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3 authors, including:

Beyza Kapucu Guzelbulut
Istanbul Technical University

Oguz C. Celik
Istanbul Technical University

Diagonal Shear Tests for Glass Fiber Reinforced Gypsum (GFRG) Panels with and Without Concrete Filled Cells

Beyza Kapucu Guzelbulut[1](✉), Ergun Binbir[1], and Oguz C. Celik[2]

[1] Graduate School, ITU, Maslak, Istanbul, Turkey
[2] Structural and Earthquake Engineering Division, Faculty of Architecture, ITU, Taskisla, Taksim, Istanbul, Turkey

Abstract. This study presents results from a number of glass fiber reinforced gypsum (GFRG) wall specimens that were monotonically tested at an angle of 45° and under increasing vertical load. Several infill configurations are considered to see possible changes in strength, stiffness, and failure modes. Eight samples with 770 mm × 770 mm × 124 mm side dimensions were prepared to be used in the diagonal shear tests. Concrete and steel reinforcement (rebar) elements were added to the system to achieve the required strength, stiffness, and ductility. C25 concrete grade and Ø12 steel deformed rebars with a steel grade of S420 were used in these samples. The samples were forced to collapse under a monotonically increasing load. Overall behavior was observed and behavioral values such as ultimate shear strength and initial wall shear rigidity/stiffness values were determined. Related load-deflection curves are given. According to the data that were gathered from the experiments, unfilled specimens and specimens filled with concrete at the middle or edge cells had load capacities around (70–85) kN, while fully concrete filled specimens achieved capacities up to (260–270) kN. Experimental results show that filling the edge or middle cells with concrete (i.e. sort of partial filling) has no significant effect on shear capacity when compared to unfilled samples. Crack patterns developed especially within the unfilled cell regions. The fully concrete filled panel, on the other hand, had a significant impact (approximately 3–4 times) on the capacity when compared with the unfilled case. The rebars used in the fully filled samples had no significant effect mainly from the occurrence of separation between the concrete core and GFRG panel for this type of loading but it increased initial stiffness. When the whole system is compared, concrete filling and rebar increase the initial stiffness of the sample. Filling the edge or middle cells with concrete (with and without rebar) has increased the initial stiffness between (1.17–1.47) times when compared to unfilled samples. Fully concrete filled panel (with and without rebar) had a significant impact (1.97–3.66 times) on initial stiffness when compared with the unfilled samples.

Keywords: GFRG · Diagonal shear test · Shear strength · Shear rigidity/stiffness · Initial stiffness

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1 Introduction

Glass fiber reinforced gypsum (GFRG) panels are assumed as a load bearing system made out of rectangular cells having thin glass fiber reinforced gypsum walls. This (GFRG) panel system, which was first developed in Australia in the 1990s [1], provides an innovative, modular, fast, and economic construction process. The fact that gypsum is a recyclable material makes this system sustainable. In addition, such panels possess high performance in terms of fire resistance and waterproofing.

Although the modular GFRG panel system imposes certain limitations on architectural design projects, it provides more cost-effective, but higher-performance structures especially in mass housing projects designed specifically as social housing. Many experimental and numerical studies have been handled to support the application of the GFRG panels. For example, In the Structural Design Manual for Glass Fiber Reinforced Gypsum (GFRG) Panels in Buildings report prepared by IIT Madras, Civil Engineering Department and Structural Engineering Department (2011), system properties, mechanical properties, design philosophy, shear strength, design of a typical multi-story building, use of the system in low-rise cost effective mass housing and GFRG panel as infill (i.e. architectural or nonloadbearing) wall in RC framed systems are investigated in detail [1]. A technical report on the structural performance and sort of certifications have been prepared by Building Materials & Technology Promotion Council [2]. This report covers technical specifications, inspection issues, a description of the system, grading of panels, installation issues, maintenance requirements, laboratory tests, dimensional tolerances, sampling, etc. The Technical Report on Evaluation of Seismic Performance of Gypsum Glass Fiber (Gypcrete) Wall Panels has been prepared by M/s. Gypcrete Building India (p) Limited Chennai, Structural Engineering Research Centre [3]. This report covers shaking table experiments were performed to verify seismic performance under earthquake load in a two-story RC frame structure with side walls made of prefabricated hollow blocks and roofs made of prefabricated shell and pre-stressed RC beam elements and built on a gravel cushion for energy absorption during a seismic event. Based on experimental work, Alagusankareswari et al. investigated the physical and mechanical properties of the GFRG empty panel [4]. GFRG panel strengthening using three different concrete mixtures filled in cavities is experimentally tested by Manjummekudiyil et al. [5]. Nominal mixture M25, fly ash concrete and recycled aggregate concrete were used. These test results were compared in terms of strength and economy. Janardhana et al. presented guidelines for the use of GFRG wall panel as a lateral load resisting component in buildings based on a numerical analysis procedure to arrive at its capacity estimation under axial compression, compression with in-plane bending and shear [6]. Variation of buckling load of unfilled GFRG wall panels for various widths is reported as well.

