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USE OF NEAR SURFACE MOUNTED REINFORCEMENT IN SINGLE-WYTHE 3D PRINTED CONCRETE WALL PANELS

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ABSTRACT: One of the most pressing challenges facing Canada and many parts of the world is the need for affordable housing. There is now an estimated shortfall of 3.5 million homes in Canada that need to be constructed by 2030. Innovation in construction is one approach to addressing these challenges, by using technology to improve efficiency and reduce costs in the construction sector and supplement labour shortages using intelligent machines. One such innovative solution is 3D concrete printing, commonly referred to as 3DCP, which is an additive manufacturing technique that uses concrete extrusion to fabricate multi-wythe concrete walls, and when operating at maximum efficiency, it is estimated that a single-family home could be printed in under 24 hours. Despite the potential advantages of 3DCP technology, one of the major limitations on the use of 3DCP for multi-storey structures and structures in seismically active regions is the integration of vertical reinforcement. One solution to this challenge is the use of post-installed near surface mounted (NSM) reinforcement. To validate the concept, this study investigates the structural behaviour of single-wythe 3DCP wall panels reinforced with NSM bars subjected to out-of-plane bending. The work investigates the use of conventional steel and glass fibre reinforced polymer (GFRP) bars bonded using either epoxy or cementitious grout. Structural performance of the walls is evaluated in terms of their stiffness, strength, and cracking behaviour.

1. INTRODUCTION

Advances in robotics and intelligent automation have transformed industrial manufacturing over the last two decades, however, the construction industry in Canada and around the world has comparatively been slow to adapt to the digital age. As Canada strives to address growing housing needs while at the same time building resilient communities, particularly under the effects of climate change, there is a need to develop new technologies to improve construction efficiency and build livable, safe, and resilient communities.

Recent advancements in cement-based additive manufacturing processes, commonly referred to as 3D concrete printing, has the potential to revolutionize the house construction industry resulting in improved efficiency and speed with reduced waste and requiring fewer skilled workers. The construction of 3D printed concrete homes typically involves the use of two thin concrete layers, commonly referred to as wythes, separated by an air gap which can be used to run utilities and place insultation. While a variety of printer types are available on the commercial market, gantry style systems have been most popular in Canadian construction and have been used in several notable projects, including Habitat for Humanity homes in Windsor, ON (Campbell, 2022), and a community project for Siksika First Nation in Alberta (Coulter, 2023). The gantry-style 3D concrete printers used in these projects have a print speed of up to 0.5 m/s and a maximum print height of 8.1 m, which translates into the ability to print a single-storey home in one day.

Despite the potential for 3DCP to revolutionize the construction industry, a significant barrier to widespread adoption and use of 3DPC in current construction is the need for large-scale structural testing. To date, there has been extensive work on evaluating the material properties of 3D printed concrete (Khanverdi and Das, 2025a), and with respect to walls, some testing on axial load-carrying capacity (Han et al., 2022; Silveira et al., 2024; Khanverdi and Das, 2025b), thermal performance (Khanverdi and Das, 2025c), and in-plane behaviour (Delavar et al., 2024; Aghajani et al., 2026). Comparatively, structural testing of 3D printed concrete walls under out-of-plane bending is limited. In addition to structural testing, there is an urgent need to develop an approach to integrate steel reinforcement (i.e., rebar) into the construction process. This is something that is required, particularly for multi-storey homes and homes in seismically active areas (e.g., in Quebec and British Columbia), where vertically oriented steel rebar is required for structural safety and ductility. In traditional reinforced concrete structure, rebar is placed inside of wooden formwork prior to placing of the concrete. However, because of the need for the printer nozzle to move laterally as it prints a structural component, vertical reinforcement cannot be included because it would impede the motion of the printer. Consequently, many 3DCP structures to-date have been unreinforced, raising concerns surrounding their performance in extreme load events (earthquakes).

