Potential Strategies for Improving Cyclic Performance of Screen Grid Insulated Concrete Form Walls

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SUMMARY:
Screen grid insulated concrete form (SGICF) walls consist of stay-in-place prefabricated blocks that when stacked form an internal lattice of hollow cores. The cores are then filled with rebar and concrete resulting in a reinforced concrete grid responsible for the wall's structural integrity for both vertical and horizontal loads. SGICF walls are expected to serve as a building's shear wall system and offer a potentially more sustainable alternative to traditional reinforced concrete or masonry walls. This investigation involved two types of SGICFs at an elemental component level in order to gain understanding of their lateral force and drift ratio capacities under cyclic loading; an indicator of the system's performance in seismic events. Two strategies aimed at improving the cyclic behaviour were employed; concrete mix with fiber reinforcement and a low cost steel mesh surrounding the cores. Both strategies showed improvements in the cyclic behaviour, suggesting these as potentially effective for SGICFs in areas of seismic activity.

Keywords: Sustainable Construction, Engineered Cementitious Composite, Cyclic Loading

1. INTRODUCTION

Residential and commercial buildings in the United States are responsible for 40% of energy consumption, more than for industry or transportation (EIA 2008). Buildings are therefore a prime target for improving thermal performance, energy efficiency, water use, and CO_2 emissions. Decreasing a building's impact on the environment involves the cooperation of a wide variety of engineers: The mechanical engineer creates efficient heating and ventilation systems; the electrical engineer creates effective and efficient power and lighting systems; the civil engineer creates a site that innovatively deals with water runoff; a chemical engineer creates interior finishes that are low in volatile organic compounds; the architect situates the building to take advantage of natural lighting, heating, and cooling to further offset energy usage. Structural engineers can contribute by designing elements and connections in a way that are less energy-intensive to fabricate and construct. They may also choose to specify materials that use recycled content, are produced locally, or have low embodied energy, which is the energy expended during extraction, production, delivery, erection, and recycling. The structural engineer should also be prepared to use new construction materials or methods that may increase the performance of structures. One such option uses several common construction materials and combines important non-structural functions is the insulated concrete form (ICF). In an ICF construction, stay-in-place insulating formwork simultaneously provides a thermal barrier and contains the reinforced concrete that performs the structural function. The numerous systems on the market are meant to be quick to erect, highly insulating, and durable.

ICF is a broad term that envelopes any system that uses stackable interlocking blocks made from typically expanded polystyrene as a stay-in-place form, into the enclosed voids of which steel and concrete are placed to quickly and easily create structural walls. Three main types of ICFs are flat, waffle, and screen grid (VanderWerf 1997). Flat and waffle grid ICFs create a continuous wall of concrete within the insulating forms. The concrete within the flat wall ICF has a uniform thickness, while the waffle grid contains a continuous concrete wall with varying thickness. The screen grid insulated concrete form (SGICF) wall has discrete concrete post and beam elements, and the space between these concrete elements is filled with the insulating material. As such, SGICF has the potential for lowering the concrete volume per square foot of wall and significantly enhancing the wall insulation characteristics. Two such examples are shown in Figure 1; the top one is made from recycled polystyrene and has round openings, the bottom one is made with recycled wood chips and has rectangular openings. The recycled content of these SGICF further contributes to the sustainability of constructing buildings with these blocks.

a) Block A

b) Block B

c) Dry-stacking forms into walls (Block B show)

Figure 1: Examples of Screen Grid Insulated Concrete Forms

The benefits of building with SGICFs are compelling, but a major hurdle of doing so is the structural system. The SGICF walls consist of intersecting beams and columns surrounded by the ICF form material. Such tightly spaced frame-like structures of small dimension beams and columns do not resemble conventional structural members. Furthermore, the role of the form material in the response is uncertain and mostly ignored during the structural design process.