To provide some additional experimental data, this paper focuses on results from eight GFRG wall specimens (ST-NF, ST-EF, ST-EFSR, ST-EFMR, ST-MF, ST-MFSR, ST-AF, ST-AFSR) that were monotonically tested at an angle of 45° and under increasing vertical load. In load bearing wall type structural systems, diagonal shear tests are very helpful in assessing the monotonic shear behavior before conducting the near full-scale cyclic load tests. The calculation methods of ASTM E519/E519M – 15 are used to calculate the shear stresses, shear strain, and modulus of rigidity of the wall samples [7].

All tests were carried out in the Structural and Earthquake Engineering Laboratory (STEEL) at Istanbul Technical University (ITU).

2 Experimental Program

2.1 Test Set-Up and Instrumentation

A previously produced test set-up was used for the diagonal shear test. The set-up is composed of two steel heads to stabilize the wall samples at an angle of 45° to the vertical axis. (Figs. 1a and 1b) show a general view of the test set-up and instrumented GFRG panel samples prior to testing, respectively. The gypsum panel was placed inside the steel subheads and the samples were placed in a vertical position in the heads. Gypsum material was used to fill the small gaps between the sample and the steel heads to ensure the desired positions in the horizontal and vertical axes. The specimens were kept in the vertical plane during loading during the experiment with metal arms which are attached to the front and back sides of the sample.

In the test method described in ASTM E519/E519M – 15 [7] standard, some changes were made with the experience gained from the previous experiments in Structural and Earthquake Engineering Laboratory (STEEL) at ITU. A force controlled test technique was applied. During the experiments, the loading was done with a hydraulic jack having a capacity of 500 kN and the load values were measured using a load cell with a capacity of 500 kN. A total of six transducers were used in the experiments. A total of 4 displacement meters, one on the vertical and one on the horizontal, were placed on the front and back sides of the samples. Two displacement meters were placed on the front side of the samples to control out-of-plane movement. Six of the 25 mm CDP-25 (LVDT) were used in all displacement meters.

2.2 Material Characteristics

A typical GFRG panel (Fig. 2) consists of gypsum (calcium sulphate hemihydrate), glass fiber yarns, clean water, and waterproofing. Ali and Grimer have shown that glass fibers significantly increased the strength of the composite material [8]. The flexural strength of the composite material increased by two and a half to three times while tensile strength was increased by three to four times by adding 10% e type glass fiber, which are the commonly produced glasses for reinforcement applications due to excellent combination of physical, electrical, and chemical properties, to the gypsum plaster [9]. Note that added fibers have changed the fracture mode of the gypsum plaster from the brittle type to the quasi-plastic type. This resulted in a greatly improved impact strength which for a glass content of 10% was twenty to thirty times greater than that of unreinforced plaster. Studies by Movahednia et al. have shown that adding fibers to the infill wall resulted in an increase in the strength of the models up to 3.2 times [10]. Also, the ductility increased up to 6.3 times. (Table 1) provides the typical mechanical properties of an unfilled GFRG structural panel.