Researchers and practitioners have proposed some solutions to this challenge, which most commonly include printing cavities in which reinforcing bars can be placed and then grouted (Delavar et al., 2024). This approach mimics what is done in traditional masonry construction. Albeit effective, this approach limits the potential advantages of 3D concrete printing, as the printing process must be paused while reinforcement is placed within cells and grouted. Furthermore, reinforcing bars are not optimally located in this construction style, and often fall near the neutral axis when subjected to out-of-plane bending. A promising alternative to this technique is the use of near surface mounted (NSM) reinforcement, in which reinforcing bars are placed within grooves on the exterior or interior of a wall, typically formed using a saw, and bonded using an adhesive (e.g., epoxy or grout). This approach has several advantages, as reinforcing bars can be placed after the printing process is complete and the bars are located at the extreme fiber (in tension or compression), maximizing structural performance in out-of-plane bending. It is noted that the use of NSM reinforcement is not a new concept, as it has been used in reinforced concrete (Lorenzis and Nanni, 2001; Taljsten et al., 2003; De Lorenzis and Teng, 2007; Abdzaid and Kamonna, 2019; Sparling et al., 2021) and masonry walls (Fam et al., 2010; Dizhur et al., 2014; Al-Jabari et al., 2015; Sparling and Palermo, 2023), however, the concept has not been extended to 3D printed concrete walls.

To address the challenges associated with the incorporation of reinforcement in 3D printed concrete walls, this study aims to investigate the potential use of NSM reinforcement as an efficient and effective reinforcement method for 3D printed concrete walls. The specific objectives of this research project are to:

1. Develop the NSM techniques for incorporating longitudinal reinforcement into 3DPC walls;
2. Investigate the behaviour and failure mechanisms of 3DPC concrete walls under out-of-plane bending;
3. Investigate the stiffness, strength, and cracking behaviour of thin printed concrete wythes; and
4. Use digital image correlation to examine the distribution of compressive strains in non-uniform 3D printed concrete wythes under out-of-plane loading.

2. EXPERIMENTAL PROGRAM

2.1 Test Specimens

The test specimens in this study represent a sub-section of a larger 3D printed concrete wall, shown in Figure 1. The specimens represent a single-wythe of what would normally be a multi-wythe composite wall system, including insulation and cross-ties to achieve composite action between wythes. This specimen configuration was selected for simplicity in this study, as it enabled evaluation of the feasibility of using NSM reinforcement in 3D printed concrete walls without the added complexities of considering composite action and much heavier concrete wall assemblies. The panels measured 600 mm wide, 1650 mm long, and were 50 mm thick on average, although it is noted that the thickness of the panels varied significantly along the specimen length as a result of the additive manufacturing process used in their construction.