Previous full-scale wall experiments have revealed that vertical cores of the grid can fail in undesirable shear dominated manner, impacting the hysteretic behaviour (Dusicka and Kay 2011). The resulting in-plane cyclic hysteresis have generally shown pinched loops at drift levels above 2% - 3%, which indicate a lower capacity for energy dissipation relative to more conventional and well-established building systems. The pinched hystereses also indicate reduced system stiffness after large deformations, which is detrimental to the overall stability of the structure. The objective of the experimental research effort outlined in this paper was to investigate representative core sections of SGICF walls under full reversal cyclic loading with the intention of improving the hysteretic response. The sections were made to capture the vertical core shape and dimensions and included tests with and without considerations of the stay-in-place form material.

2. SPECIMEN CONFIGURATION

The experiments considered two different SGICF blocks. Block A is shown in Figure 1a and measured 406 mm (16 in) tall, 1219 mm (48 in) wide, and 254 mm (10 in) thick. The blocks were manufactured from recycled polystyrene that was cementiously bound together. When stacked, the interior 152 mm (6 in) diameter hollow cores that run both horizontally and vertically at 406 mm (16 in) on centre are aligned. For these tests, two blocks were stacked, resulting in a 813 mm x 1219 mm (32 in x 48 in) specimen comprised of two horizontal cores and three vertical cores. A limitation of 965 mm (38 in) imposed by the width of the load frame necessitated trimming each side of the stack by 156 mm (6 in), resulting in a 813 mm x 902 mm (32 in x 35.5) in sample which still retained the same number of cores, though slightly reduced the outer cores' cross section.

Block B is shown in Figure 1b and measures 610 mm (24 in) wide, 305 mm (12 in) deep and 203 mm (8 in) tall. The blocks were manufactured from crushed and mineralized recycled pallet wood cementitiously bonded together. When stacked, the forms create an interior concrete screen grid, with vertical rectangular concrete cores measuring 127 mm (5 in) deep x 223 mm (9 in) wide columns, with 51 mm (2 in) of space between adjacent cores. Vertically, the cores are connected to one another every 406 mm (16 in) by a reinforced 102 mm x 102 mm (4 in x 4 in) horizontal core. Stacking four B blocks yielded a specimen 610 mm x 813 mm (24 in wide x 32 in) tall, which fitted the load frame similarly to the block A specimens. The frame width of 965 mm (38 in) allowed for additional concrete at both sides of the Faswall specimen to increase their cross-sectional and thus strength for their roles as static supports during the test.

The internal reinforcing of the specimens considered a conventional construction, which consisted of a single #13 Grade 420 MPa (No. 4 Grade 60 ksi) reinforcing placed in the centre of each of the cores. The challenge in trying to improve the cyclic behaviour using conventional means such as adding shear reinforcement was the lack of space and the relatively small size of the cores as compared to typical reinforced concrete columns and beams. To address this, two different strategies were pursued:

- The first strategy was wire mesh inserted into the openings prior to being filled with concrete. Given the core small size, the wire mesh was rolled into 152 mm (6 in) diameters cylinder for block A and 114 mm (4.5 in) diameter cylinder for block B.

- The second strategy was utilizing concrete mix with fibre reinforcement so as to improve the shear strength properties of the cores. The conventional concrete mix design specified 30% coarse aggregate (3/8 in pea gravel), 70% clean sand, 8.5 in slump, and a 28-day compressive strength of 27.6 MPa (4000 psi). The fibre concrete utilized 8mm long polyvinyl alcohol fibres at a rate of 2% by volume of a concrete mix that contained only clean sand as aggregate, i.e. there were no coarse aggregate. The fibres chemically bond with the cement to prevent pull-out prior to reaching their 1862 MPa (270 ksi) tensile strength. Inclusion of the fibres has been shown to increase the tensile strength of the concrete by two orders of magnitude, effectively improving the concrete's tensile strain capacity from nearly non-existent to 4% - 6% (Li, et al., 2005).

