Experimental Investigation on In-Plane Lateral Stiffness and Degree of Ductility of Composite PVC Reinforced Concrete Walls

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Abstract: This study investigates the in-plane lateral stiffness and ductility of composite PVC encased concrete walls subject to the lateral loads using pushover tests to determine lateral strength and ductility characteristics of composite PVC encased walls filled with plain concrete, macro-synthetic fibre reinforced concrete, and steel reinforced concrete. Eighteen concrete wall specimens were cast and subjected to pushover test to determine the load-deflection curves. Based on the capacity curves resulting from the pushover tests, the yield and maximum displacements and subsequently structural ductility and performance factors according to Australian Standard for seismic design of buildings have been determined. The determined parameters as well as the initial and effective lateral stiffness values measured from the load-deflection curves for all three cases were compared and the final findings have been discussed. Based on the outcomes of this study, it has become apparent that the tested composite PVC encased macro-synthetic fibre reinforced concrete walls can exhibit superior performance in terms of ductility when compared to the unreinforced concrete specimens. In addition, the results indicated that the initial in-plane lateral stiffness values of the tested composite PVC encased macro-synthetic fibre reinforced concrete walls increased by 25% compared to the tested walls filled with plain concrete. In order to enable structural designers to design composite PVC encased concrete walls, ductility factors for this type of walls have been extracted from the test results for the three mentioned cases and proposed for practical applications. It has been concluded that all the PVC encased concrete walls evaluated in this study can be categorised as fully ductile structures.

Keywords: *Reinforced concrete, Composite PVC encased concrete walls, Lateral strength, Pushover analysis, Capacity curve, Macro-synthetic fibre reinforced concrete, Load carrying capacity*

1. Introduction

All over the world many existing reinforced concrete (RC) structures, constructed prior to earthquake-resistant design procedures, are unable to provide sufficient ductility during earthquakes [1, 2]. Today, several countries including the United States and Australia move towards applying performance-based design concepts [3, 4]. The new seismic design requirements based on this philosophy will require engineers to carry out non-linear analyses of structures [5]. As many investigators have expressed [6-9], these analyses can be in the form of a full non-linear dynamic analysis or a static non-linear pushover analysis. The former, as mentioned by Sung et al. (2005) [7], is one fundamental approach capable of depicting dynamic responses of a structure during the entire vibration period, but it also may cost huge computer time to perform exhausting iterative process. This shortcoming has made this method to become not so popular in practical design except for some special purposes of structural investigation [7]. On the other hand, as

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explained by Ucar, Merter & Duzgun (2015) [8], non-linear static pushover analysis which considers the inelastic behaviour of structures, is a straightforward and practical tool for computing seismic demands imposed by the design earthquake on the structures and in most cases, provides sufficient information on the strength and deformation capacities of structures in the inelastic range.

As described by Le Nguyen et al. (2014) [10], although reinforced concrete walls are able to dissipate the generated seismic energy, they exhibit serious post-earthquake damage mainly due to incidence of unpredictable high seismic activity, inappropriate design, and construction flaws. Therefore, they must be properly designed to provide not only adequate strength, but also sufficient ductility to avoid brittle failure under strong lateral loads. Even though over the recent years many studies [11-13] have been carried out in the development of non-linear and analytical models to predict the inelastic strength of walls subjected to reverse cyclic loading, there is still a lot to be done for reinforced concrete structural walls. Le Nguyen et al. (2014) [10] conducted an experimental and numerical investigation to evaluate the effects of carbon fibre reinforced polymer (CFRP) strips on the behaviour of two short and slender lightly reinforced concrete walls with the aspect ratios equal to 0.67 and 2.5, respectively. In that study, pushover tests were conducted in the laboratory under constant compressive load and the numerical results in terms of the load-displacement curves were compared with the experimental data. Eventually, it was shown that in both cases, the CFRP strengthening modifies the crack pattern at failure due to more noticeable shear effects and also the distributive role of the CFRP strips in the damage development over the surface of the wall was highlighted. Mostofinejad & Anaei (2012) [12] discussed the confinement of the boundary elements of shear walls with FRP composites and their influence on flexural behaviour of the walls. Nonlinear finite element analysis was performed on two shear walls using damage plasticity model and considering tension stiffening effect. Results of the latter study show the remarkable effectiveness of strengthening FRP composite layers on ductility of concrete shear walls; the confinement of the boundary elements with FRP increased the ultimate displacements, under almost constant load, by up to 50%. Su & Wong (2007) [13] performed an experimental study on three reinforced concrete (RC) wall specimens to study the impacts of axial load ratio (ALR) and confinement on their performance under artificial earthquake loads. In that study, the walls in the form of a slender vertical cantilever, constructed with high strength concrete and high longitudinal reinforcement ratio, were tested and the effects of ALR and confinement on failure mode, strength degradation, ductility capacity, and axial load capacity were precisely evaluated. It was concluded that axial load ratio (ALR) has substantial effect on the deformability and failure mode of the walls and it was shown that an increase in ALR has adverse effects on strength degradation and energy dissipation of reinforced concrete walls. As discussed by many researchers [14-17] (Gobinath & Selvi 2014; Havez 2014; Havez et al. 2016; Murillo et al. 2019) stay-in-place (SIP) formworks, as permanent formworks for the concrete walls, are more-practical alternatives to traditional steel or wood formworks due to their improved constructability and durability. Stay-in-place formwork systems are mainly assembled on site, hence facilitating the construction process and decreasing the construction time as the removal procedure is eliminated [15]. Most of these systems are made of lightweight and prefabricated materials such as PVC and FRP [16]. Abdulla (2017) [18], in a comprehensive study on PVC encased reinforced concrete members, pointed out that more practical work, laboratory and field tests, and detailed information from analytical and experimental studies will be required for developing appropriate design guidelines for composite PVC encased reinforced concrete members. In addition, structural material properties and characteristics significantly influence the performance of structural members [19, 20]. As a result, in this study, by conducting pushover tests, the structural behaviour of the composite PVC encased concrete walls under lateral loading is investigated. The variables in this study are the type of the concrete specimen used inside the PVC formworks including plain concrete, macro-synthetic fibre reinforced concrete, and reinforced concrete. Based on load-deflection curves resulting from the pushover tests, the yield capacity and the maximum displacements and subsequently structural ductility and performance factors, according to the Australian Standard (AS 1170.4-2007) [21] for seismic design of buildings, have been determined. Procedures for evaluating the existing ductility of structures are of importance to enable designers to ensure that structures have adequate ductility to satisfy the required ductility. Since Australian Standards including AS1170.4 (2007) [21] and AS 3600 (2018) [22] do not prescribe the ductility factors for composite PVC encased concrete walls, in order to enable structural designers to design this type of walls, those coefficients have been extracted from the test results for the three mentioned cases and proposed for practical applications.

2. Experimental Testing Program

The experimental testing program has been carried out at the structural laboratory at University of Technology Sydney (UTS). It involved the construction and testing of eighteen composite PVC encased concrete walls prepared as the cantilever beams clamped at their end supports and subjected to concentrated lateral load at the top of the beams. In fact, for each concrete type, six wall specimens (two specimens for each test) were tested for statistical analysis purposes. The base of each sample was also restrained to provide fixed boundary conditions as close as practicable. The experimental tests were conducted on specimens of 4000 mm long, 825 mm wide with 275 mm thickness. The test setup is displayed in Figures 1-3. The specimens were composed of PVC panels anchored at their end and base supports and subjected to concentrated lateral loads by a hydraulic jack. As shown in Figure 1, hydraulic jack (Enerpak 2MN) for applying lateral load, was mounted 2.5 m away from the end supports and the supports (i.e. base supports and end supports) were located 1 m apart from each other (edge to edge). For each test, ten displacement sensors (five sensors for each wall specimen) were used along the length of the walls (Figure 3) to capture the lateral deflection of each sample and subsequently to determine the stiffness of individual specimens. The test setup and loading rates of the tests were derived in a way that satisfy the requirements of AS3600 (2018) – Appendix B [22].