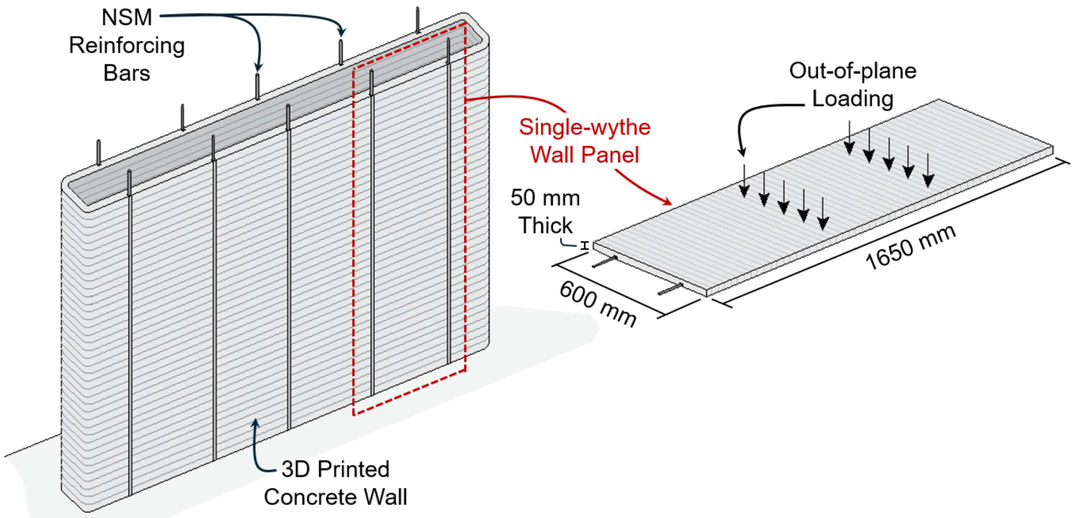

Figure 1: Geometry of a typical 3D printed wall specimen

Figure 2 shows the installation process for the NSM reinforcement in this study as well as the configuration of the reinforcement within the cross-section. Two different wall specimens are discussed in this study, including one wall panel reinforced with three #2 GFRP bars (6.2 mm diameter) and a second reinforced with two 10M steel reinforcing bars (11.3 mm diameter). The reinforcement ratios for the GFRP and steel reinforced wall panels were 0.4 % and 0.8 %, respectively. Two different adhesive types were used in this study, which included an epoxy adhesive as well as a cementitious mortar. Two tests of each wall panel type (GFRP and steel) are discussed in this study. In the GFRP reinforced panels, one test used epoxy (referred to as GFRP-E), while the second used mortar (referred to as GFRP-M). In the steel reinforced panels, both specimens used epoxy (referred to as Steel-E1 and Steel-E2).

The installation of the NSM bars in the wall panels followed a four step process: (1) parallel grooves measuring ~3 mm wide and ~25 mm apart were cut along the length of the panels using a concrete saw, (Figure 2(a)) (2) material between the saw cuts was removed using a chisel (Figure 2(b)), (3) an adhesive (epoxy or grout) was placed within the grooves to approximately half the groove depths, (3) the reinforcing bar was pressed into the adhesive, and (4) the remaining groove area was filled with adhesive and a trowel was used to make the surface smooth (Figure 2(c)).

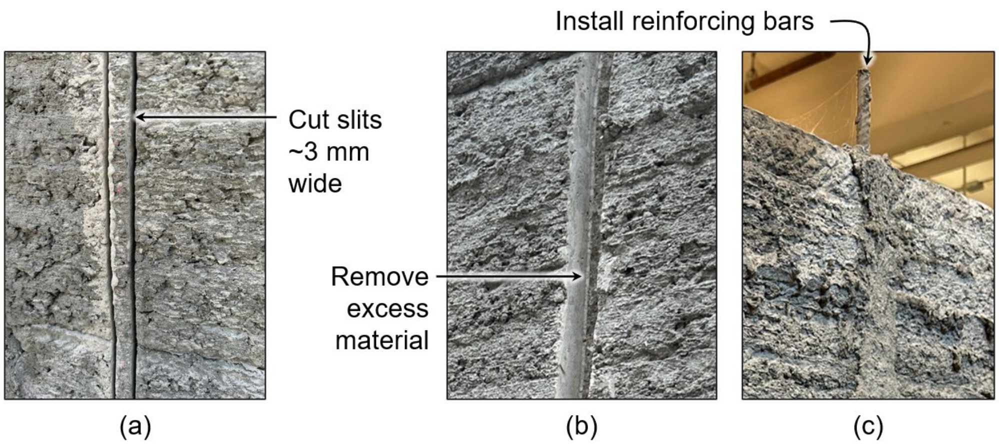

Figure 2: Typical installation of NSM reinforcement: (a) cut grooves in wall panel, (b) partially fill groove with adhesive, and (c) install reinforcing bar and fill remaining area with adhesive.