3. TEST SETUP AND LOADING

A self-reaction load frame equipped with 445 kN (±100 kip) hydraulic actuator with ±76 (±3 in) stroke was utilized. The frame consisted of two parallel longitudinal beams separated by 1111 mm (44 in) in and connected by two transfer girders as shown in Figure 3. One girder acted as a reaction support for the actuator assembly, while the other acted as a reaction support for the ICF specimen. The specimen, which lied flat on the laboratory floor and in plane with the load frame, was placed on a wheeled support frame dolly. The outer support cores were held in place by two pairs of threaded rods and rested on 51 mm (2 in) thick steel plates, thereby keeping the specimen snug against the aforementioned girder. The servo-controlled hydraulic actuator was attached to the centre core of the specimen using bearing plates and threaded rods such that both push and pull actions of the actuator could be accommodated. Moving the centre core resulted in deformations relative to the supports. The induced deformation can be translated to drift values as the cores oriented perpendicular to the actuator could be thought of as the vertical cores of the wall. The symmetry of the application of load was intended to balance the internal forces in the test specimen so that they do not have to be resisted by the self-reacting frame.

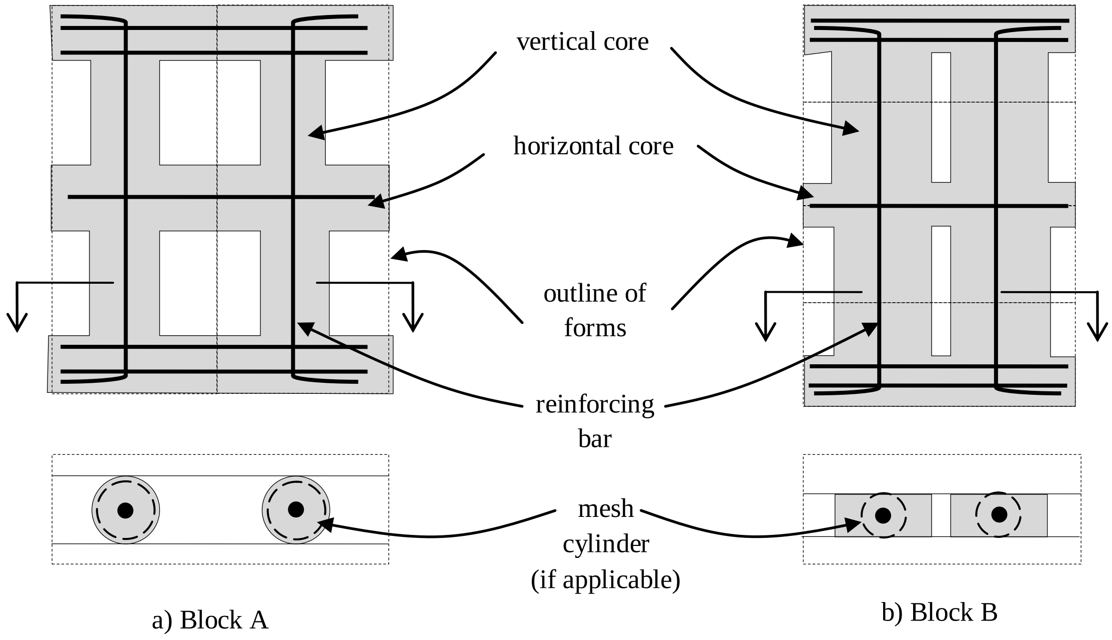


Figure 2: Sketch of Specimen Variations

The instrumentation consisted of the following: force data was collected from the load cell mounted in line with the actuator and deformation was monitored a linear variable differential transformer (LVDT). The LVDT was connected on one end to a threaded rod imbedded in the central core, while the other end was connected to a wooden cross beam that was affixed to the outer support cores; thus measuring the deformation of the specimen was made relative to the supports and independent of the test frame deformation or specimen support movement.