2.1.Employed Materials

All eighteen composite PVC encased concrete walls were prepared and poured with concrete having compressive strength of 40 MPa and 200mm slump and cured on site at UTS Tech Lab. Cylinder testing for both tensile and compressive capacities were carried out by qualified UTS staff for each specimen at the age of 28 days when the testing on the specimens was carried out. The stay-in-place PVC formwork system used in this study is known commercially as Dincel panels. All Dincel panels filled with three different concrete specimens including plain concrete, BarChip 48 fibre reinforced concrete, and steel reinforced concrete. Figure 4 illustrates one PVC encased wall with steel reinforcements made of three 275mm Dincel panels with overall dimensions of 825mm wide × 275 mm thickness. Three-dimensional views of 275 mm Dincel structural walling panels are shown in Figure 5. In addition, BarChip 48 synthetic fibre reinforcement (as shown in Figure 6) which is a high performance polypropylene fibre used as structural reinforcement in concrete. It works by distributing hundreds of thousands of high tensile strength fibres throughout the entire concrete mix [23]. BarChip 48 reinforces every part of the concrete structure, front to back and top to bottom, leaving no vulnerable unreinforced concrete part [23] (BarChip Inc 2020). Mechanical properties of Dincel panels and characteristics of BarChip 48 micro-synthetic fibres are presented in Tables 1 & 2 [24].

2.2. Test Procedure

In this study, composite PVC encased concrete walls were subjected to pushover test to determine the load-deflection curve for each specimen. The specimens were laterally loaded monotonically in stroke control (deflection) mode at a constant rate of 3.0 mm per minute equal to 1.5 mm per minute for each sample until failure occurred. The lateral load was controlled using a closed loop PID control system (FCS SmartTest One) and the lateral displacements were recorded using the sensors attached to the compression side of the specimens at different locations as shown in Figure 1. During the test, data was recorded using a data acquisition system (Figure 7). Pushover testing was conducted on the test specimens, which were cast with plain concrete, BarChip 48 fibre reinforced concrete, and steel reinforced concrete and tested at the age of 28 days with the following details:

- Six PVC encased wall specimens filled with plain concrete;
- Six PVC encased wall specimens filled with BarChip 48 macro-synthetic fibre (unit mass 5kg/m^3) reinforced concrete; and
- Six PVC encased wall specimens filled with steel reinforced concrete (N20@275mm normal ductility class deformed reinforcing bars grade D500N with yield strength 500 MPa according to AS3600-2018 [22])

Although the faces touching the base support had a slight curvature due to the fabrication of the specimens, the faces at the load point were reasonably flat. To apply the load laterally on the wall, a system was used at the load point consisting of a steel plate and a hydraulic jack. The steel plate was 10 mm thick by 300 mm wide by 300 mm long. During loading, Sample 2 indicated less movement at the end support compared to Sample 1 and consequently it lead to less rotation. In order to prevent rotation in some samples, they were reasonably packed tight at the end support with packing plates to minimise looseness in the system during the test procedure. The quasi-static test was stopped when the specimen was completely cracked at the base of the wall. The crack pattern characterising the bending failure mode of sample 1 is illustrated in Figure 8 at maximum top displacement. During the test, bending cracks developed at the tensile side of the wall, then horizontally propagated towards the centre line of the wall, and finally passed the centre line of the wall, towards the compressive side. Crack lengths continued to increase with the imposed top displacement. Prior to the bending failure of the wall, the bottom face of the wall was heavily cracked, emphasising the strong penetration of the bending crack in the core wall.

3. Results and Discussion

The main focus of this study is the non-linear static (pushover) analysis of PVC encased concrete walls based on the provisions for seismic design of buildings AS 1170.4 (2007) [21]. The average results of pushover tests for the structural walls subjected to lateral loads, which capture the material non-linearity of the structures, are presented in form of load-deformation curves in Figures 9-11. As it can be seen in Figures 9-11, in all the conducted tests, Sample 2 exhibits less movement under the lateral load compared to Sample 1. A more careful look at the results reveals that although all walls show similar response patterns, PVC encased concrete walls with steel reinforcements exhibit a considerable increase in strength during the test. The ultimate strength of Sample 1 is improved by nearly three times, from 72 kN and 75 kN for the plain and BarChip concrete specimens respectively to 221 kN for the steel reinforced concrete specimens. The enhancement in terms of ductility is also clearly noticeable, with a shear failure at 150 mm and 80 mm (measured by top laser), for steel reinforced and other specimens (plain and BarChip concrete), respectively. As a result, using steel reinforcements appears to be effective for delaying the shear failure.

Average results of non-linear static tests, measured by top sensors, on Dincel structural walling systems filled with three different types of concrete are shown in Figure 12. As illustrated in Figure 12, the first stage of the load–displacement curve is very similar for both steel and BarChip 48 reinforced concrete specimens up to the displacement equal to 4 mm. Indeed, the initial stiffness remains almost unchanged by using reinforced concrete specimens. In addition, for BarChip 48 specimens, the failure becomes more ductile than plain concrete specimens for which displacement increases at the constant load of 70 kN. For BarChip 48 specimens, it can be remarked that the strength decrease is very progressive highlighting the ductility of the failure and it can be understood that the PVC encased walls filled with BarChip 48 could be pushed to a higher level of displacement. However, filling Dincel panels with BarChip 48 concrete does not provide a significant gain of ultimate strength in comparison to the plain concrete specimens.

From the capacity curves, the yield displacement and the maximum expected displacement (target displacement) can be determined. As mentioned by Park (1988) [25] and Martino, Spacone & Kingsley (2000) [5] in dynamic analysis of structures responding to a major earthquake in the inelastic range, it is usual to express the maximum deformations or displacements in terms of ductility factors, where the ductility factor (μ) is defined as the maximum deformation (Δ_u) divided by the corresponding deformation present when yielding occurs (Δ_y). In fact, the use of ductility factors permits the maximum deformations to be expressed in non-dimensional terms as indices of inelastic deformation for seismic design and analysis [26]. Various methods have been presented by different studies [25, 27-31] to estimate the maximum and yield displacements based on the pushover test results. In this study, according to Park (1988) [25], the yield displacement is determined based on the equivalent elasto-plastic curve with the same elastic stiffness and ultimate load as the real structure. In addition, as a conservative method pointed out by Park (1988) [25], the maximum deformation is defined as the displacement corresponding to the peak of the load-displacement curves.

Average load-displacement curves, measured at the top laser, for both Samples 1 and 2 are shown in Figures 13-15. As illustrated in Figures 13-15, the maximum deformation (Δ_u) measured for reinforced concrete specimens (120 mm) is three times the deformations measured for plain and BarChip 48 specimens. Although the measured yield displacements (Δ_y) show the same ratio for steel reinforced and BarChip 48 samples, they indicate twice ratio (Δ_u/Δ_y) for plain concrete specimens. According to Figures 13-15, while ductility factor (μ) calculated for plain concrete walls is 4 ($\mu = 4$), this factor increases to 6 for BarChip 48 and steel reinforced specimens. The ductility factor required by AS 1170.4 (2007) [21] may vary between 1 for elastically responding structures to as high as 4 for fully ductile structures. In this way, all the PVC encased concrete walls evaluated in this study can be categorised as fully ductile structures according to Table 14.3 of AS3600 (2018) [22], although BarChip 48 and steel reinforced specimens exhibit more ductility which results in higher performance of BarChip synthetic fibre reinforcements during lateral loading than plain concrete. Indeed, using BarChip 48 macro-synthetic fibre reinforced concrete turns out to be very efficient by improving ductility compared to unreinforced concrete specimens. In addition, structural performance factor (S_p) as an additional ability of the total structure, including PVC panels and concrete specimens, for resisting earthquake motion can be determined based on AS 1170.4 (2007) [21] and AS 3600 (2018) [22]. According to Table 14.3 of AS 3600 (2018) [22] for all concrete walls with fully ductile behaviour, structural performance factor (S_p) can be considered equal to 0.67. Ductility factors (μ) and structural performance factors (S_p) of composite PVC encased concrete walls studied in this paper are summarised in Table 3.