2.2 Material Properties

To evaluate the material properties of the 3D printed concrete, traditional material testing methods used in reinforced concrete were employed, including cylinders to evaluate the concrete compressive strength and prisms to evaluate the modulus of rupture. Future work should consider the use of testing standards intended for evaluating the in-situ properties of 3D printed concrete. The concrete cylinders had an average compressive strength of 64.7 MPa (standard deviation (SD) = 7.42 MPa) and the prisms had an average modulus of rupture of 5.97 MPa (SD = 0.52 MPa). The steel reinforcement used in one wall panel had a yield strength of 510 MPa. The GFRP bars had a tensile modulus of 40 GPa and a tensile strength of 800 MPa, which was provided by the manufacturer (VRod Grade I).

2.3 Experimental Test Setup and Instrumentation

Figure 2 shows the experimental test setup and instrumentation used to test the 3D printed concrete wall panels. The panels were tested under 4-point loading, with a total span of 1350 mm and a distance between point loads of 450 mm. Because of the complex and uneven geometry of the surface of the panels, a grout pad was cast at the support locations and the loading point on which the steel loading plates were placed. The steel loading plates were 100 mm wide and 12.7 mm thick. A servo-controlled hydraulic actuator was used to apply the load (+/- 500 kN force capacity, +/- 150 mm stroke). A steel spreader beam was used to create two equal point loads.

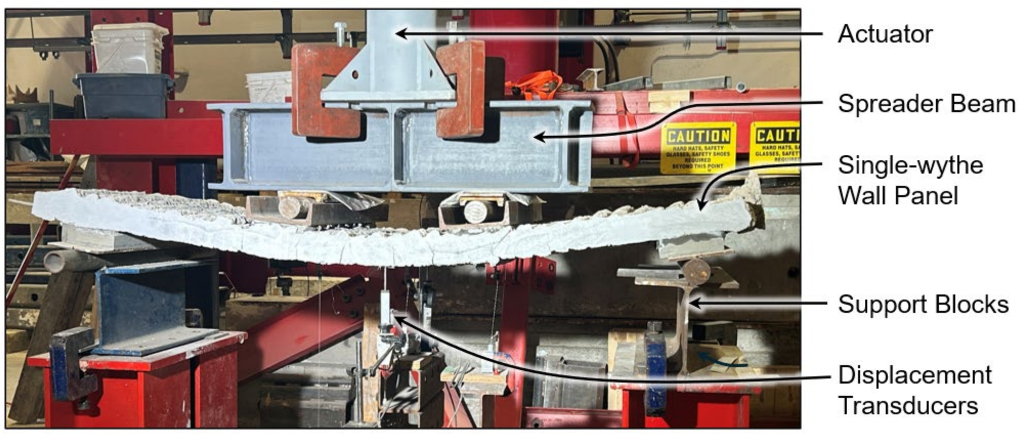

Figure 3: Experimental test setup and instrumentation

To measure the structural response of the wall, both discrete and distributed measurement technologies were employed. Discrete sensors included a load cell mounted to the hydraulic actuator, which was used to measure the force applied to the panels. Displacement transducers were also used to measure the midspan deflection of the panels, as shown in Figure 3.

In addition to conventional discrete sensors, digital image correlation was also used to capture the response of the walls. Although not a new technology, digital image correlation is still considered an advanced sensing technique, which uses digital cameras to capture images of a test specimen under load. By painting the surface of the test specimen with a unique speckle pattern, the displacement of individual pixels of an image can be tracked throughout a test and used to create full-field displacement and/or strain distributions. While digital image correlation has been used extensively in structural testing and field monitoring applications, it is particularly well suited for laboratory experiments on 3D printed concrete test specimens because of their complex and often uneven geometries, which makes the use of conventional discrete sensor technologies challenging, for example, mounting electrical resistance strain gauges or even mounting displacement transducers.

Figure 4 shows the setup for the digital image correlation system used in this study. A pair of cameras were used in this work, which enables stereo vision and three-dimensional displacement/strain results. The cameras were 5 MP digital cameras, which captured images of the test specimen at 0.2 Hz throughout the test using the VIC-Snap camera triggering software (Correlated Solutions, 2026). The region of interest in this study consisted of a section of the face of the wall panel extending a distance that was approximately equal to the constant moment region (i.e., from load point to load point). Analysis of the images was carried out using the VIC-3D commercial software package (Correlated Solutions, 2026).

