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LATERAL CYCLIC LOAD BEHAVIOUR OF GFRG BUILDING SYSTEM – EXPERIMENTAL STUDIES

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Abstract

GFRG (Glass Fiber Reinforced Gypsum) panels are prefabricated load-bearing panels used primarily as wall and slab elements in buildings. With the key advantages of rapidity and economy in construction, GFRG technology is finding a key role in affordable mass housing construction in India. Multi-storied buildings can be constructed using GFRG panels without the necessity for any beams and columns. GFRG panels are hollow composite panels that can conveniently be filled with any structural material like concrete, and RC (reinforced concrete) if required, in order to improve its load carrying capacity. With low grade concrete fill, GFRG panels exhibit very high axial resistance, but the relatively reduced shear strength of the panels limits the number of stories of GFRG buildings to 8 - 10 in moderate seismic zones, and to lesser number in higher seismic zones in India. Studies conducted for the evaluation of seismic behavior of GFRG wall panels showed that the panels behaved satisfactorily under lateral loads. The studies conducted had been limited to only wall components. When GFRG is used for constructing medium-rise buildings, it is important to know the performance of the connections between the wall and the slab. Tests on building systems comprising walls and slabs made of GFRG have never been conducted.

This paper presents the results of an experimental study on the lateral load behavior of a typical GFRG building system. A GFRG system unit of height 3m, comprising of GFRG wall panels and GFRG-RC composite slab, of plan dimension 2 x 2m, was subjected to cyclic lateral loads. GFRG-RC composite slab behaving as one-way slab, spans between the walls in the in-plane direction. Cyclic lateral displacements were applied at the slab (diaphragm) level, as per ISO 16670 protocol. The amplitudes of the displacements were fixed based on the ultimate displacement obtained from a monotonic test done a similar wall component.

From the analysis of experimental results, the performance parameters of the system such as connection between wall and slab, system ductility, strength and mode of failure is discussed in this paper. The proposed wall-slab connection behaved satisfactorily and was adequate in transferring shear force from slab to wall panel till the system reached the ultimate stage of failure. The failure of the system was by formation of longitudinal cracks at the web-flange interfaces, a unique mode of failure. This unique failure mode exhibited by GFRG resulted in higher ductility of the unit compared to other conventional systems.

Keywords: GFRG; Building system; Composite panel; Cyclic load; Connection

1. Introduction

GFRG (Glass Fiber Reinforced Gypsum) panels are light-weight load-bearing building panels, developed as an alternative construction material in Australia in 1990. These are factory-made hollow panels, manufactured out of gypsum plaster reinforced with glass fiber rovings. Fig. 1 shows a GFRG panel of standard size 12m × 3m and 124mm thickness. GFRG is a structural material capable of resisting axial (gravity) loads and lateral loads like wind and earthquake [1]. Almost a decade back, this technology was introduced in India with a view of utilizing the huge stock of waste gypsum obtained from fertilizer industries. Construction of buildings in India using GFRG panels thus produced, not only reduced the cost, but also facilitated sustainable construction. The major benefit of using this technology is that the construction is quick, since it involves only installation of light–weight prefabricated units weighing about 44 kg/m^2. These hollow wall panels have been used for the construction of buildings up to two stories in Australia.