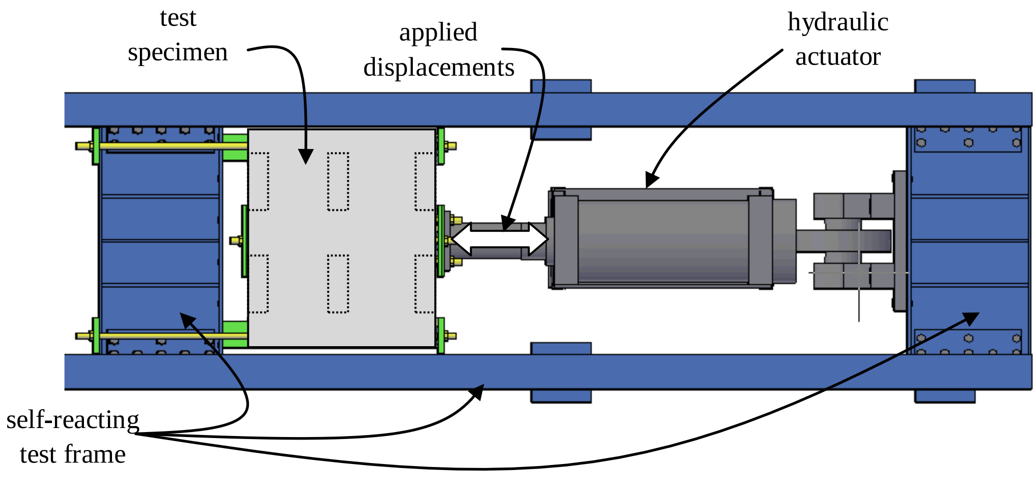


Figure 3: Self-reaction Frame Used for Applying Cyclic Deformations

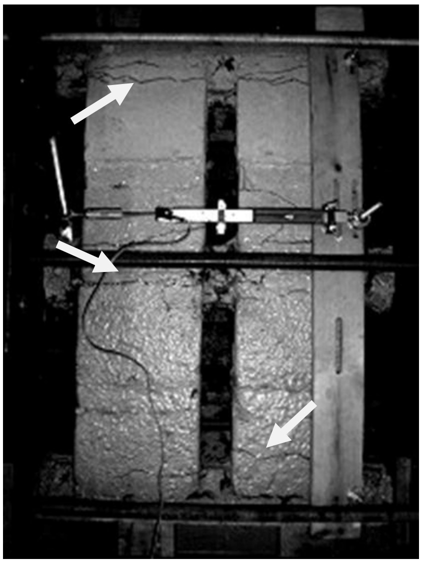
The cyclic loading history performed in the tests was adopted from that used for precast wall validation test requirements (ACI 2008). The test was displacement controlled, where desired displacement during each cycle was obtained from a target drift ratio. The drift ratio was calculated as the ratio of the lateral deformation of the loaded core to the distance between the loaded core and the adjacent support cores; Drift(%) =100%*(Δ/h) where Δ is the relative deformation of the centre core to the supports and h is the distance between the cores. For the cyclic test, the central core underwent three fully reversed in-plane cycles for each prescribed drift level. The drift level began with a drift of ±0.04%, which was intended to be primarily elastic, was then increased by 40% after each set of three complete cycles and continued until the specimen failed or an instrumentation limit was reached. The LVDT's stroke of 4 in limited the experiment to a maximum level drift of ±10%.

4. EXPERIMENTAL RESULTS

4.1 Failure Modes

After completing three full reversals at each drift level, each test specimen was inspected for damage, and permanent marker was used to note the development of cracks. For specimens tested with the ICF form in place, developments of cracks on the surface of the forms were difficult to detect due to the surface condition of the blocks. The forms were removed after the test to inspect the failure of the concrete cores whenever possible, however at that stage the core concrete often fell to the ground or came off with the formwork. Duplicate tests were conducted with formwork striped prior to testing so as to observe the crack development, which was much easier to observe. Observed cracks and failures are shown with arrows in Figure 4, where arrows point to marked cracks.