Based on the capacity curves, also the initial stiffness (K_i), the effective stiffness (K_e), and the post-yield stiffness (αK_e) of the reinforced concrete structures can be determined. According to the method demonstrated by Martino, Spacone & Kingsley (2000) [5], while initial stiffness (K_i) is defined as the slope of linear section (elastic part) of the load-displacement curves, the effective stiffness (K_e) can be defined as the slope of the line passing through a point corresponding to $0.6F_y$ where F_y is the yield load. Different in-plane lateral stiffness parameters of PVC encased concrete walls investigated in this study are determined in Figures 16-18 and are summarised in Table 3. Referring to Figures 16-18 and Table 3, it is observed that steel reinforced concrete walls generate the highest in-plane lateral stiffness value, followed by BarChip 48 and then plain concrete specimens. It is noticed that in PVC encased concrete walls filled with steel reinforced concrete compared to BarChip 48 specimens, the initial in-plane stiffness is not considerably modified; the behaviour is almost identical up to the load of 40 kN corresponding to a lateral displacement of 4 mm. As shown in Figures 16-18, for the PVC encased walls filled with reinforced concrete, the pushover analysis gives the in-plane lateral effective stiffness of 6400 N/mm, while it yields the in-plane lateral effective stiffness of 5300 and 4800 N/mm for BarChip and plain concrete walls, respectively.

4. Conclusions

The pushover analysis, by providing additional information on the force redistribution caused by a seismic event and detailed member information, increases the effectiveness and efficiency of the design. This is in turn allows the engineers to make a more informed decision on what kind of design they wish to have for their structures. In this study, the in-plane lateral stiffness and ductility of composite PVC encased concrete walls subjected to the lateral loads for composite PVC encased walls filled with conventional plain concrete, macro-synthetic fibre reinforced concrete, and steel reinforced concrete have been investigated. The preliminary conclusion that can be drawn from the obtained results is that *all composite PVC encased walls can be designed as fully ductile structures ($\mu = 4$) in accordance with Table 14.3 of AS3600 (2018)* [22], although higher performance of BarChip 48 fibre reinforcements increased the ductility factors of the walls to 6.0. For steel reinforced concrete walls, the pushover analysis indicated a target displacement of 120 mm, while it yields the maximum displacement of 40 and 42 mm for the PVC panels filled with plain and BarChip 48 concrete, respectively. In addition, in case of using BarChip 48 macro-synthetic fibre reinforced concrete, the initial and effective in-plane lateral stiffness values of the walls were clearly enhanced by 25% and 10%, respectively, compared to the PVC profiles filled with conventional concrete.

The procedure of evaluating the available ductility of walls is of importance to enable designers to ensure that structures have adequate available ductility to satisfy the required ductility. Therefore, in order to enable structural designers to design composite PVC encased concrete walls adequately, ductility factors for this type of walls have been extracted from the test results for the three mentioned cases and proposed in Table 3 of this study for practical applications.

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Data Availability Statement

The raw/processed data required to reproduce these findings cannot be shared at this time due to legal reasons.

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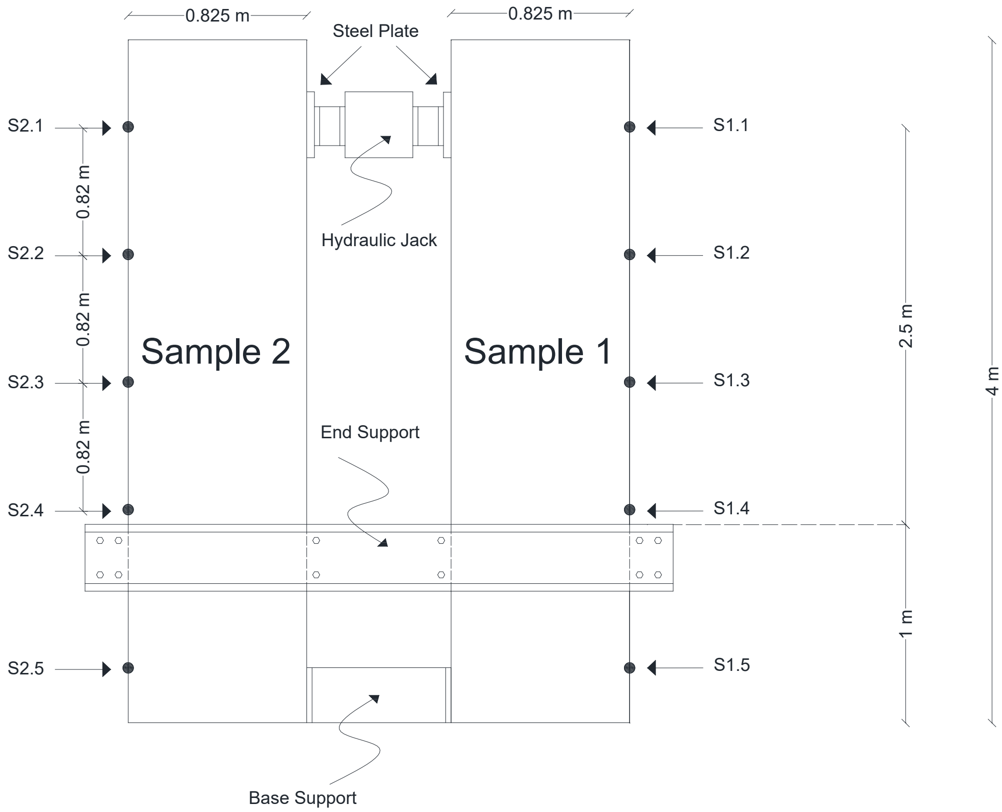


Figure 1. Schematic diagram of pushover test setup (S illustrates sensors)

