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COMPRESSIVE BEHAVIOR OF CONCRETE MASONRY WITH RANDOMLY DISTRIBUTED FIBER REINFORCEMENT

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ABSTRACT

Design of reinforced concrete masonry shear walls for seismic loading is constrained by maximum flexural reinforcement limits of the MSJC Code and by Code requirements for wall boundary elements. These provisions are written to ensure that walls loaded in-plane can attain the minimum levels of ductility during a seismic event implied by Code R values, and are directly related to the ultimate masonry compression strain capacity, ε_{mu}. Whereas previous researchers have utilized confinement plates or combs to increase the masonry ultimate compression strain, this research aims to develop a new type of ductile concrete masonry containing randomly distributed fibers in both the grout and masonry units. Inclusion of fiber reinforcement within the grout and block mixes can potentially improve the tensile behavior of the materials thereby increasing the compression strain capacity of the composite masonry material. Consequently, reinforcement limits could be increased while maintaining the same level of curvature ductility capacity. As part of a pilot study, experimental axial compression tests on fiber reinforced concrete masonry units (FRCMU) containing synthetic polymer macro fibers at volume percentages of 0.0%, 0.10%, 0.20%, 0.25%, and 0.50% were conducted and it was found that significant improvements in both pre- and post-peak response can be achieved with addition of the fibers to the block mix. Compression tests on 18, three course tall CMU prisms were also conducted. Six ungrouted prisms were tested, where randomly distributed reinforcement in the FRCMU consisted of synthetic polymers at volume percentages of 0%, 0.10%, and 0.25%. Twelve fully grouted prisms with fiber reinforced grout (FRG) and traditional CMU were tested with both synthetic and steel fiber reinforcements at 1.0% by volume. Prism test results showed a general improvement in stress – strain falling branch characteristics when fiber is present, and pilot study results considered in whole indicate that further study of fiber reinforced concrete masonry is warranted.

KEYWORDS: *fiber, ductile, seismic, concrete masonry*

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INTRODUCTION

Reinforced concrete masonry shear walls are used extensively across the western regions of the United States as the main lateral force resisting system in low-rise buildings. For seismic loads, a critical wall attribute of interest is its ductility, or ability to undergo significant inelastic deformation without strength loss. In the Masonry Standards Joint Committee (MSJC) design standard (“Code”) [1], wall ductility is controlled by maximum flexural tension reinforcement limits that are related to a prescribed strain profile at the maximum moment location where plastic deformation occurs (see Figure 1). The ultimate compression strain of the masonry is taken as ε_{mu}. = 0.0025 while the strain in the extreme tension reinforcement is set equal to a multiple of the yield strain, $\alpha\varepsilon_y$. The strain factor α varies between 1.5 and 4.0 and depends on the type of shear wall – “ordinary”, “intermediate”, or “special”. These values of the strain factor result in expected curvature ductility capacities that are assumed approximately equal to expected displacement ductility demands, and the maximum area of flexural reinforcement is determined by axial force equilibrium with this strain condition at the critical section of the wall. If the designer finds that more tension reinforcement than allowed by the code is needed, they are forced to: a) incorporate boundary elements at ends of the wall, or b) increase wall width or length.

According to MSJC Code Section 9.3.6.5, upper limits on tension reinforcement can be waived if special boundary elements are provided at walls ends, and 9.3.6.5.5 lists requirements for the elements. Special transverse confinement reinforcement is required within the elements, but as noted by Banting and El-Dakhakhni [2], the Code does not provide prescriptive detailing requirements for the transverse steel. Presumably, the engineer is expected to extrapolate from similar practices for reinforced concrete shear wall boundary elements or from design standards used in other countries, and furthermore, testing is required to verify the enhanced ultimate compression strain capacity of the confined element. For the majority of the types of structural projects utilizing concrete masonry shear walls within the U.S., the validation by testing provision is highly impractical. Moreover, construction of walls with boundary elements adds construction complexity and cost compared to walls of equal length but without elements. Thus, without a feasible alternative to the maximum tension reinforcement limits of the Code, the design engineer must either increase wall width or maintain width but increase length to achieve sufficient flexural strength and to satisfy Code requirements.