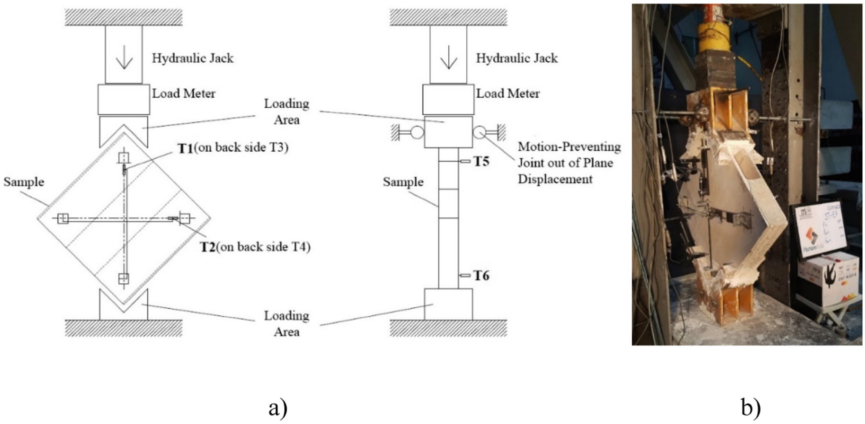

Fig. 1. a) General view of test set-up for specimens, b) Overall view from the specimen prior to testing.

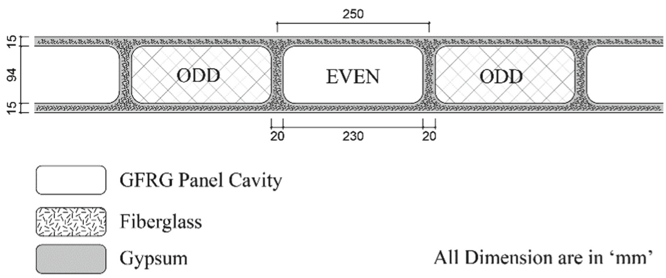

Fig. 2. GFRG panel cell dimensions.

Table 1. Mechanical properties of an unfilled GFRG structural panel [1].

Mechanical property	Nominal value
Unit weight	0.433 kN/m^2
Modulus of elasticity	7500 N/mm^2
Uni-axial compressive strength, P_{uc}	160 kN/m
Ultimate shear strength, V_{uc}	21.60 kN/m
Mechanical property	Nominal value

2.3 Specimens

Wall samples to be used in diagonal shear tests were produced (using the same gypsum panel) and tested under monotonically increasing loads under the effect of vertical compression force. A C25 class concrete that has a characteristic compressive strength of 25 MPa and a S420 grade rebar steel with a minimum yield strength of 420 N/mm^2 Ø12 longitudinal rebars and Ø8 transverse rebars were used in the concrete part of the specimens. Prior to the experiments, material samples were taken to check the strength of concrete and rebar steel. Material tests showed that concrete had an average compressive strength of 23.90 MPa. Ø12 and Ø8 rebars had yield strength values of 458 MPa and 464 MPa, respectively. For the experiments, specimen dimensions were determined to be 770 mm × 770 mm considering the GFRG panel dimensions and the dimensions allowed by the test setup. Note that the sample sizes recommended in the ASTM E519/E519M – 15 standard are 1200 mm × 1200 mm for brick masonry assemblages [7]. A total of eight specimens with dimensions of 770 mm × 770 mm × 124 mm were produced due to limitations in the laboratory. The wall samples produced were classified into 4 groups and compared with each other. One of the specimens was not filled, two of them were fully filled with concrete (with and without rebars), three of the samples were filled with concrete at edge cells (with rebar, with multi rebar, and without rebar), two of the samples were filled with concrete at middle cells (with and without rebars) (Fig. 3). Results from these tests would allow a fair comparison of the performances of the specimens.