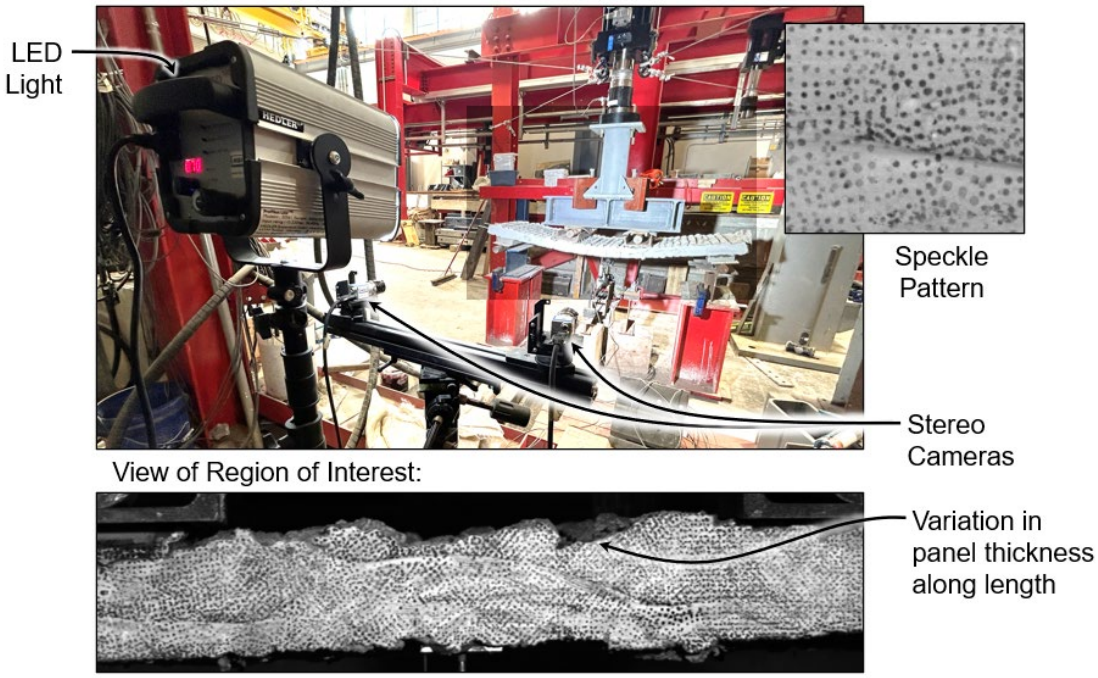

Figure 4: Instrumentation setup for digital image correlation

2.4 Loading Protocol

The panels were loaded in out-of-plane bending in displacement control at a rate of 2 mm/min up to yield, after which the panels were loaded in displacement control at 4 mm/min up to failure.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Tabel 1 summarizes the structural response parameters of each wall panel, including the initial stiffness (k_i), cracking load (P_{cr}), maximum load (P_{max}), midspan deflection at the maximum load (Δ_{max}), and the average crack spacing (s_{crack}) and average crack width (w_{avg}) based on digital image correlation results. Specimen name include a wall panel number, followed by reinforcement type (i.e., steel or GFRP), and the adhesive type (e.g., E for epoxy and G for grout).