a) Block A



b) Block B

Figure 4: Observed Failure Sequence

The tests performed on both block types proceeded in similar ways, as shown below. Flexural cracks often appeared first at the joint between the vertical (perpendicular to the direction of loading) and the horizontal (parallel to the direction of loading) cores. As the cyclic loading program advanced, those flexural cracks eventually appeared at both ends of each vertical core, completely severing the connection of concrete between perpendicular members, leaving them connected only by the rebar they shared. In the conventional construction, shortly after the development of all eight flexural

cracks, one of the four vertical cores would typically fail catastrophically. The failure would take the form of a diagonal shear crack as depicted for Block A. Such core failure was immediately followed by a large reduction in force. Unfortunately, the forces developed in Block B often lead to a bearing support failure via crushing. In these cases the failure of the vertical core was not achieved.
Shear cracks and ultimate failure of the specimens with fiber reinforced concrete were not observed. The tests were terminated when the LVDT measuring drift reached the end of its stroke, which turned out to be close to the end of stroke of the hydraulic cylinder also.

4.2 Cyclic Behaviour

The recorded force vs. deformation behavior is summarized in Figure 5, where the left graphs correspond to specimens made using block A and right graphs for block B. In all cases the hysteresis is pinched, which is a function of the single rebar reinforcement that was placed in the center of the core. Once the reinforcing yields in one direction, the rebar elongates and therefore requires greater deformation on the reversal to fully engage again. This effect is expected to not be as severe on full walls where there are numerous reinforcing spread along the length of the wall.

The lower overall strength achieved by specimens constructed with block A are not surprising. The round core is not as effective in resisting the loads as the rectangular taller core. Within each type however, all of the specimens achieved similar strengths, suggesting that the employed methods did not contribute significantly to the lateral strength of the vertical cores.

The insertion of wire mesh around the perimeter of the block openings prior to placement of concrete had significantly enhanced the ductility of the round cores of block A. Degradation of strength started shortly after 2.5% drift and even then was reasonably gradual. This enhancement is caused by the confinement achieved by the mesh reinforcing around the perimeter of the core. In block B, the effectiveness is not as evident because the specimens failed outside of the test zone by crushing the supports of the specimen. The round confinement in the rectangular space would have likely been only moderately effective as compared to the round cores of block A.