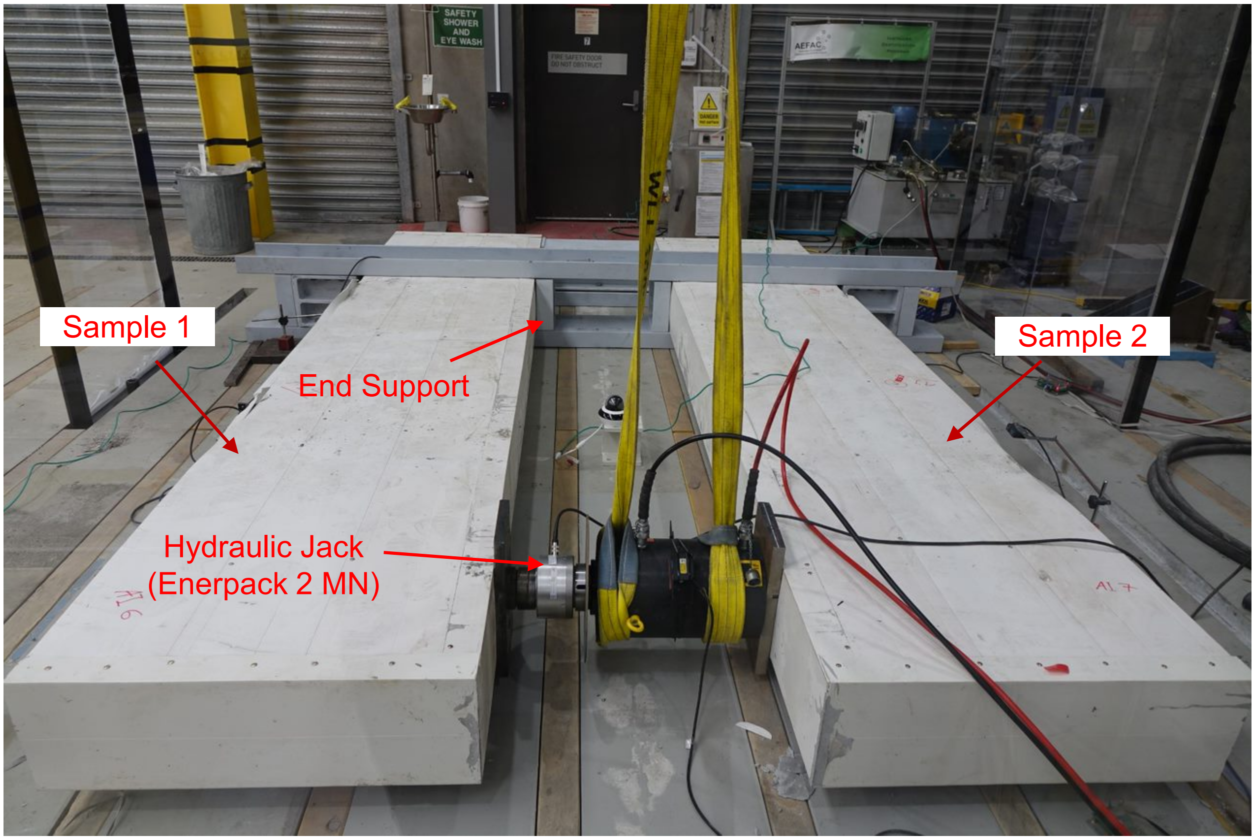


Figure 2. Non-linear static pushover test setup in experimental study

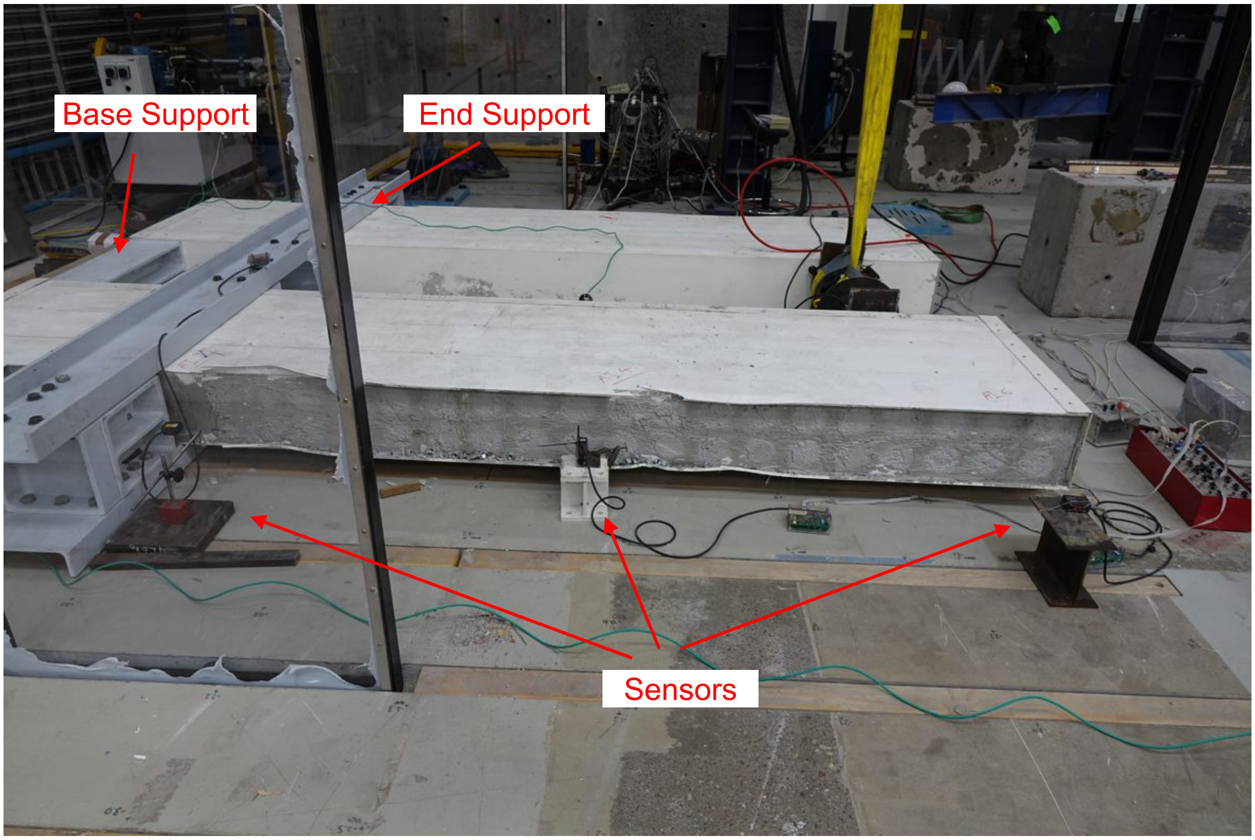


Figure 3. Base and end supports in composite PVC encased concrete walls

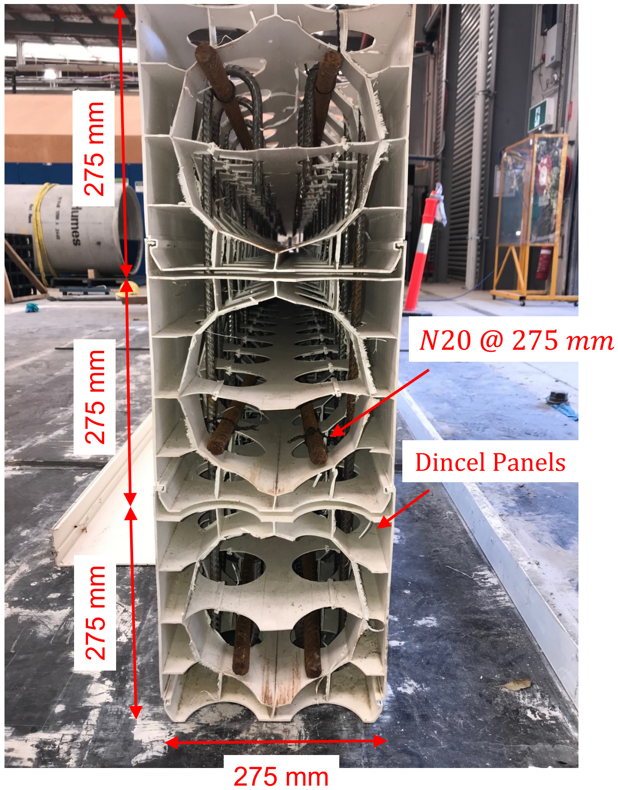


Figure 4. Front view of a PVC encased wall with steel reinforcements

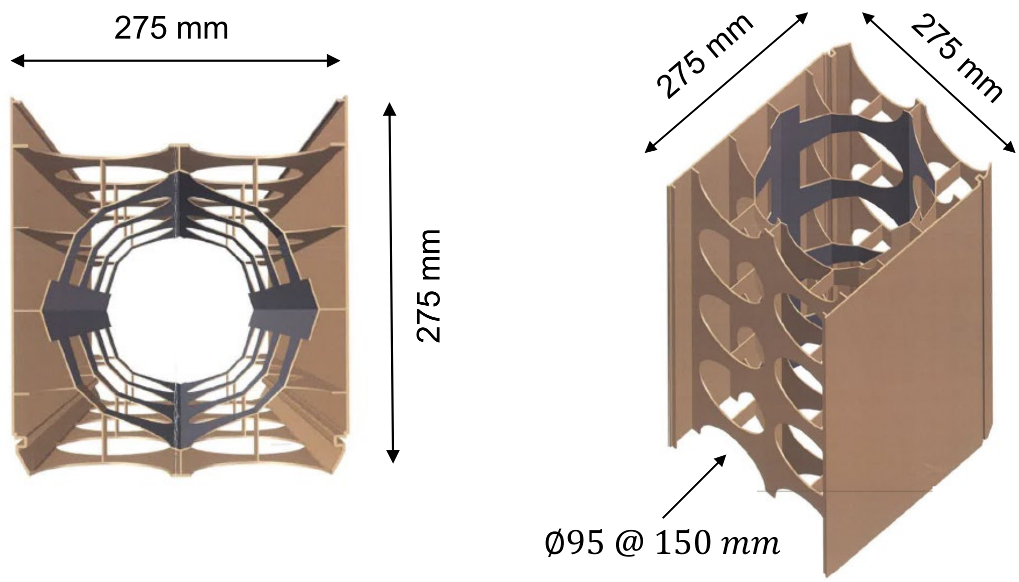


Figure 5. Three-dimensional views of 275 mm Dincel structural walling panels

Figure 6. BarChip 48 macro-synthetic fibre concrete reinforcement [23]

