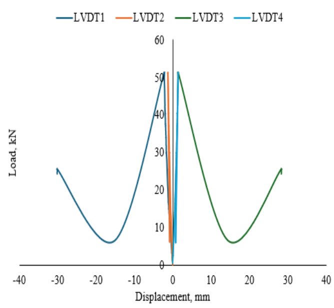

FIGURE 8. The relationship between load (kN) and displacement (mm) for control proposed model of wall-to-wall connection for dapped wet T1S2

Overall, from load-displacement relationship, dapped wet shows promising behaviour in resisting shear load applied on the samples compared to the control sample, with total displacement value recorded smaller than the latter, as well as maximum load recorded at yielding point were much higher compared to the control sample.

RELATIONSHIP OF STRESS-STRAIN

The maximum strain on both sample T1S2 and T1C1 was measured through strain gauges which were strategically placed on the samples. As shown in Table 5, maximum strain was recorded occurred at 500 mm on the connection interface along the established Y-axis, which were 70 µm/m for T1S2, and 1517 µm/m for T1C1.

Examining the stress-strain relationship illustrated in both Figure 9 and Figure 10 reveals that SG6, situated at the connection interface 500 mm along the Y-axis, recorded the highest strain up to the failure point for both the control and sample S1. This behavior aligns with the crack propagation observed along the connection interface, as discussed in subsequent topic.

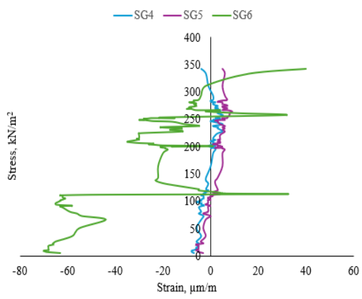

FIGURE 9. The relationship between stress-strain for proposed model of dapped wet wall-to-wall connection for sample T1S2

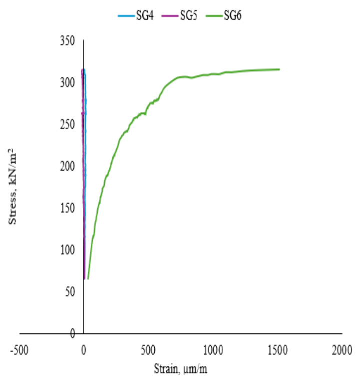

FIGURE 10. The relationship between stress-strain for proposed model of dapped wet wall-to-wall connection for sample T1C1

VISUAL INSPECTION ON CRACK PROPAGATION

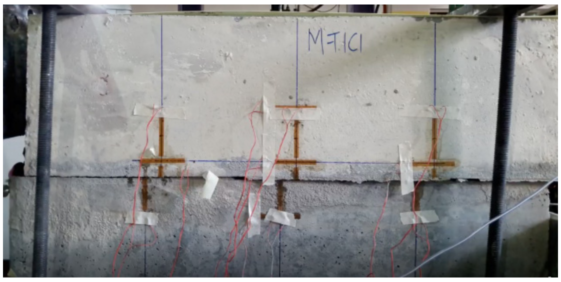

FIGURE 11. Condition of the proposed design model wall-to-wall connection type 1, Dapped Wet (MT1C1) at failure

Both proposed T1C1 and control T1S2 shows major failure along the connected interface where the joint was connected using grouting method when inspected visually as shown in both Figure 11 and Figure 12 respectively. This shows that the dapped region along the centre line of each sample was able to withstand shear load applied along the established Y-axis without any surface cracks occurred when visually inspected.

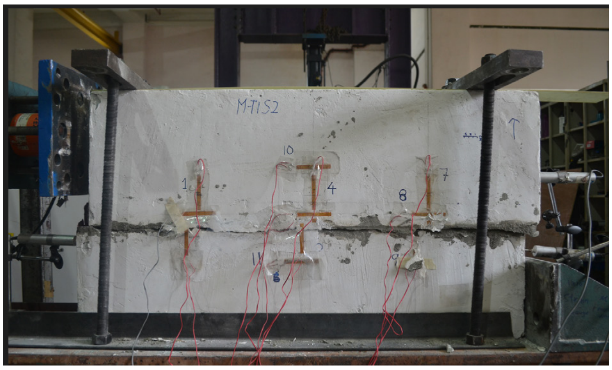

FIGURE 12. Condition of the proposed design model of wall-to-wall connection type 1, Dapped Wet (MT1S2) at failure.