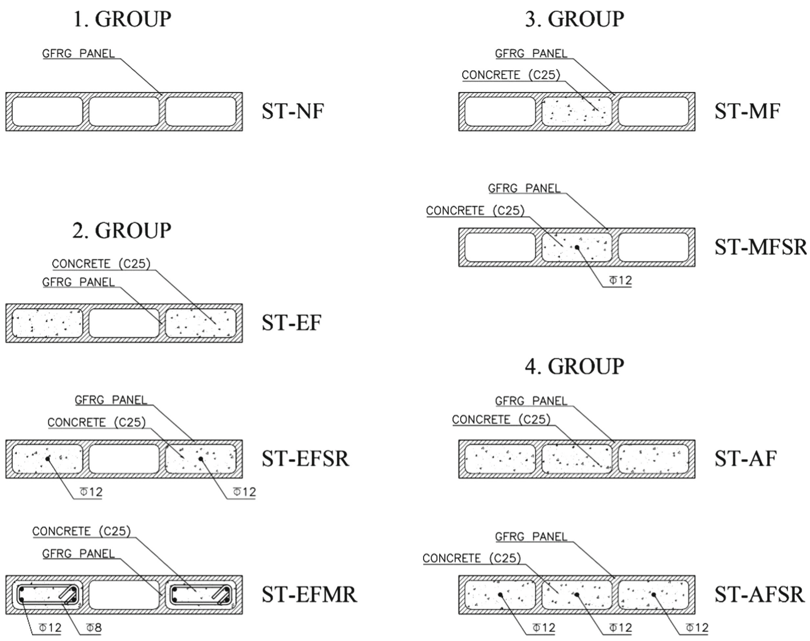

Fig. 3. Diagonal shear test samples.

Shear stresses, shear strains, and shear modulus of the panel (with and without concrete fill) were determined according to ASTM E519/E519M – 15 (Eqs. 1, 3, 4) [7].

$$\tau = (0.707 \times P)/A_n \tag{1}$$

Here, τ is the shear stress on the net area [MPa], P is the applied load [N], and A_n is the converted/transformed net area of the specimen [mm^2]. A_n can be calculated by using (Eq. 2).

$$A_n = A_g + A_c \times (E_c/E_g) + A_s \times (E_s/E_g) \tag{2}$$

in which A_g, A_c, and A_s are the net areas of gypsum, concrete, and steel rebars. E_g, E_c, and E_s are elastic moduli [MPa] of gypsum, concrete, and steel rebars. Note that since equivalent areas are used, the calculated stress values are transformed stresses corresponding to gypsum material. Shear strain value can be calculated by using the measurements gained from the horizontal and vertical LVDTs and is given below:

$$\gamma = (\Delta_x + \Delta_y)/g \tag{3}$$

γ is defined as the shear strain [mm/mm]. Δ_x values show shortening in the direction parallel to loading [mm] while Δ_y is elongation in the direction perpendicular to loading [mm]. Note that g is the gauge length in the direction parallel to loading [mm]. Using the shear strain and shear stress, shear modulus (G) for the specimens [MPa] is obtained by (Eq. 4):

$$G = \tau/\gamma \tag{4}$$

2.4 Loading Protocol

To characterize the behavior of the GFRG panels, the test was carried out based on the acceptance criteria given in the loading protocol of ASTM E519/E519M – 15 [7] with some changes with the experience gained from previous experiments at the ITU Structural and Earthquake Engineering Laboratory (STEEL). A force-controlled loading protocol is used to better observe the behavior. Two loadings and unloading steps up to 10% of the collapse load of the sample were applied and the sample was loaded to the collapse load in the third cycle. The loading steps were carried out in increments of about 10 kN, trying to keep the loading speed constant. Displacement measurements were taken after each loading step. After this level, the specimen was loaded to failure, overall behavior was observed and behavioral properties such as strength and stiffness values are determined.

3 Testing and Results

Eight wall samples to be used in diagonal shear tests were produced using the same gypsum panel and tested under monotonically increasing loads under the effect of vertical compression force. Under this vertical force, cracking loads, collapse loads of the heads, separation of infill concrete from the gypsum board, and displacements are read and noted for each specimen. Small changes in the capacities are possibly from testing setup and stability issues. Vertical load (kN) versus vertical displacement (mm) graphs and shear stress (MPa) versus shear angle/deformation/strain graphs are given in (Figs. 4, 5, 6, 7, 8, 9, 10 and 11). 0.80 Pmax values (i.e. a 20% reduction in the capacity) that could be assumed as the collapse limit are also shown on the curves. Observations during the tests are given below.