Table 1: Summary of structural response parameters

Wall Panel Name	k_i (kN/mm)	P_{cr} (kN)	P_{max} (kN)	Δ_{max} (mm)	s_{crack} (mm)	w_{avg} (mm)
W1-Steel-E	4.01	5.49	20.2	19.2	-	0.16
W2-Steel-E	3.49	9.65	19.2	20.2	147	0.10
W3-GFRP-G	3.16	2.78	16.8	79.1	114	0.62
W4-GFRP-E	3.19	6.93	14.3	81.3	100	0.96

Figure 5 shows the load versus midspan deflection behaviour of the four wall panels described in this study. The results in Figure 5(a) for the steel reinforced specimens (W1-Steel-E and W2-Steel-E) show that both panels exhibit the traditional behaviour that is expected of reinforced concrete, including an initial elastic response, followed by cracking of the concrete and a second post-cracked elastic response. The two steel reinforced panels cracked at very different loads (5.49 kN versus 9.65 kN), however, the cracking load was found to be largely influenced by the minimum thickness of the wall, which varied significantly because of the layering effect of the concrete. Despite the differences in cracking load, both steel reinforced panels yielded which was followed by a yield plateau. One wall panel was tested to a maximum midspan deflection of 80 mm, at which point it was unloaded, demonstrating the ductility of these specimens and effective performance of the steel reinforcement. The maximum load carrying capacity of the wall panels was similar (19.2 versus 20.2 kN), which indicates that despite the influence of the difference in thickness on the behaviour of the wall panels, it did not significantly influence the ultimate load-carrying capacity.

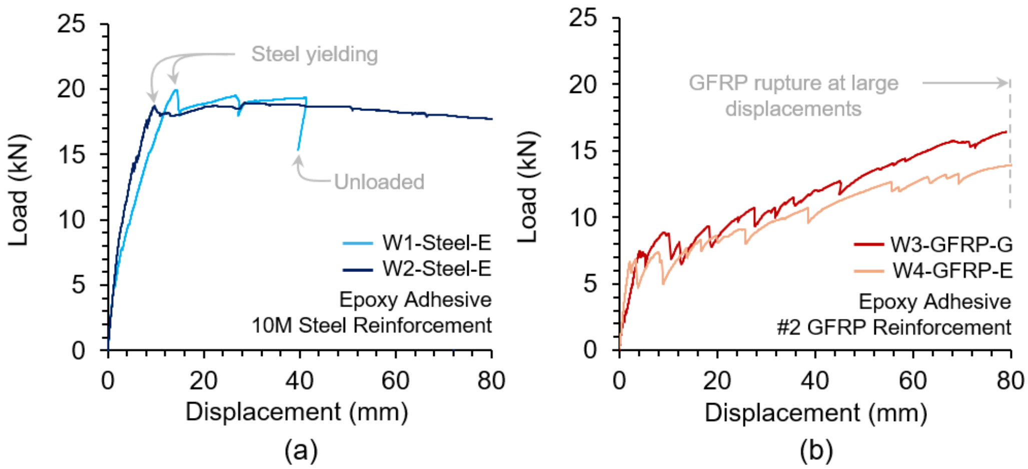

Figure 5: Load versus deflection behaviour of 3D printed wall panels with NSM reinforcement: (a) steel-reinforced panels (W1-Steel-E & W2-Steel-E), (b) GFRP-reinforced panel (W3-GFRP-G & W4-GFRP-E).

Figure 5(b) shows the load versus midspan deflection of the GFRP reinforced panels. The results highlighted the difference in behaviour between the two reinforcement type, as the GFRP reinforcement has a much lower elastic modulus (40 GPa for the GFRP versus 200 GPa for the steel) which results in a lower post-cracked stiffness. Furthermore, the GFRP reinforcement does not yield, and thus, the specimens exhibit a nearly elastic response up to the maximum load, which coincided with the maximum deflection of the specimens. Comparing the behaviour in Table 1, the panels once again had differences in cracking strength (2.78 kN versus 6.93 kN), which was attributed to the panel geometry, while the maximum load carrying capacities were similar (16.8 kN versus 14.3 kN). Nonetheless, the specimen exhibited significant ductility, achieving an ultimate displacement of approximately 80 mm in both panels. It is noted that one of the variables of interest that was compared amongst the test specimens was the adhesive used to bond the NSM reinforcement, which included either epoxy or grout. Based on the limited number of specimens tested in this study, there was no notable difference in behaviour amongst the panels tested with different adhesive types, however, additional research should be conducted to better understand the influence of adhesive type over a broader range of specimen geometries and design details.