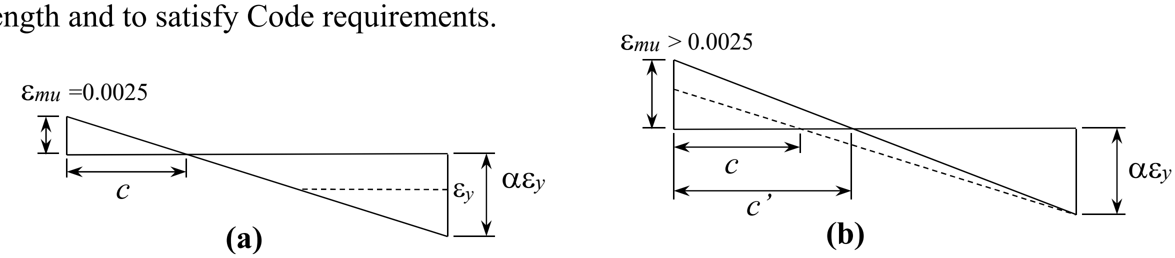


Figure 1: Normal Strain Distribution Across Critical Section in Masonry Shear Wall

A slightly different approach to the above is to enhance the compression behavior of the concrete masonry composite by transverse confinement reinforcement placed directly in the mortar beds between courses. Priestley and Elder [3] proofed this concept by testing concrete masonry prisms with stainless steel confinement plates, and found that lateral reinforcement dramatically improved the compression stress-strain response of concrete masonry. In place of the vertical splitting in masonry unit face shells, a failure mode well-documented and explained by Drysdale and Hamid [4], the failure of prisms changed to a shear-compression failure with almost no face shell splitting. Changes to the stress-strain response included increased compression strength, f'_m, a more gradual descending branch, and increase in the ultimate compression strain, ε_{mu}. Transverse confinement plates restrict the high lateral expansion of mortar and grout which is to blame for large masonry unit lateral tension stresses and subsequent rapid failure. More recently Ewing and Kowalsky [5] have demonstrated similar results for clay masonry with mortar bed confinement. Other types of possible confinement reinforcement include steel wires or combs (Hart *et al.* [6]), also placed in between courses, but in general use of confinement reinforcement within the mortar bed is not common for shear walls in the U.S.

A novel idea that has not yet been fully investigated is to improve the basic compression strain-strain characteristics of the concrete masonry material – primarily its ductility – by inclusion of randomly distributed fiber reinforcement within either the concrete masonry unit (CMU), the grout, or both. It has long been established that use of fibers in a concrete mix can improve the toughness and ductility of concrete when loaded in compression. Fanella and Naaman [7] reported on experimental tests on mortars with steel and synthetic fibers. They experimented with fiber volume percentages varying between 1% to 3%, different types of fibers (steel, glass, polypropylene), and different fiber aspect ratios (length/width). Results of the work showed that both an increase in strain at peak stress and a more gradual descending branch is obtained with fiber reinforcement in the mortar matrix. Generally, no increase in compression strength was observed, but ductility was much improved as fiber percentage increased. Para-Montesinos [8] describes the possible ways high performance fiber-reinforced cement composites (HPFRCC) can improve the seismic response of structures, including the relaxation or elimination of the need for transverse reinforcement in plastic hinge zones at concrete beam-column connections. Cyclic testing of subassemblages under simulated seismic loading demonstrated the ability to achieve lateral drifts up to 6% for the specimens with fiber reinforcement and no transverse reinforcement.

The most relevant work on this topic is experimental studies by Hervillard [9] as part of a Master's Thesis at Washington State University. The thesis documents research on the influence of synthetic macro fibers (mix of polyethylene and polypropylene) in the grout of concrete masonry prisms. Thirty masonry prisms utilizing a grout with fiber volume percentages of approximately 0%, 0.33% and 0.52% were constructed and tested in uniaxial compression in a laboratory. Results of the prism tests include observation of a vertical face shell splitting failure mode, grout cores almost completely intact after face shell spalling, increase in strain at peak stress and peak compression strength, and more gradual falling branch of the stress-strain response. The conclusions of the work however, state that the positive influence of fibers on compression stress-strain behavior is much less than that observed when transverse confinement reinforcement is utilized. A final conclusion to the work was to consider incorporation of fiber into either the mortar or masonry units.