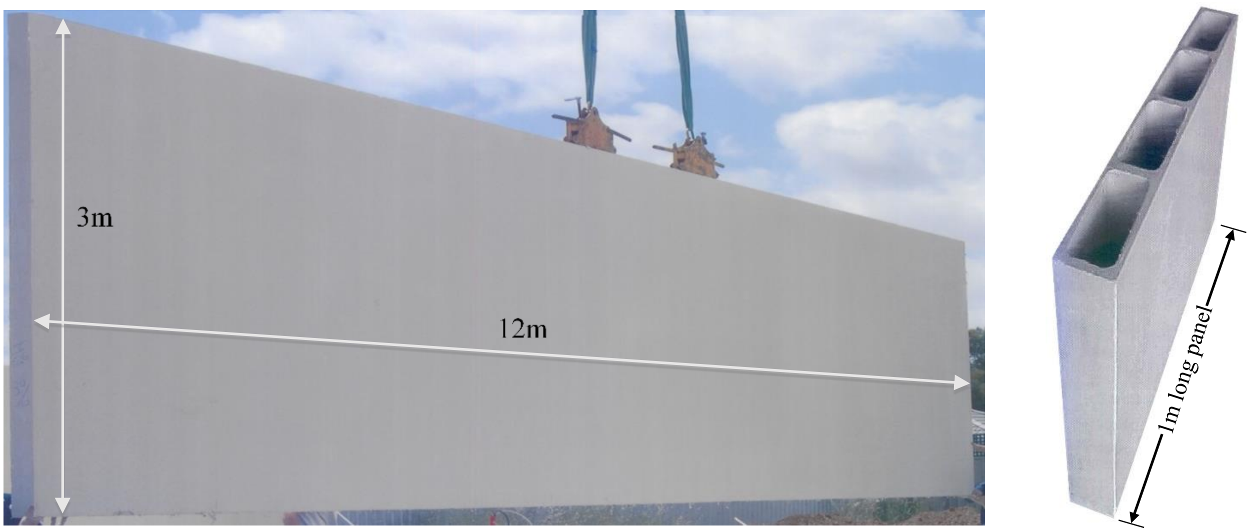

Fig. 1 - GFRG panel

Founded on the studies carried out in Australia, it was realized that GFRG can be designed as a composite wall panel with increased axial and shear load carrying capacities by filling the cavities with low grade plain concrete, thus enabling them to be used in the construction of multistoried buildings; further increase in shear carrying capacity was observed with the introduction of vertical reinforcement [1,2]. Almost 3000 dwellings – mostly low-rise buildings, and a few medium-rise buildings were constructed in Australia. Of the buildings constructed, GFRG panels were used as load-bearing walls resisting only gravity loads. The slabs were conventional RC (reinforced concrete) slabs, which were designed as either one-way or two-way slabs. Additional RC shear walls were provided in multistoried buildings, to take care of the high base shear due to earthquakes. Further studies carried out in China and India also resulted in construction of GFRG buildings in these countries. Based on the large-scale tests carried out at IIT Madras in India, a building system was proposed using GFRG, with the entire components of the building built only using GFRG panels, in combination with RC, thus completely eliminating the use of bricks and minimizing the use of concrete to the largest extent possible. A structural design manual titled, 'Use of Glass Fiber Reinforced Gypsum (GFRG) Panels in Buildings', was prepared by IIT Madras in this regard, which aids in analysis and design of GFRG buildings [3].

Currently, GFRG is used in India mostly for construction of low-rise buildings, typically 1 – 2 storied buildings. GFRG building system has the potential for multistoried building construction and can be used for construction of medium-rise buildings (up to 8 – 10 floors) in the moderate seismic zones of the country, without the need for any beams and columns or additional RC shear walls; but requires proper testing to be done. This paper describes the evaluation of behavior of a GFRG building system, tested under gravity and lateral load, done as part of a project sponsored by the Department of Science and Technology (DST), Government of India.

2. Review of Literature

Limited studies were found to have been reported on GFRG (mostly on the axial and lateral load behavior of GFRG component units), which were aimed at exploring the possibility of using panels for building construction. Initial studies comprised tests on GFRG prisms (GFRG panel units of reduced size) subjected to compression, tension, out-of-plane bending, etc. [2,4]. Later axial [1,2,4] and shear studies [1,2,4,5] were carried out on full scale panels (of 2.85m height). Shear studies were done by subjecting the panels to monotonic and cyclic lateral loads in order to estimate the shear carrying capacity and to study the behavior of panels under seismic loads. The test results obtained are summarized in Table 1.