TABLE 5. Connection flexibility analysis of Type 1, Dapped Wet connection at failure. All units are in millimeters (mm)

Sample Name	Max LVDT 1	Max LVDT 2	Max LVDT 3	Max LVDT 4	|L2-L1|	|L4-L3|	Average
T1C1	31.77	1.41	25.54	1.06	30.36	25.48	27.92
T1S2	30.2	1.38	28.25	1.31	28.82	26.94	27.88

TABLE 6. Average connection flexibility and the percentage differences between sample and control

Connection name	Average (mm)	Percentage difference (%)
T1C1	27.92	
T1S2	27.88	-0.14

CONNECTION FLEXIBILITY ANALYSIS

Connection flexibility analysis is the degree of flexibility of the connection that can be determined based on the maximum value of LVDTs gave after the test has ended. These values can be calculated by finding the absolute difference value between LVDT 1 and LVDT 2, as well as between LVDT 3 and LVDT 4. The two values will then be calculated as the average of displacement where this value will give an insight on how well the flexibility of the connection are performed where lower values mean the connection have lower flexibility, and vice versa. Zero value, however, would indicate the connection is rigid.

From Table 5 above, the average flexibility for each sample T1S2 and T1C1 are 27.88 mm and 27.92 mm respectively. This shows that the usage of RCA in forming the connection geometry just affect the flexibility slightly. Overall, it shows that the usage of RCA in the mix of precast wall panels will reduce the flexibility of the connection between panels, albeit slightly. The percentage of difference between T1S2 and T1C1 is shown in Table 6.

ACOUSTIC EMISSION ANALYSIS

Results of hits coordinate with respect to X and Y axes of each model sample as well as their energy versus time elapsed are shown below. Figure 13 and Figure 14 shows located event which were detected based on the hits coordinates by all AE sensors on the samples. These hits coordinates were plotted on the axes which corresponds to the geometry of the samples. Both T1C1 as well as T1S2 shows hits propagate along the connection interface which were located about 260 mm on the established X-axis of the samples, which in lieu with the visual inspection shown in previous Figure 11 and Figure 12 respectively.

Figure 15 shows the relationship between energy level, and its cumulative energy level with time taken in second for the sample T1S2 to fail under shear load applied through push-off method. As we can see, higher energy level occurred at the end of test period where there was a spike of energy level that corresponds to the major crack that occurred along the connection interface.

When compared to control sample of T1C1 in Figure 16, high energy spike were detected at the beginning of the test period, each at about 34 seconds as well as at 160 seconds. No surface cracks were detected visually during these period, suggesting that the cracks were occurred internally in the mortar matrix. However, a significant high energy was detected towards the end of the test period at about 358 seconds and onwards, and these energy spikes corresponds to the cracks propagate along the connection interface that were confirmed with visual inspection.

Both samples in Figure 15 and Figure 16 gave the coefficient of determination, R^2 of 0.8656 and 0.9861 respectively, shows that both gave a good fit in the model they represented.

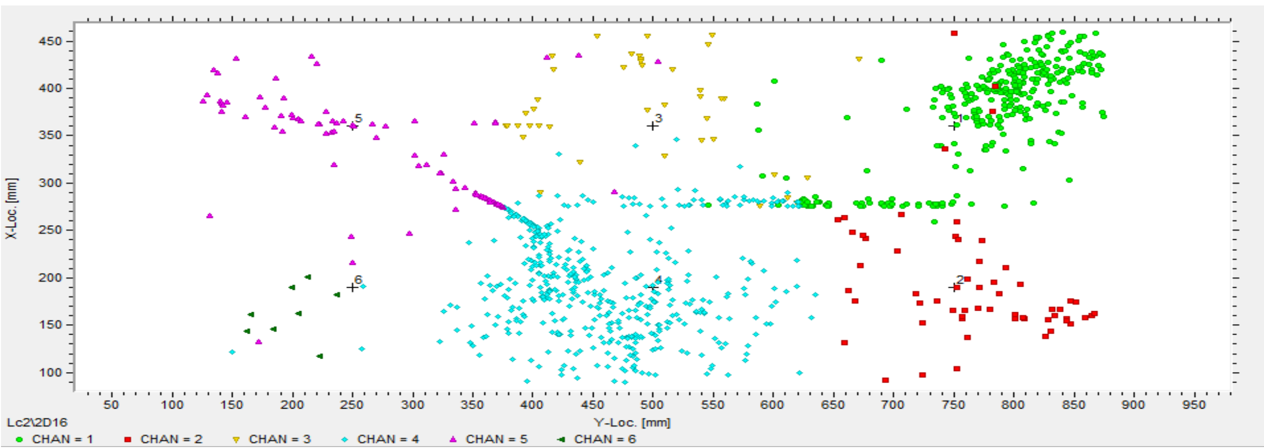

FIGURE 13. Hits distribution throughout the sample of T1C1 detected by the AE sensors AE1 thru AE6