Based on the typical masonry failure mode of CMU splitting caused by rapid lateral expansion of mortar and grout at high compression stresses, it is theorized that incorporating a mechanism to delay the expansion of the grout and to increase the CMU's ability to resist tensile stresses will in turn result in attainment of both higher compression strengths and ultimate masonry compression strains. With reference to Figure 1b, an increase in the maximum usable masonry compression strain while maintaining the same strain factor results in a larger possible neutral axis depth, *c'*. The consequence is the ability to withstand larger axial forces, i.e. larger total tensile force in the flexural reinforcement (larger *c*' implies larger C_m and $C_m = P + T$). For example, an increase of ε_{mu} from 0.0025 to 0.003 can yield an increase in the maximum tension reinforcement of approximately 50% depending on wall design characteristics (i.e. f'_m, axial load *P*, strain factor α, etc). Thus, an increase in the maximum reinforcement ratio may be possible with a more ductile concrete masonry. This paper documents the results of an initial experimental investigation into the possible benefits of incorporation of distributed fibers into concrete masonry construction, with aim to improve overall material and wall ductility. Specific features of interest include failure mechanisms and stress-strain characteristics of fiber-reinforced concrete masonry units (FRCMU) individually, and of grouted and ungrouted prisms using traditional CMUs and FRCMU, respectively.

PILOT EXPERIMENTAL PROGRAM

FRCM were produced with macro-synthetic fibers at dosages of 0% (control), 0.10%, 0.20%, 0.25%, and 0.50% by volume. Four specimens for each FRCMU group were tested. Twelve grouted prisms with unreinforced CMU and fiber reinforced grout (FRG) at dosages of 0% (control) and 1% were tested. Fiber types used in the grout included steel hooked-end fibers and two different types of synthetic fibers. Finally, six ungrouted prisms utilizing FRCMU with fiber dosages of 0% (control), 0.10%, and 0.25% by volume were also tested.

Materials Properties and Construction

A local masonry unit manufacturer provided block for the project using their standard normal weight block mix without any modifications undertaken to compensate for addition of fibers. A unit size of 200mmx200mmx200mm was adopted so that compression strengths would be below the capability of the laboratory test machine. Fibers were added by hand to the mechanical mixer at the block plant, and during production, significant clumping of fibers in the finished blocks as well as regions with voids were observed for the 0.25% and 0.50% FRCMUs.

A commercially available bagged coarse grout mix (SPEC MIX®) meeting ASTM C476 was utilized for grout-filled prisms. Grout was mixed by hand in a wheelbarrow for approximately five minutes, after which time fibers were added during additional mixing over a period of three minutes. Admixtures were not added to modify the workability of grout with fibers. Three grout test specimens were made following ASTM C1019 procedures, with molds created with four adjacent CMU blocks and absorptive paper. A commercially available bagged Type S mortar mix meeting ASTM C270 was used for all prisms, and was mixed by hand. Sample cubes of the mortar were created using brass molds with 50mmx50mmx50m dimensions and the samples were placed in sealed plastic bags for the same duration as the prism curing time. A tradesman mason completed all work associated with construction of prisms including mortar and grout mixing, and layup of blocks. Prisms were three courses tall with 10 mm flush mortar joints.

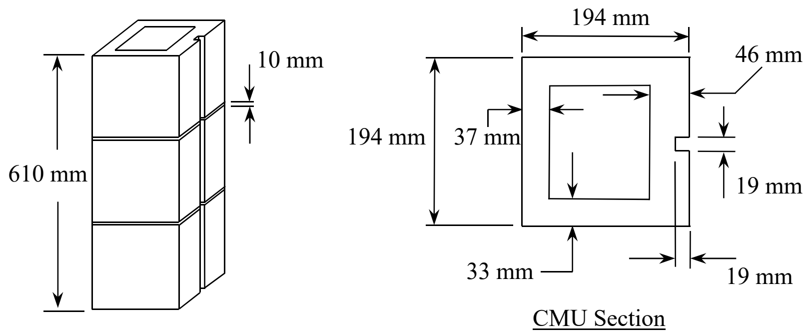


Figure 2: CMU Section and Prism Geometry

Fibermesh® 650, a graded macro-synthetic fiber, was used in the FRCMU. This proprietary fiber utilizes a blend of polypropylene (PP) and polyethylene (PE) materials, and has fiber lengths between 37mm and 50mm with an aspect ratio of 96.5. Both Fibermesh® 650 and Enduro® 600 fiber types were used in prisms utilizing FRG. Proprietary Enduro® 600 fibers are a PP/PE macro-monofilament fiber with deformations to enhance mechanical bond. Steel Novocon® hooked-end fibers with 50mm length and aspect ratio of 50 were also utilized in FRG. Material properties for fibers as well as grout and mortar are provided in Table 1.