Figure 6 shows a typical deflected shape for one of each type of panel at the ultimate load. In both panel types, the formation of a significant number of cracks along the length was noted, which is desirable behaviour in reinforced concrete, and encouraging in these specimens given their comparatively small thickness. Figure 6 also shows the typical failure mode that was observed in the GFRP panels at the ultimate load, which included rupture of the GFRP reinforcement at their ultimate strain, characterized by the classic 'broom failure' of the bars in tension.

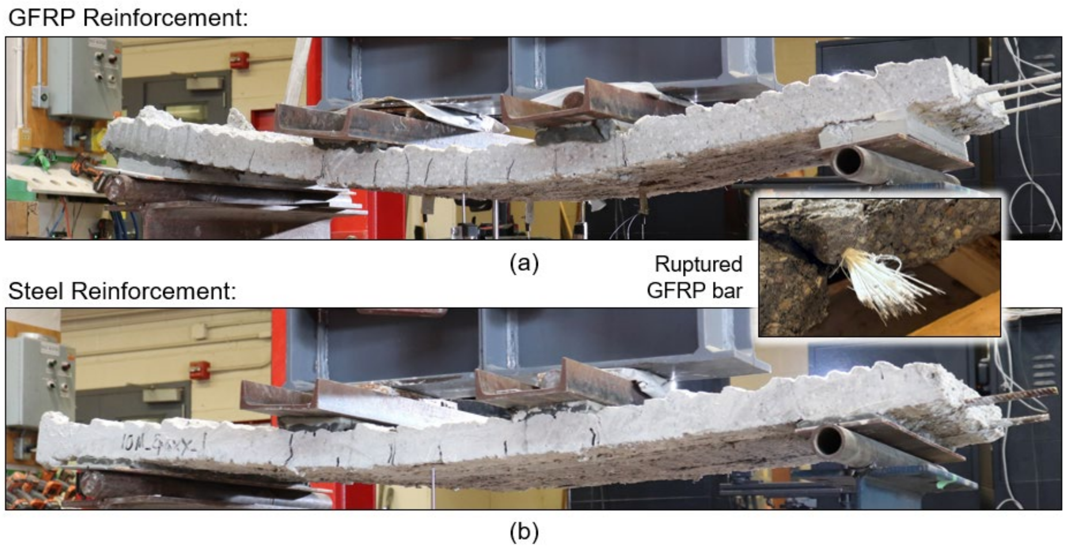

Figure 6: Deflected shape at the ultimate load and failure modes for 3D printed wall panels with NSM reinforcement: (a) GFRP-reinforced panel (W4-GFRP-E), (b) steel-reinforced panel (W2-Steel-E).

In addition to observing the cracking behaviour of the specimen in photographs, this study also employed digital image correlation to study the distributed displacement and strain behaviour of the panels. The crack spacing and crack width measurements in Table 1 were measured using DIC analysis within the constant moment region, and the results show that the crack spacing was similar for the two GFRP panels (114 versus 100 mm) while the crack spacing was slightly larger for the 10M specimen (147 mm). Crack widths were measured using digital extensometers across each crack, which were averaged along the member length to get the average crack width. The results show that the crack width was higher in the GFRP reinforced specimens, ~1 mm versus 0.15 mm, respectively, which is once again attributed to the lower elastic modulus of the GFRP reinforcement.

In addition to measuring crack width and spacing, digital image correlation can also be used to capture detailed two-dimensional strain fields over the surface of the concrete, which are shown in Figure 7 at the ultimate load for each specimen type. It is noted that only compressive strains are shown in Figure 7, and the maximum strain is limited to -500 με (i.e., any compressive strains below -500 με will also show in the same colour) to enable visualization of the variation in compressive strain through the depth of the section. The results show that a complex state of compressive strain, and thus stress, exists through the depth of the section and along the length, something that is largely influenced by the changes in thickness of the section. At regions between cracks, compressive strains are noted along the top (compression side) of the specimens, but these compressive strains are not highly non-uniform. These results provide some insight into the challenges with monitoring the strain in 3D printed concrete components and lead to questions surrounding the accuracy of theoretical approaches to compute the strength of these panels (e.g., stress-block analysis approach), something that should be considered in future work.