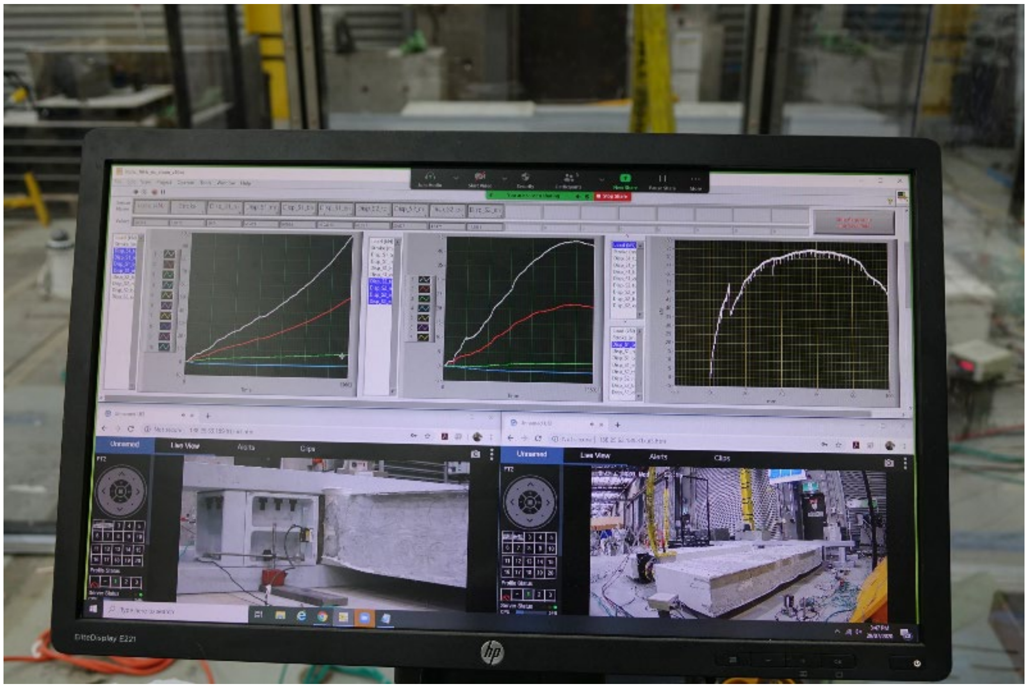
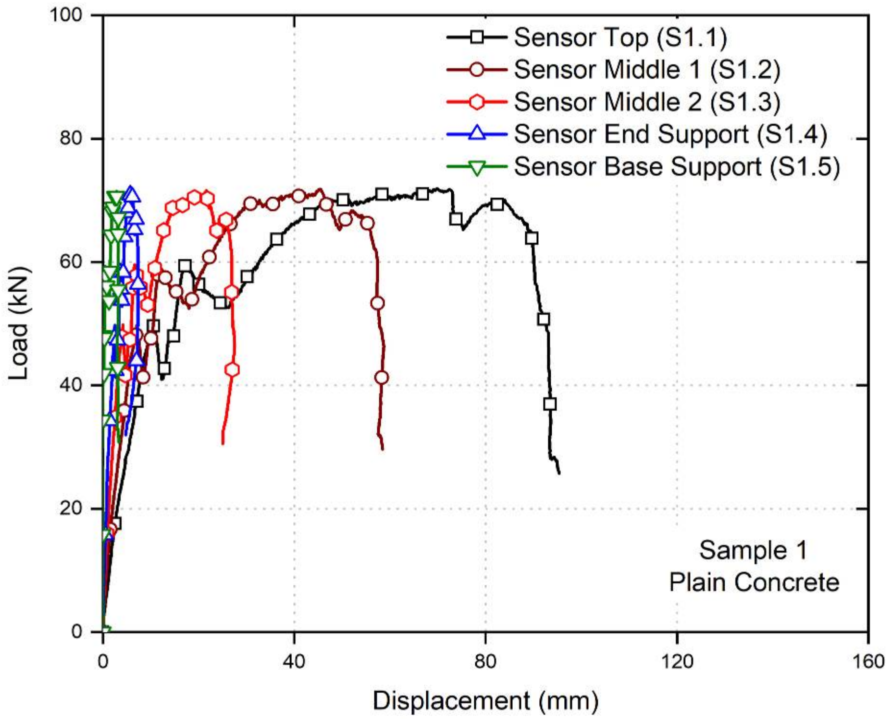
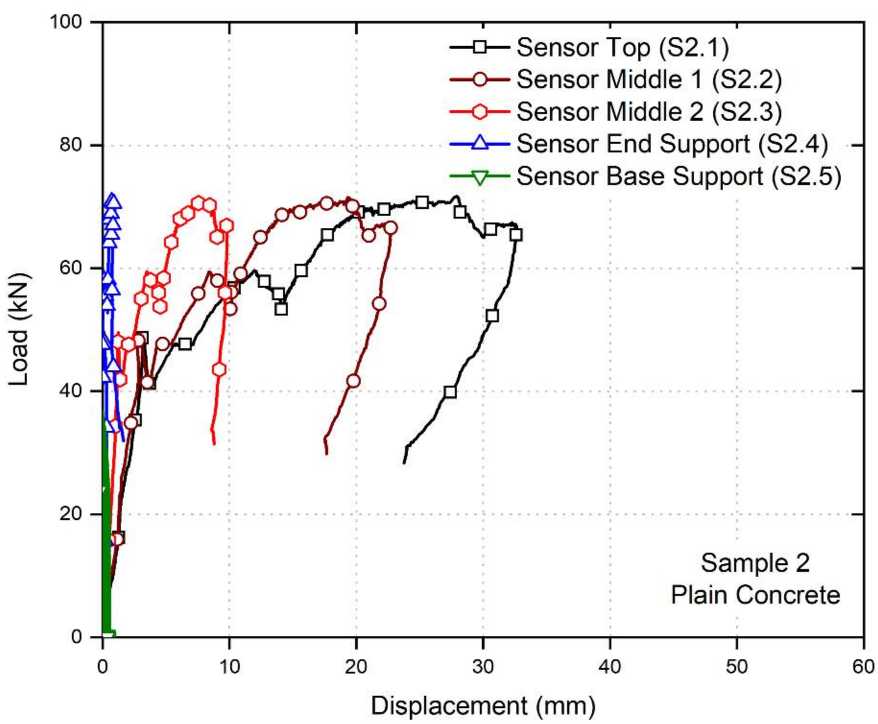