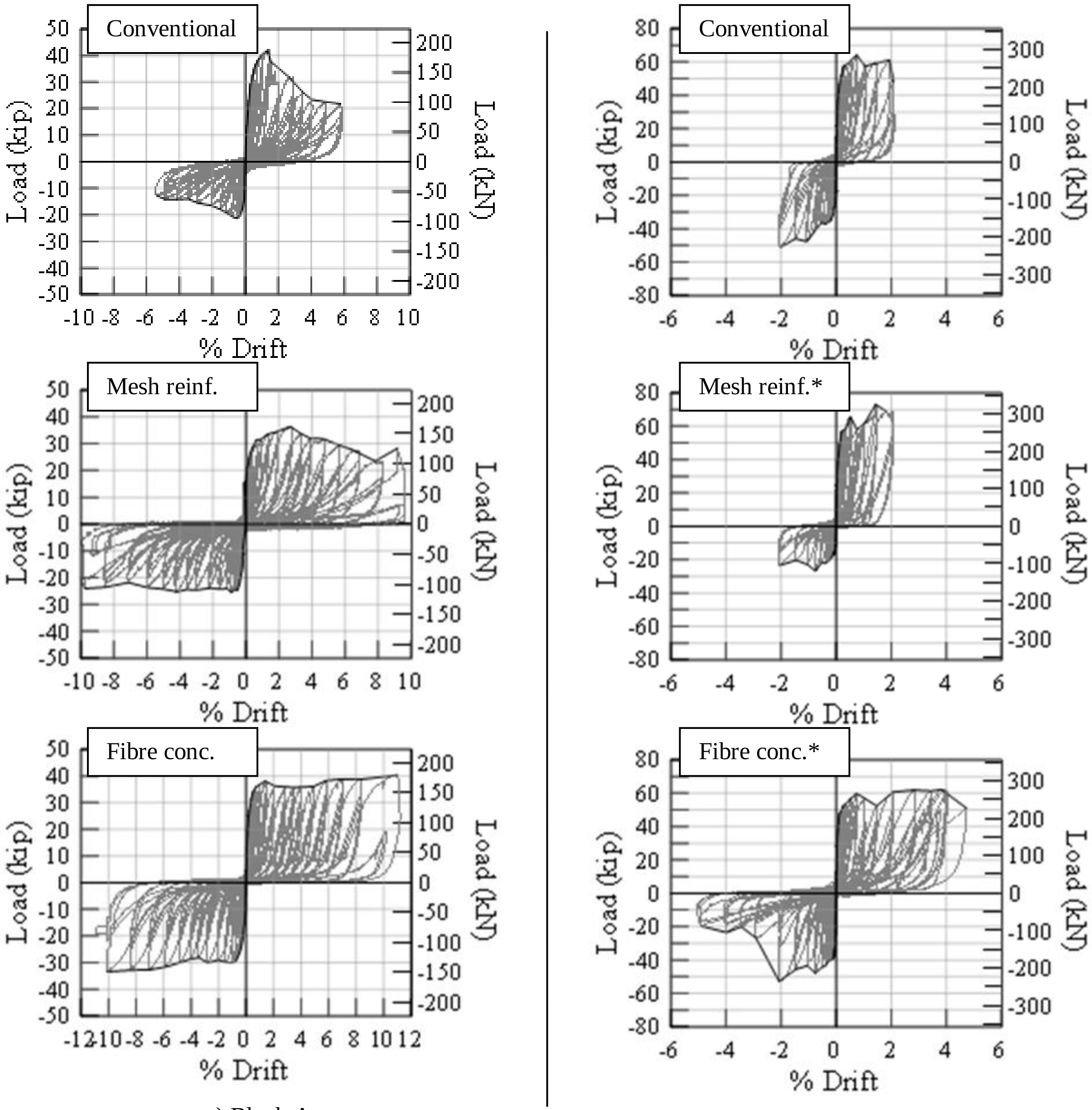
The utilization of engineered cementitious composite via the introduction of polyvinyl alcohol fibers resulted in significant improvements in behavior for both block types. In block A, there is very little degradation in strength. In block B where the support had also started to degrade, causing the degradation in resistance, the improvement in behavior is nevertheless evident. Large inelastic deformations are possible. With the lack of conventional options of providing increased shear resistance in the cores, the use of fibers is showing significant promise in greatly enhancing the cyclic behavior of ICFG walls. Full scale tests on walls are needed to validate the strategies on fully interacting grid within the wall, but these smaller size experiments still demonstrate the potential of achieving sustainable construction using ICFGs in moderate to high seismic zones.

5. SUMMARY AND CONCLUSIONS

Experimental investigation was conducted on screen grid insulated concrete form wall sections. These sections were made symmetric and were tested in a self-reaction frame with the purpose of evaluating the cyclic behaviour of the vertical cores. Conventional confinement and detailing of columns was not possible given the dimensional constraints of the wall cores. In an effort to enhance the cyclic performance of the wall sections, wire mesh cylinders were introduced into the form openings prior to placing the reinforced concrete fill. This strategy was demonstrated to be very effective in enhancing the ductility of the cores for the round cores and due to unexpected support failure, inconclusive for the rectangular cores.

A second strategy was investigated in using polyvinyl alcohol fibres to increase the shear strength of the concrete mix. This was demonstrated to be very effective for both types of cores, whereby the tests became limited by the laboratory equipment rather than the deformation limits of the test specimen.

Based on these tests, both of these strategies are likely to result in significant improvement in cyclic behaviour of screen grid insulated concrete form walls. Full scale tests on walls are recommended to validate these approaches.



a) Block A

b) Block B

Figure 5: Hysteretic Behaviour

(* specimen failed at support and not within the core)

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