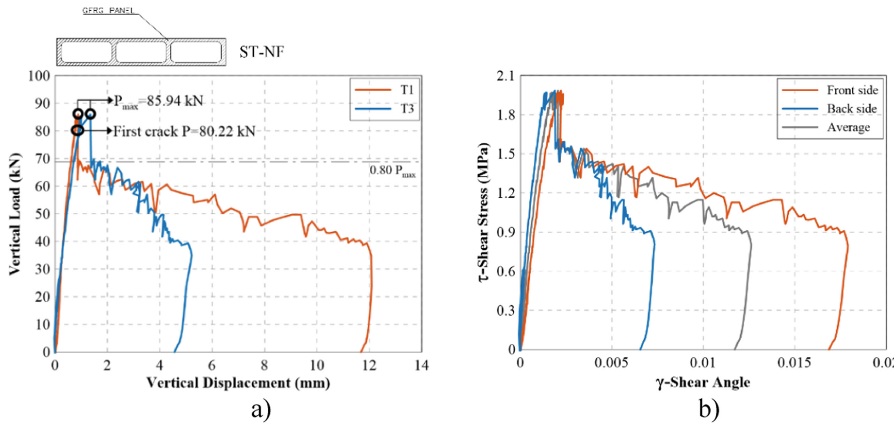

Fig. 4. Specimen ST-NF experimental results: a) Vertical displacements (T1-T3), b) Shear stress - shear angle (front side, back side, average).

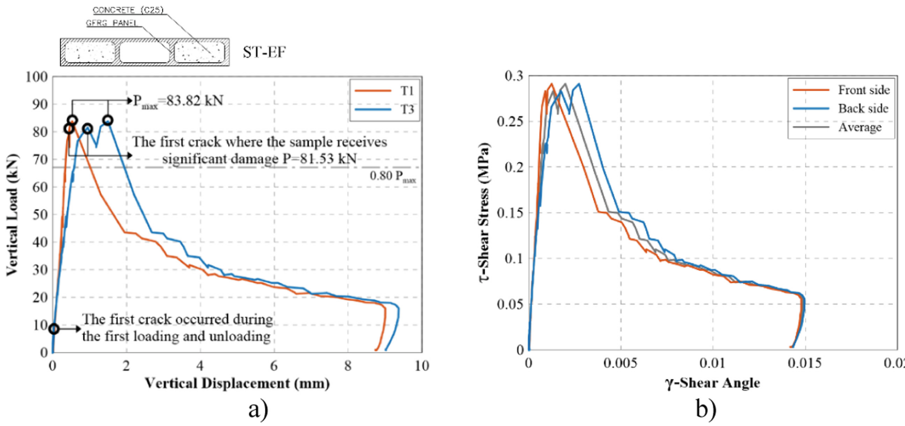

Fig. 5. Specimen ST-EF experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

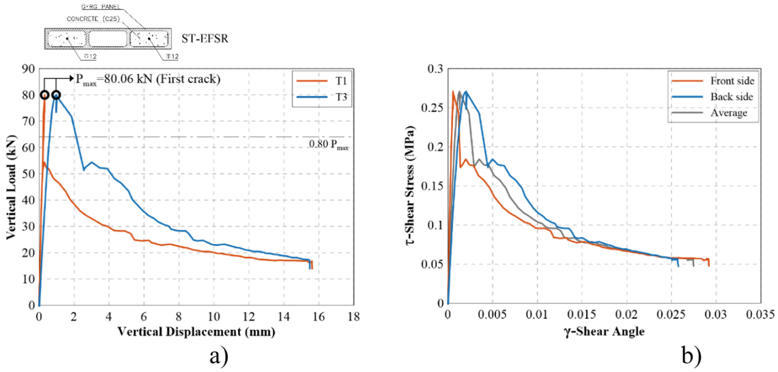

Fig. 6. Specimen ST-EFSR experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

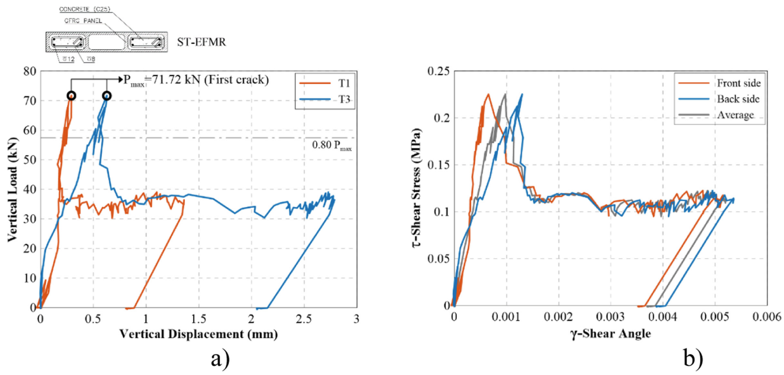

Fig. 7. Specimen ST-EFMR experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