Figure 7. Data acquisition system used in the experimental study

Figure 8. Failure mode of the walls under compressive lateral loads

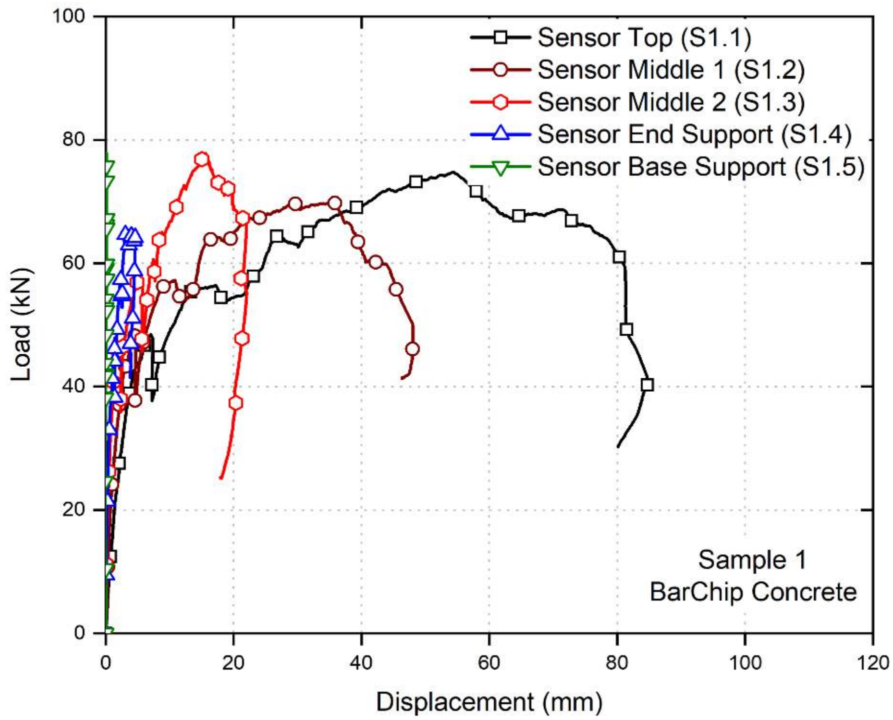

Sensor Top (S1.1)
Sensor Middle 1 (S1.2)
Sensor Middle 2 (S1.3)
Sensor End Support (S1.4)
Sensor Base Support (S1.5)
Sample 1
Plain Concrete
Load (kN)
Displacement (mm)
0
20
40
60
80
100
0
40
80
120
160

(a)

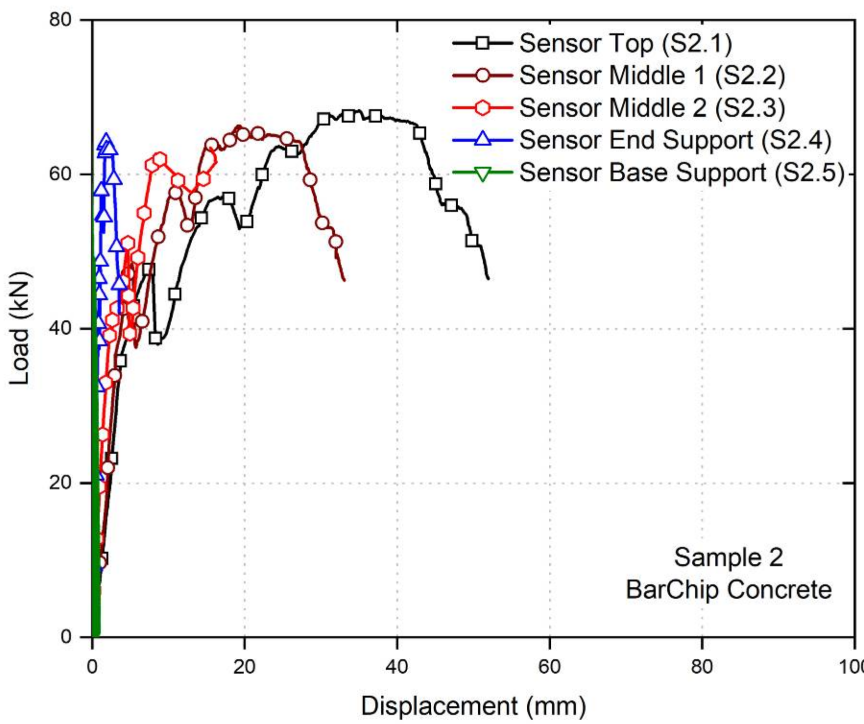

Sensor Top (S2.1)
Sensor Middle 1 (S2.2)
Sensor Middle 2 (S2.3)
Sensor End Support (S2.4)
Sensor Base Support (S2.5)
Sample 2
Plain Concrete
Load (kN)
Displacement (mm)
0
20
40
60
80
100
0
10
20
30
40
50
60

(b)

Figure 9. Average load-displacement curves measured by different sensors in composite PVC encased walls filled with plain concrete for (a) Sample 1 (b) Sample 2

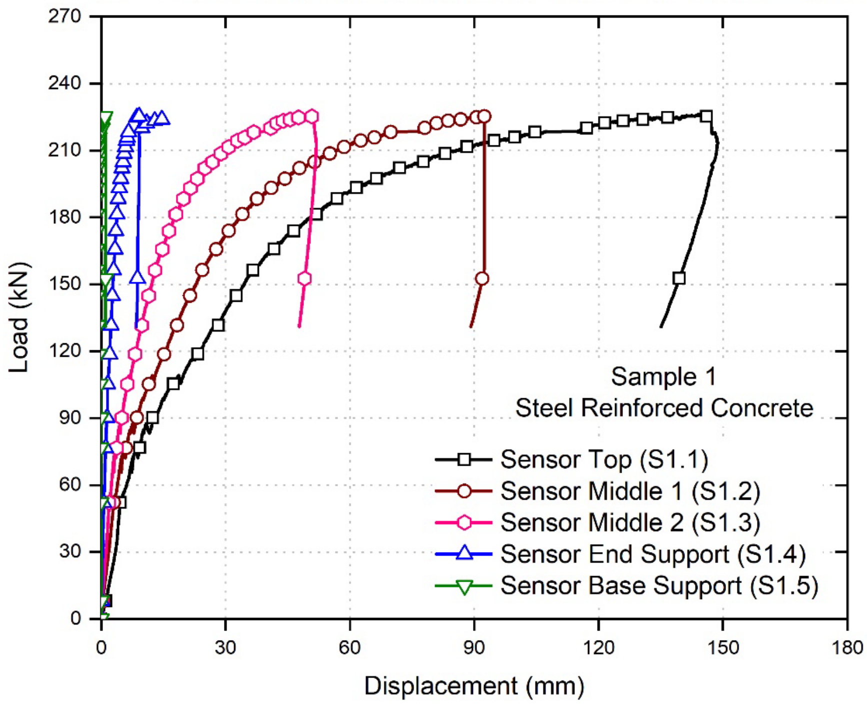


(a)

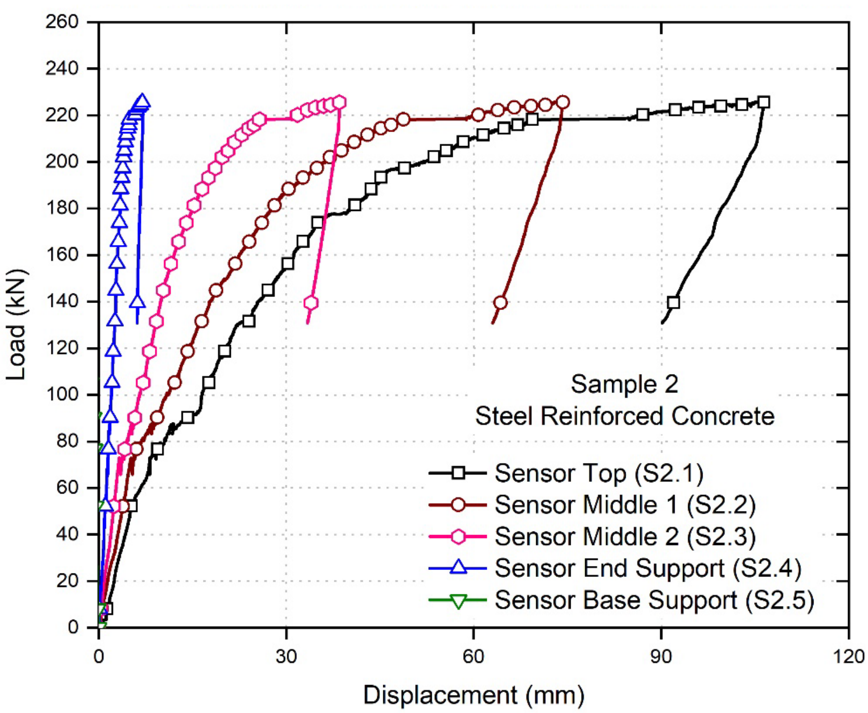


(b)

Figure 10. Average load-displacement curves measured by different sensors in composite PVC encased walls filled with BarChip concrete for (a) Sample 1 (b) Sample 2



(a)



(b)