Table 1: Properties of Materials Used in Masonry Specimens

Grout	f'_g (MPa)	43.0
Mortar	f'_m (MPa)	31.4
PP/PE fibers	f_{UTS} (MPa)	620
	E (GPa)	10.6
Steel fibers	f_{UTS} (MPa)	1048
	E (GPa)	200

Testing Details

All test specimens were loaded in uniaxial compression by a servo-hydraulically controlled Tinius Olsen universal test machine (UTM) with 1780 kN capacity. Pressure recordings of the UTM hydraulic system were used along with the known UTM ram area to calculate axial load imparted to the test specimens. The tests were run in displacement control using the UTM ram stroke which was monitored by a linear encoder. Since displacements derived from the encoder included machine platen flexibility, four linear potentiometers were used to measure displacement between the UTM crossheads, thereby allowing for direct calculation of axial compression strain in the specimens. The linear position sensors were protected during testing from potential impacts by spalled pieces of masonry using a plywood shield positioned between the specimen and the sensors. All test specimens were capped at their ends with a 3 to 6 mm bedding of high-strength gypsum cement according to ASTM C1552 in order to provide a smooth surface for uniform bearing on the UTM plattens and to ensure specimens were loaded axially in a plumb orientation. Specimens were arranged in the UTM so that the center of thrust acted through the block or prism centroid. Testing of CMU and prisms followed ASTM C140 and C1314, respectively.

EXPERIMENTAL RESULTS

A description of the test results for each of the three test groups is provided in separate sections below, with discussion of failure modes and stress-strain behavior.

Fiber Reinforced CMU

Generally, observed failure of the FRCMU was compression crushing. Very large compression strains were attained without disintegration of the block, and the decline in strength after peak stress was gradual. At the end of testing, FRCMU appeared largely intact across all fiber percentages. Figure 3 shows a 0.10% FRCMU after testing. Unreinforced CMU exhibited a high degree of spalling and rapid strength loss once peak stress was attained.

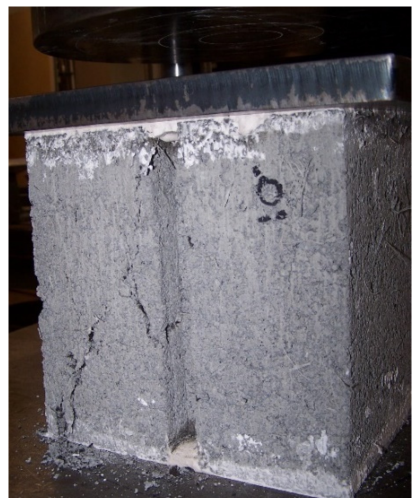
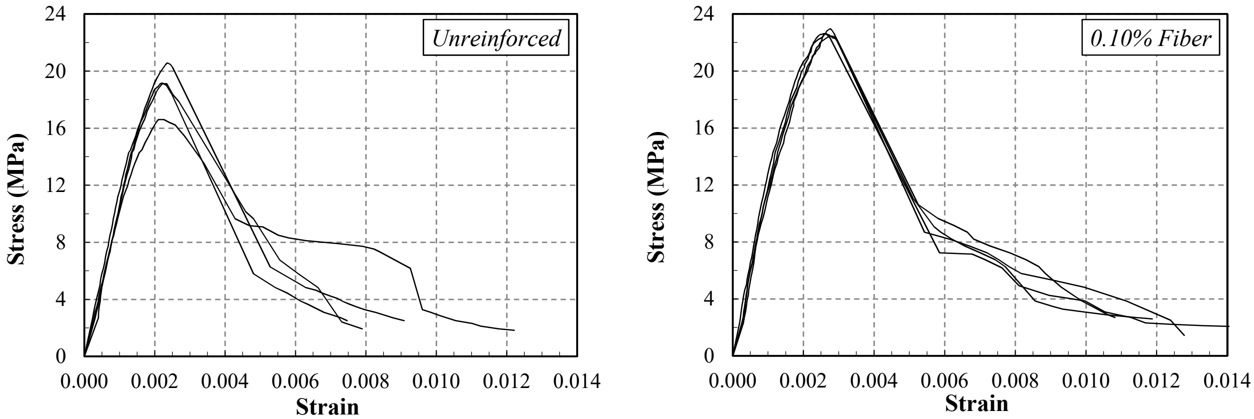