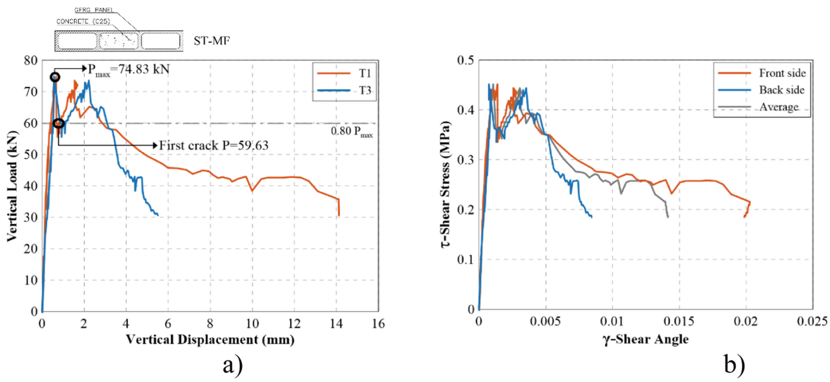

Fig. 8. Specimen ST-MF experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

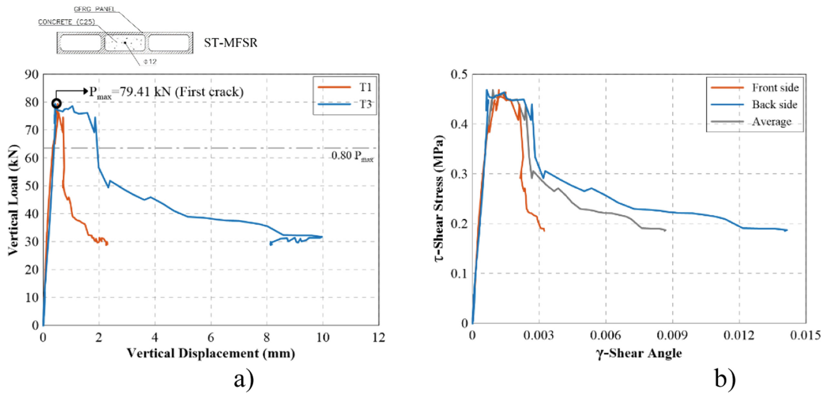

Fig. 9. Specimen ST-MFSR experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

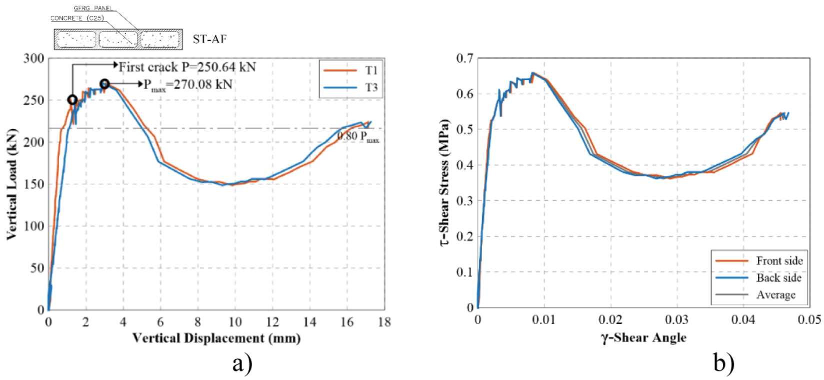

Fig. 10. Specimen ST-AF experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