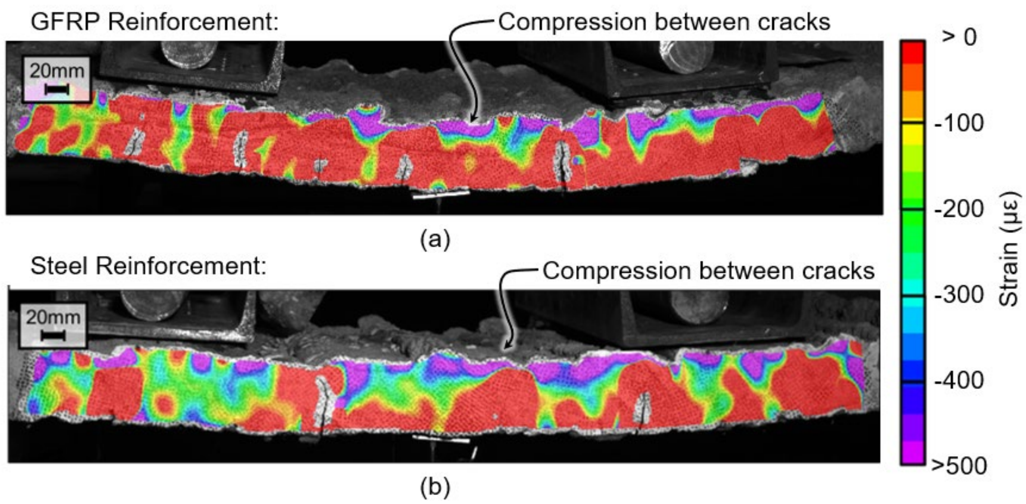

Figure 7: Digital image correlation results for compressive strains in the constant moment region: (a) GFRP-reinforced panel, (b) steel reinforced panel.

4. CONCLUSIONS AND FUTURE WORK

This paper focused on the potential use of near surface mounted reinforcement in 3D printed concrete walls. Overall, the results are promising and highlight the benefits of using NSM reinforcement as a means to integrate longitudinal reinforcement into 3D printed concrete structures. The specific conclusions of the work include:

1. The installation of NSM reinforcement in the wythe of a 3D printed concrete wall was found to be an efficient approach for the post-construction integration of longitudinal reinforcement.
2. Failure of the steel-reinforced wall panel was ductile and included yielding of the steel reinforcement and significant post-yield ductility, even in a very thin element (~50 mm thick).
3. Failure of the GFRP-reinforced wall panel was characterized by rupture of the GFRP bars in tension at the maximum load. For epoxy and cementitious mortar adhesive, no bond failure was observed.
4. Both GFRP and steel reinforced wall panels exhibited distributed cracking behaviour, including the formation of several cracks along the member length, mimicking the behaviour that would be expected of conventional reinforced concrete.
5. Two-dimensional strain distributions from digital image correlation highlighted the complex state of strain that existed in these wall panels, which had significant variations in geometry along the member length, something that could be encountered in practice.

While this study showed potential promise for the use of NSM reinforcement in 3D printed concrete walls, it represents a first step in what is an area that requires significant research efforts. The results presented in this study focused solely on single-wythe wall panels and a limited number of reinforcement ratios and configurations. Future work should consider examining the out-of-plane behaviour of multi-wythe 3D printed concrete wall panels, including those with varying tie details to examine the influence of the degree of composite action on their performance. Furthermore, future work should study a broad range of reinforcement types, reinforcement ratios, and different adhesive types for NSM applications.

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