Figure 3: 0.10% CMU after testing

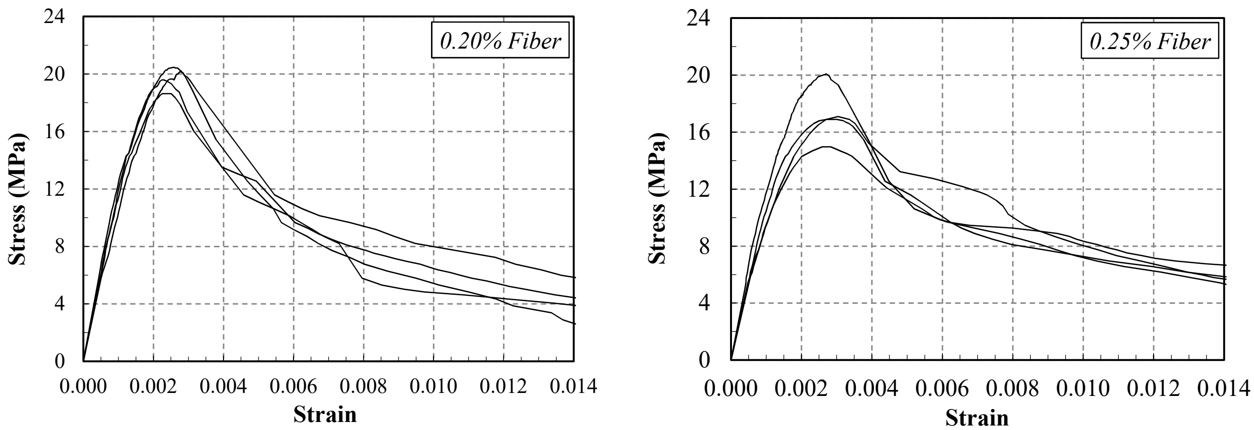
Stress-strain response for all specimens are depicted in Figures 4 through 6. Stress-strain plots for each fiber percentage are shown individually to assess consistency of behavior across the samples within each group. Averages of stress-strain curves for each group were determined by linear interpolation between recorded stress data at set strain values, and these average response curves are compared in Figure 6b. The peak compression strengths (f'_b) for both 0.10% and 0.20% groups are respectively 20% and 4% higher than the unreinforced CMU control group. For 0.25% and 0.50% groups, a decrease in f'_b is observed with strengths of 8.4% and 45% lower than the control group, respectively. The increased f'_b for 0.10% and 0.20% is likely due to the stabilizing effect of the fibers on concrete microcracks at high compression strains. The decrease in compression strength for the 0.25% and 0.50% groups is explained by the previously discussed clumping of fibers with visible voids in the FRCMUs.

Except for the 0.50% group, FRCMU strains at peak stress are greater than the unreinforced group. With respect to falling branch characteristics, the control and 0.10% groups appear to have almost identical descending slopes, while the 0.20%, 0.25%, and 0.50% exhibit a more gradual decrease in stress as fiber percentage increases. Another important attribute of the FRCMU is the higher residual strengths at large compression strains – say at ε=0.006 – where the 0.20% FRCMU group has a strength of 10 MPa while the unreinforced control has a strength of 5.90 MPa. This represents a 70% strength increase at this strain. The significance is that a higher useful ultimate compression strain might be possible with FRCMU, but block response when incorporated into a prism will be the best measure of the ability of fiber reinforcement to enhance concrete masonry behavior.