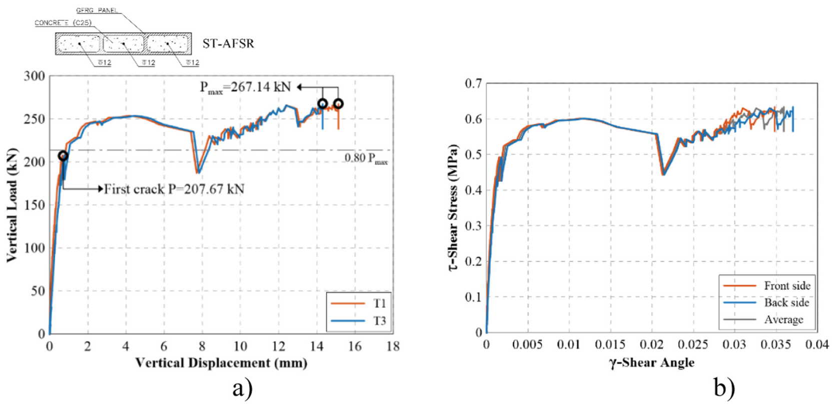

Fig. 11. Specimen ST-AFSR experimental results: a) Vertical displacements (T1-T3), b) Shear stress (transformed) - shear angle (front side, back side, average).

3.1 Specimen ST-NF (no Fill)

In this specimen, all cells are empty (i.e. unfilled). A much stable behavior was obtained in T1 and T3 while the horizontal LVDTs measured far different displacements mainly from crushing problem around the head regions (loaded corners) of the specimens. A maximum capacity of P = 85.94 kN was obtained for this unfilled specimen.

3.2 Specimen ST-EF (Edges Filled, no Rebar)

This specimen used plain concrete (without rebars) infill for edge cells only. The central cell is unfilled. Small changes in the capacity are possibly from testing setup and stability issues. Vertical load capacity was obtained to be P = 83.82 kN. The behavior was stable. Load-deflection curves were similar both for vertical and horizontal measurements. Concrete infill had no significant impact on the capacity when compared with ST-NF. Again, compared with ST-NF, concrete infill had no significant impact on capacity although it increased initial stiffness (K). Crack patterns, which are caused by shear stresses, developed especially within the middle unfilled cell region, leading the specimen to fail. Concrete infill increased initial stiffness by 17.75% when compared with ST-NF.

3.3 Specimen ST-EFSR (Edges Filled, Single Rebar)

Edges of the specimen are filled with concrete having a single rebar configuration while keeping the central cell unfilled. No confinement is provided by rebars. Out-of-plane displacements were prevented successfully. Reliable data were obtained from this testing. A maximum capacity of P = 80.06 kN was obtained for this specimen. Although the edges were strengthened with concrete infill and rebars, this had no significant impact on capacity. Compared with ST-NF and ST-EF, concrete infill and single rebar increased initial stiffness (K) by 25.83% and 6.86%, respectively. Shear cracks occurred in the middle of the specimen under increased loads. This specimen lost its strength rapidly.

3.4 Specimen ST-EFMR (Edges Filled, Multi Rebar)

Edges of the specimen are filled with concrete having a multi rebar configuration while keeping the central cell unfilled. Closely spaced transverse rebars (stirrups) were also used to confine the edge cells for a better ductile behavior. Again, out-of-plane displacements were prevented successfully. Reliable data were obtained from this testing. A maximum capacity of P = 71.72 kN was obtained for this specimen and then an abrupt loss (up to 50%) in strength was recorded. Although the edges were strengthened with concrete infill and rebars, this did not increase the capacity mainly from the observed damages in the central unfilled cell. Compared with ST-NF, ST-EF, and ST-EFSR, concrete infill and multi rebars increased initial stiffness (K) by 41.45%, 20.12%, 12.41%, respectively. This is thought to be an important result from this and ST-EF testings and has affected the whole design of near-full scale wall specimens. Shear cracks observed in the second group samples like ST-EF,ST-EFSR also occurred in the middle of this specimen.

3.5 Specimen ST-MF (Middle Filled)

Edges of the specimen are unfilled while the central cell is filled with plain concrete. Out-of-plane displacements were prevented successfully. A maximum capacity of P = 72.83 kN was obtained for this specimen and a gradual loss in strength was recorded. Again, although the middle part was strengthened with concrete infill, this option did not increase the capacity mainly from the observed damages in the unfilled cells. Concrete infill increased initial stiffness (K) by 35.87% when compared with ST-NF. This specimen has lost its strength due to crushing in the head regions (loaded corners).