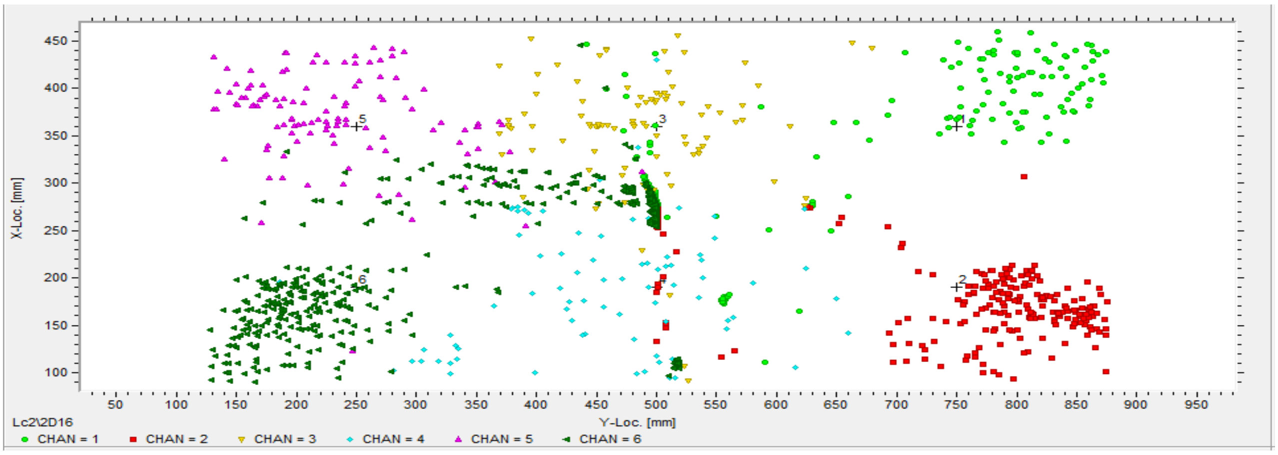

FIGURE 14. Hits distribution throughout the sample of T1S2 detected by the AE sensors AE1 thru AE6

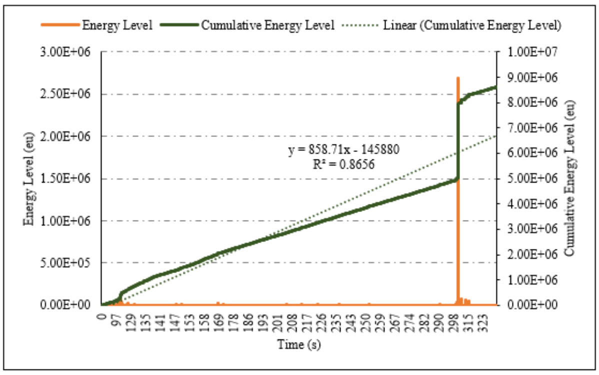

FIGURE 15. Relationship between energy level and cumulative energy level with time elapsed for connected samples T1S2

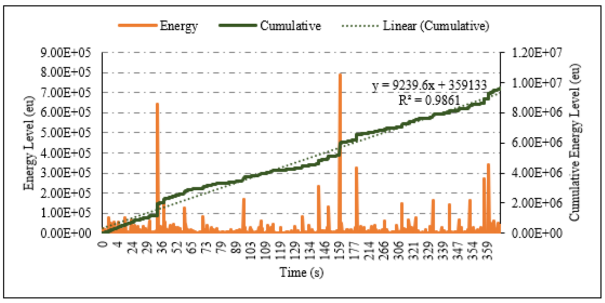

FIGURE 16. Relationship between energy level and cumulative energy level with time elapsed for connected samples T1C1

CONCLUSION

This study has successfully proposed a new wall-to-wall connection and tested it under shear load with push-off test method to further investigate the failure analysis of dapped wet vertical wall-to-wall connections. It was concluded that the inclusion of RCA in the casting of wall panels with the proposed geometrical shape of dapped produced a significant improvement in the maximum shear strength, which are 341.8 MPa and 315.1 MPa for T1S2 and T1C1 respectively. The strain at the 500 mm along the established Y-axis of each samples recorded the highest strain, which are 70 µm/m, and 1517 µm/m for T1S2 and T1C1 respectively. However, in terms of connection flexibility, both T1S2 as well as T1C1 shows slight differentiation between each other at 0.14% difference, showing that the inclusion of RCA on effect the flexibility of the connection slightly.

Analysis of the acoustic emission energy for both T1S2 as well as T1C1 samples correspond with the major cracks occurred along the connection interface at the end of the test period, which verify with the visual inspection recorded at the end of the test. To conclude, the analysis results confirmed that the weakest segment of the components was the connection interface. This study's primary contribution lies in introducing a novel vertical wall-to-wall connection type suitable for application in prefabricated wall panel systems within industrialized building systems.

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DECLARATION OF COMPETING INTEREST

None

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