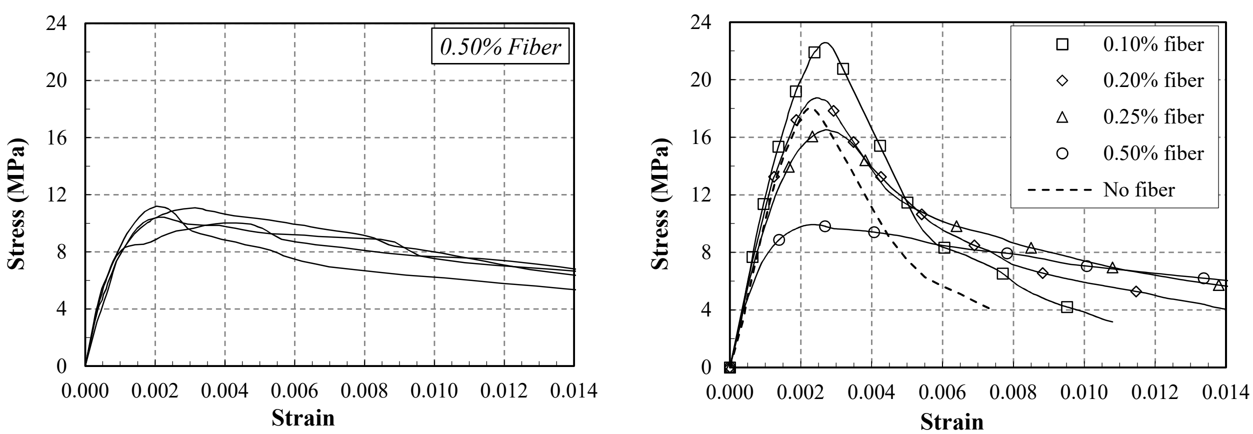
(a) (b)

Figure 4: Stress-Strain of blocks with (a) No Fiber, and (b) 0.10% Fiber



(a) (b)

Figure 5: Stress-Strain of blocks with (a) 0.25% Fiber, and (b) 0.50% Fiber



(a) (b)

Figure 6: Stress-Strain of blocks with (a) 0.50% Fiber, and (b) Averages

Fiber Reinforced Grouted Prisms

Failure of grouted prisms with unreinforced CMU was by face shell vertical splitting and subsequent spalling with rapid loss in strength. Grout cores were observed to be mostly intact with some exhibiting shear failure within the core. Vertical splitting of face shells originated at mortar beds and propagated towards the central region of CMU, as seen in Figure 7.

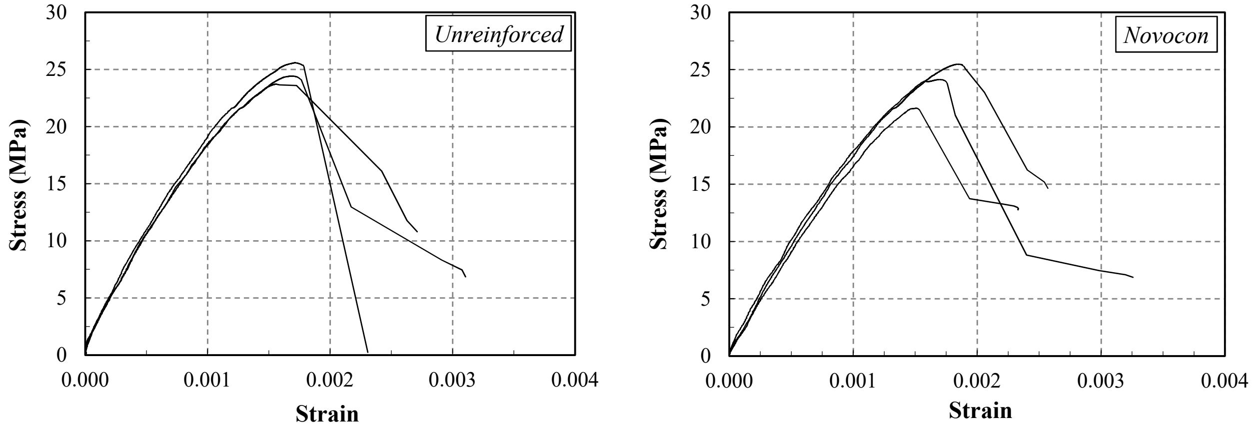
Figure 7: Failed FRG Prism

Stress-strain curves for each specimen of the four groups are shown in Figures 8 and 9. Within each test group, peak stresses and strains at peak stress are consistent except for the Novocon FRG group. This could possibly be explained by more variation in the consolidation of grout between specimens in the steel fiber group, as the relatively stiff steel fibers (as compared to the synthetic fibers) tended to a result in a less workable grout mixture. Data for only two of the Enduro specimens was recorded due to an error in data acquisition during testing.

Averages for each group were determined in the same manner as described previously for block tests, and comparison of the average stress-strain curve for each of the four FRG groups in shown in Figure 10. Grouted prisms with synthetic fiber reinforcement achieved higher peak strengths, at slightly larger peak strains, than the control group without fiber in the grout (unreinforced). Mean compression strengths, f'_m, for Enduro and Fibermesh groups were 15.5% and 4.8% greater than that for the unreinforced grout control group, respectively. Because the Enduro fibers are deformed while the Fibermesh fibers resemble very thin flat plates, it is hypothesized that better bond for the Enduro fibers lead to improved ability to delay lateral expansion of the grout core. Average compression strength for the steel group was 6.5% below that of the control.