3.6 Specimen ST-MFSR (Middle Filled, Single Rebar)

Edges of the specimen are unfilled while the central cell is filled with plain concrete and a single rebar. Out-of-plane displacements were prevented successfully. A maximum capacity of P = 79.41 kN was obtained for this specimen and a gradual loss in strength was recorded. Again, although the middle part was strengthened with concrete infill and single rebar, this did not increase the capacity mainly from the observed damages in the unfilled cells. Concrete infill and single rebar increased initial stiffness (K) by 47.41%, 8.50% when compared with ST-NF and ST-MF, respectively. Reason for losing the strength of the specimen is from crushing in the head regions (loaded corners).

3.7 Specimen ST-AF (All Filled, no Rebar)

This specimen used plain concrete (without rebars) infill for all cells. Very stable behavior was obtained (as expected) until the load capacity of P = 270.08 kN. Load-deflection curves were quite similar both for vertical and horizontal measurements. Concrete infill had a significant impact on the capacity when compared with ST-NF (3.14 times ST-NF at maximum load). Concrete infill increased initial stiffness (K) compared with ST-NF (1.97 times ST-NF) and other specimens (1.33–1.67 times). After a certain amount of compressive load is applied, the GFRG panel and concrete core are separated from each other.

3.8 Specimen ST-AFSR (All Filled, Single Rebar)

This specimen is filled with plain concrete and single rebar for all cells. Overall behavior was quite stable until failure. No significant data were obtained for the out-of-plane displacements. A maximum capacity of P = 267.14 kN was obtained for this specimen. This shows that the infill concrete with central single vertical rebar has contributed to capacity significantly when compared with ST-NF (3.11 times ST-NF at maximum load). There was no significant change in capacity when central rebar was added but increased initial stiffness (K) compared with ST-AF (1.86 times ST-AF). This is mainly due to separation (or loss of bond upon loading) between the concrete core and GFRG panel for this type of loading.

4 Evaluations

Table 2 shows each specimen's performance based on some behavioral values such as the maximum shear strengths reached, initial stiffnesses, and the ratios of these values to the maximum ones obtained during the tests. Such a comparison reveals that completely filled specimens performed better (as expected) than the others. On the other hand, wall specimens with partially filled cells (or cavities) pose no significant advantage over the GFRG panels without any infill material since the empty cells (being the weakest link in the system) control the overall behavior.

Table 2. Summary of diagonal shear test results.

Specimen	Group	Shear strength (P_{max}) [kN]	Shear ratio to Max	Initial stiffness (K) [kN/mm]	Stiffness ratio to max	Shear modulus (G) [MPa]	Failure modes
ST-NF	1	85.94	0.32	131.86	0.27	1626.9	Crushing around the head regions
ST-EF	2	83.82	0.31	159.84	0.33	345.95	Shear cracks in the middle cell
ST-EFSR	2	80.06	0.30	168.20	0.35	319.87	
ST-EFMR	2	71.73	0.27	190.10	0.39	317.02	
ST-MF	3	74.83	0.28	183.24	0.38	647.38	Crushing around the head regions
ST-MFSR	3	79.41	0.29	198.19	0.41	669.79	
ST-AF	4	270.08	1.00	253.06	0.52	311.48	Separation or loss of bond between the concrete core and GFRG panel
ST-AFSR	4	267.14	0.99	484.65	1.00	575.09	

5 Conclusions

The following results can be drawn from this experimental work:

- The capacities of the fully filled wall samples in Group 4 are about 3.5–4 times higher than the other groups.

- The initial stiffness (K) of the wall samples in Group 4 is considerably higher (1.33–3.60) than the initial stiffness (K) values of the other samples.
- Although Group 2 and Group 3 samples are reinforced with plain concrete or concrete + rebar, it is observed that it does not increase the strength capacity when compared with the Group 1 sample which is completely empty.
- Observations on Group 2 and Group 3 specimens after testing show that these specimens were damaged in the unfilled cells which are the weakest points of the specimens.
- Comparing Group 2, Group 3 and Group 4 specimens reveals that used rebars had no effect on the load capacity. However, the specimens with steel rebars have higher initial stiffness between min. 8.50% (ST-MFSR/ST-MF) and max. 87.75% (ST-AFSR/ST-AF).
- Typical damages observed in Group 4 samples are that the GFRG panels and infill concrete stop working together and move separately from each other. There was not much reduction in load capacity due to the frictional movement on each other. However, it is observed that there may be a sudden collapse due to the damages it has received.

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