Figure 11. Average load-displacement curves measured by different sensors in composite PVC encased walls filled with steel reinforced concrete for (a) Sample 1 (b) Sample 2

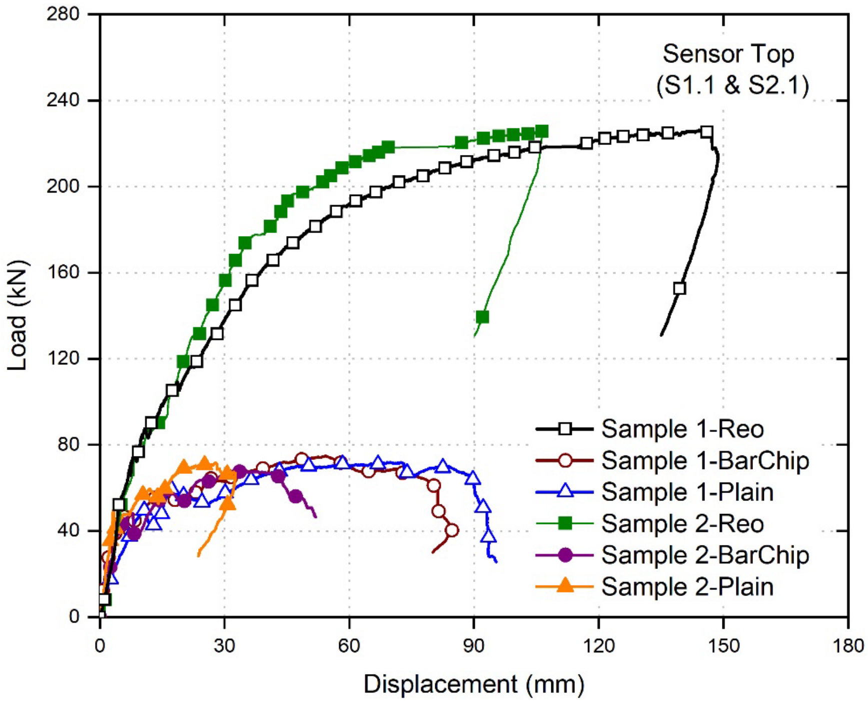


Figure 12. Average load-displacement curves measured by top sensors in Samples 1 and 2 for all specimens

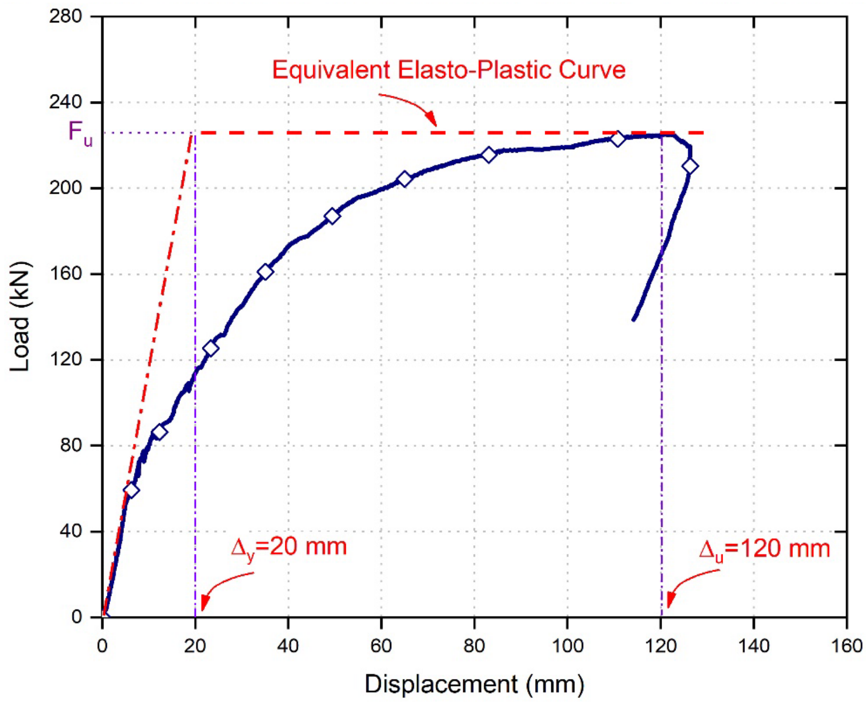


Figure 13. Finding yield and target displacements for reinforced concrete specimens (average of Samples 1 and 2)

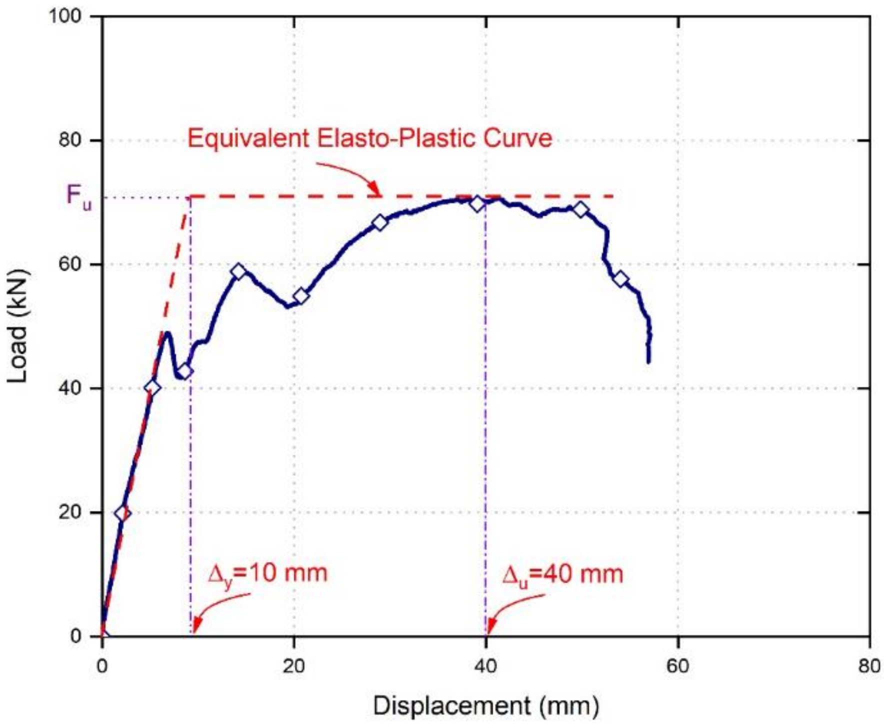


Figure 14. Finding yield and target displacements for plain concrete specimens (average of Samples 1 and 2)

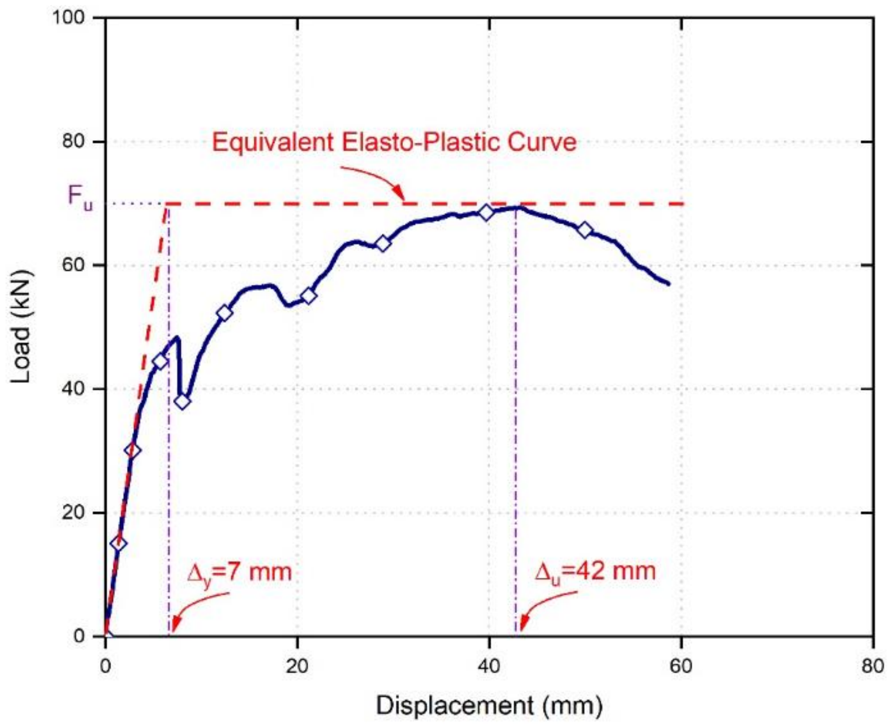


Figure 15. Finding yield and target displacements for BarChip concrete specimens (average of Samples 1 and 2)