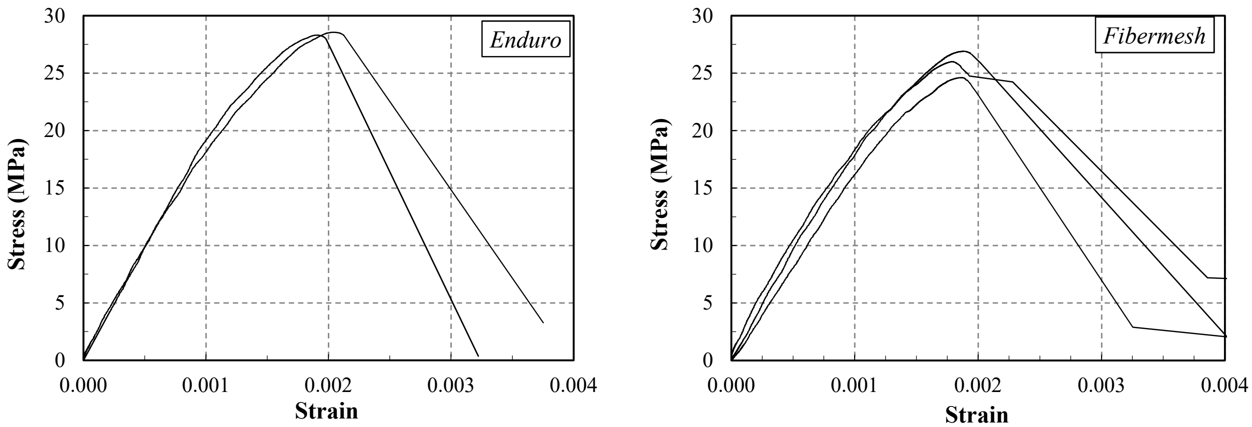
Fiber Reinforced Concrete Masonry Unit Prisms

The compression failure behavior of ungrouted prisms was drastically different for prisms using regular (unreinforced) CMU compared to that for prisms constructed of FRCMU. Explosive and rapid complete failure was observed for traditional CMU prisms – once peak strength and strain were reached, specimens essentially exploded with only a pile of CMU and mortar pieces remaining. Failure of prisms with FRCMU on the other hand was much more gradual, and at the end of testing, the specimens were largely intact but with large vertical and/or inclined cracks, as shown in Figure 12. Two specimens, an "A" and "B", were tested for each of the 0%, 0.10% and 0.25% FRCMU prism groups. The compressive stress-strain response for these tests are compared in Figure 11. Average stress-strain curves were not determined because of the very high degree of variability in response, as visible in Figure 11. The initial stiffness of ungrouted prisms varied dramatically, and reasons for this are not clear. Peak compressive strengths of the two traditional CMU prisms are very similar (16.9 MPa and 16.5 Mpa for A and B respectively), but because of



(a) **(b)**

Figure 8: Stress-Strain of prisms with (a) No FRG, and (b) Novocon FRG 1%



(a) **(b)**

Figure 9: Stress-Strain of prisms with (a) Enduro FRG 1%, and (b) Fibermesh FRG 1%