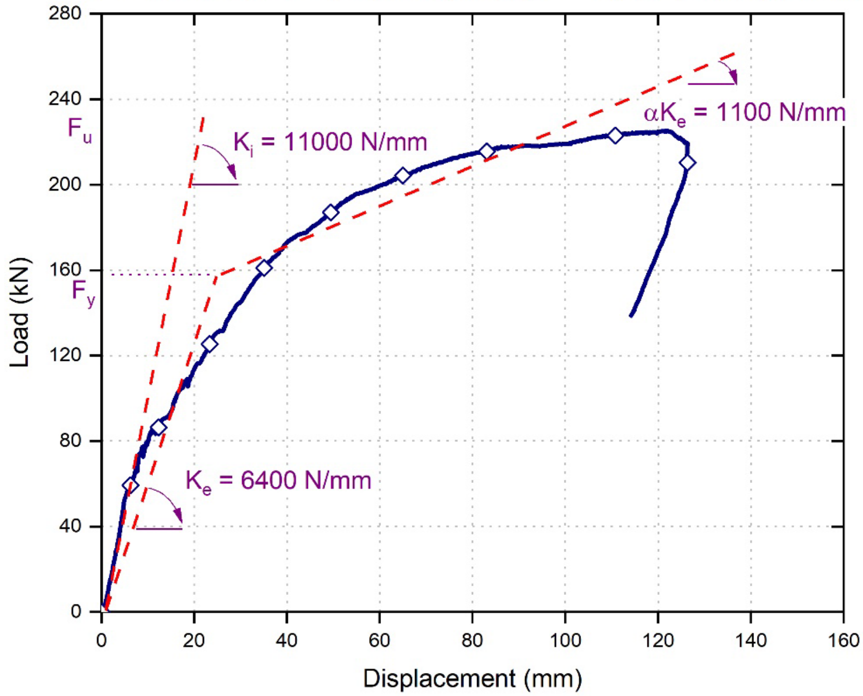


Figure 16. Finding lateral stiffness values for reinforced concrete specimens (average of Samples 1 and 2)

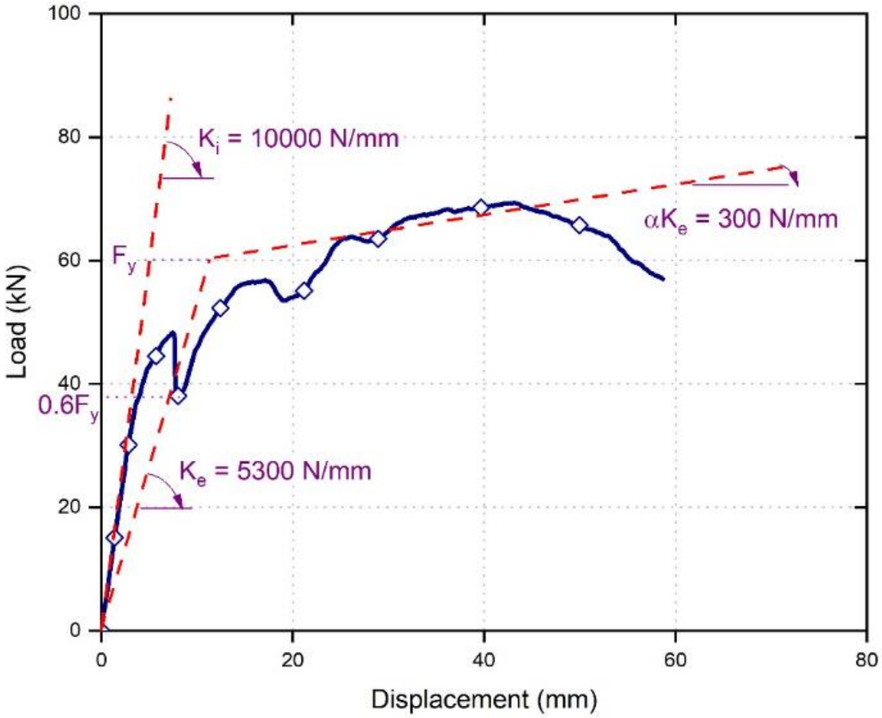


Figure 17. Finding lateral stiffness values for BarChip concrete specimens (average of Samples 1 and 2)

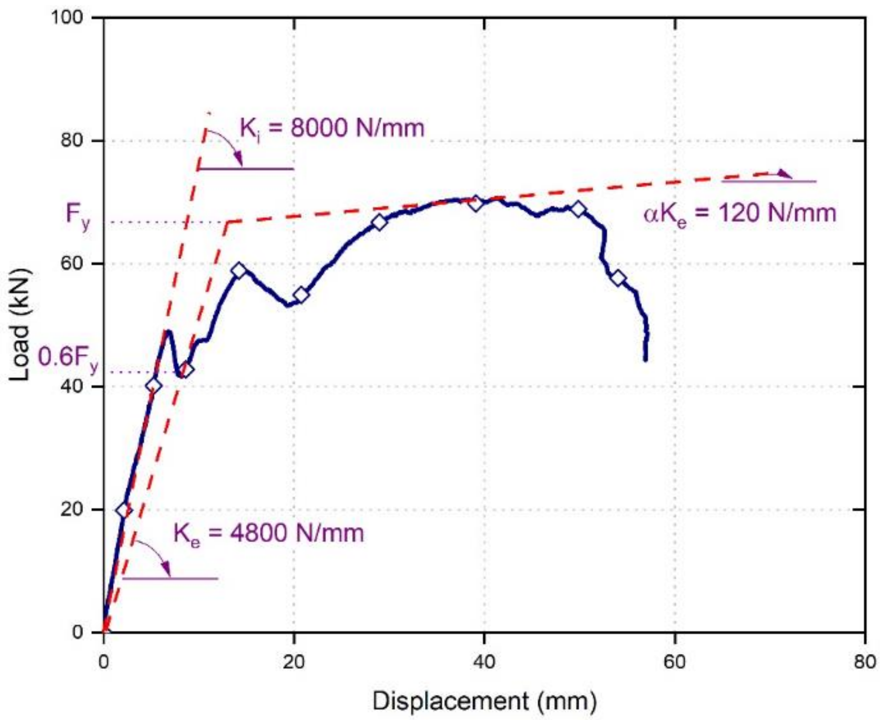


Figure 18. Finding lateral stiffness values for plain concrete specimens (average of Samples 1 and 2)

Table 1: Mechanical properties of tested PVC material [24]

Young's Modulus E (MPa)	Tensile Strength σ_u (MPa)	Poisson's Ratio υ
2609	37.20	0.39

Table 2: Characteristics of BarChip 48 macro-synthetic fibre concrete reinforcement [23]

Young's Modulus E (MPa)	Tensile Strength σ_u (MPa)	Length (mm)	Base Material	Anchorage
12000	640	48	Virgin Polypropylene	Continuous Embossing

Table 3. Ductility and stiffness parameters of composite PVC encased concrete walls

Specimen	Ductility Factor (μ)	Performance Factor (S_p)	Initial in-plane lateral Stiffness (K_i) (N/mm)	Effective in-plane lateral Stiffness (K_e) (N/mm)	Post-Yield Stiffness (αK_e) (N/mm)
Steel Reinforced Concrete	6	0.67	11000	6400	1100
BarChip Concrete	6	0.67	10000	5300	300
Plain Concrete	4	0.67	8000	4800	120