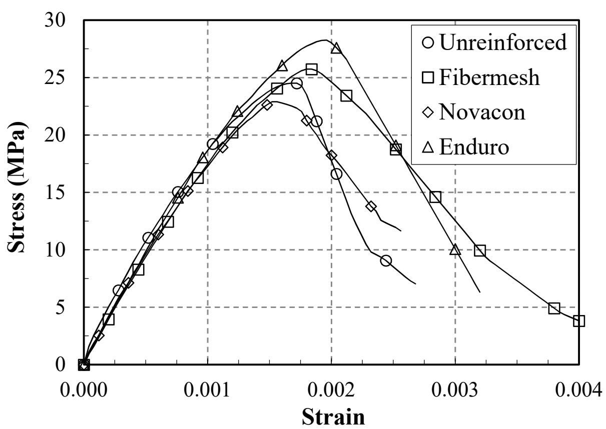


Figure 10: Average Stress-Strain of FRG Prisms

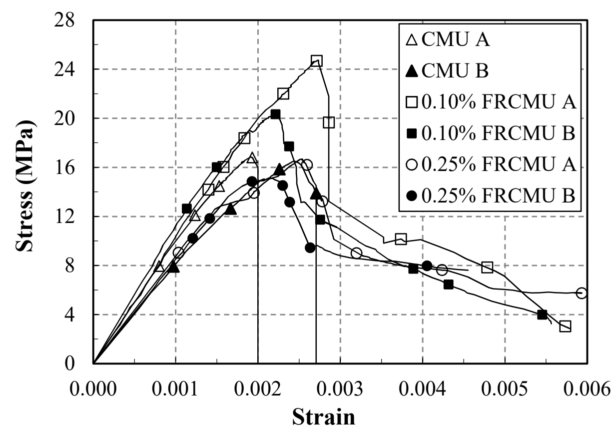


Figure 11: Stress-Strain of Ungrouted Prisms

stiffness differences, strains at peak stress are significantly different. Peak strengths of prisms with 0.10% FRCMU were significantly higher than the unreinforced CMU prisms – approximately 25% and 50% greater for specimen "A" and "B" respectively. Although the 0.10% FRCMU prisms did experience a significant, rapid drop in strength after peak stress, both specimens exhibited residual strength on the order of 50% or more of the peak strength at a compression strain of $\varepsilon_m = 0.003$. Response of 0.25% FRCMU prisms was similar to the unreinforced prisms in terms of peak compression strengths, but post-peak descending branch behavior was much more ductile with residual strengths of 50% of peak strength at $\varepsilon_m = 0.003$. In a general comparative sense, prisms with FRCMU exhibited improved post-peak ductility over the prisms with traditional CMU.

Figure 12: 0.10% Prism After Test

CONCLUSIONS

The results of the experimental research presented here, taken as a whole, indicate that there is a potential benefit of including randomly distributed fiber reinforcement in concrete masonry to improve its compression stress-strain response. Because of the preliminary nature of the research work, experimental design did not seek necessarily to optimize the materials and methods used to construct the masonry units and the grout mix design. Much of the selection of specimen characteristics was guided by a proclivity towards the least effort needed for the block manufacturer. Thus, changes to experimental design for future work will be incorporated so that the maximum performance of the system can be attained. These changes will also be informed by the results of this work. Specific conclusions based on this pilot research program include:

- Incorporation of synthetic fiber reinforcement into the concrete masonry unit can increase compression strength and strain at peak stress, at small fiber dosages (as little as 0.10% by volume). At higher fiber dosages, a decrease in the falling branch slope of the stress-strain response is possible, thereby leading to higher residual strengths at larger compression strains. Thus, overall ductility of the masonry unit is enhanced. Clumping of fibers during production of masonry units was significant at fiber volume percentages of 0.25% and greater, and changes to mix design, or reduction in fiber aspect ratio, may be required to yield blocks with a uniform distribution of fiber and without significant voids in FRCMU.
- Masonry prisms with fiber reinforced grout exhibited both an increase in peak stress (strength, f'_m) and strain at peak stress. Falling branch slope of the stress-strain response was not greatly influenced by the presence of fibers in the grout, but because of the improvement in peak stress and strain, a reduction in neutral axis depth for a given total wall axial force level would be expected because of the increased area of the stress-strain

response. Alternatively, a higher tensile reinforcement ratio could be supported with the improved stress-strain behavior.

- Only a limited number of ungrouted prisms with FRCMU were able to be constructed, and thus the results must be weighted with this in mind. However, despite the significant variability in individual specimen response within a test group, clear and consistent trends indicate a significant positive influence on strength and ductility when masonry units include tensile fiber reinforcement.
- It is apparent that wall curvature ductility and thus displacement ductility can be increased by use of concrete masonry with distributed fiber reinforcement. An increase in ductility could allow for the use of larger force reduction factors, which in turn would result in lower required wall flexural strengths and reinforcement. Alternatively, if the current ductilities implied by Code are maintained, wall flexural strength can be increased while still meeting those ductility provisions.
- The next phase of research work will identify: a) ideal fiber percentages, geometries and mechanical properties for FRCMU production, b) block mix design modifications to improve the distribution of fibers and finished product, c) grouted prisms, both without and with fiber in the grout, and using FRCMU, d) small scale wall subassemblage testing.

ACKNOWLEDGEMENTS

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