Table 1 - Test results [1,2,4,5]

Sl. No.	Property	Value obtained
1	Unit weight	44 kg/m^2
2	Compressive strength (unfilled prism)	4.77 MPa
3	Elastic Modulus	7500 MPa
4	Poisson's ratio	0.15 – 0.23
5	Compressive strength (concrete filled panel*)	10.96 MPa
6	Tensile strength	1.04 MPa
7	Shear strength (unfilled panel)	21.6 kN/m
8	Shear strength (RC filled panel*)	61 kN/m

* M20 concrete filled inside the cavities

Further, tests were conducted on GFRG building systems in order to study the system behavior and their failure mechanism. Tests on building systems were done only in China and India.

2.1. Performance of a 5-storeyed GFRG building under lateral load [6]

Cyclic lateral load test was performed on a 5-storeyed GFRG building of plan dimension 7.5m × 8.5m at Shandong Construction University in China. The story height of each floor was 2.7m. In this building, empty GFRG panels were used for walls. At the wall corners, a 14mm diameter tie bar of length 500mm was provided inside the cavities at the wall-slab junctions at all floor levels, with M25 concrete filled in those cavities. The slab provided was 120mm thick RC floor / roof slab. Appropriate live loads were applied on the floor slabs. This system was subjected to quasi-static reversed cyclic lateral load by means of actuator connected to the floor slab. The failure load could not be reached before which the test had to be stopped, as it exceeded the actuator capacity. It was observed that the integral performance of the structure was good and the structure had enough load-bearing capacity. The connection between the walls and the slabs performed well, showing that the load from the slab was effectively transferred to the walls. Micro cracks started to appear on the panel only at about 45 to 60% of the predicted ultimate load.

2.2. Shake table testing of GFRG building system [7]

In India, shake table testing was done on single storied GFRG model houses with different plan configurations to evaluate the seismic performance of GFRG building system. Here, empty GFRG panels were used for walls. For slabs, GFRG panels in combination with RC was used, the design of which was proposed by IITM (explained in the next section). Details on connection between the wall and the slab have not been given, but it is assumed that this connection was properly designed and provided. In the cavities at the wall-corners, starter bars (dowel bars) were provided. This is the first of the kind test conducted on a system with both walls and floors constructed using GFRG panels. On the top of the slabs, a 2 ton mass was placed in order to feign the effect of two stories. The buildings were subjected to random seismic base excitations. Those of the highest intensity was that corresponding to the maximum PGA for zone V (most vulnerable zone), as per the Indian seismic code, IS 1893 (Part 1) : 2002 [11]. The buildings showed only minimum structural damage, with cracks occurring at the joints between slab and walls and wall to wall joints. This was attributed to reduced resistance to shaking offered by corner joints, and hence it was recommended to have solid filling inside all the cavities of the panel for improved seismic performance.

2.3. GFRG floor / roof slabs

GFRG slabs are one-way slabs designed to carry gravity loads, with RC fill inside every third cavity and a layer of screed concrete of minimum 50mm thickness on the top, as shown in Fig. 2. GFRG panels have considerable out-of-plane bending capacity and exhibit tensile mode of failure when the cavities are spanned along the supports. The panels are laid horizontally with the cavities aligned in the shorter direction (span). Later, every third cavity of the slab is cut open from the top and reinforcement cage is inserted. The reinforcement cage typically contains two 10mm diameter bars at the bottom, with a clear cover of 15mm below and one 8mm diameter bar at the top (above the top flange level). The top and bottom bars are connected together by triangular stirrups of 8mm diameter. On the top of the slab, a 50mm thick screed concrete is provided with a layer of weld mesh at the center. The screed concrete along with reinforced concrete inside the cavities constitutes series of RC T-beams. While designing this slab, it is found to be conservative to ignore the composite action of GFRG and RC T-beams, since the bond between the two needs to be established through tests. The strength of the slab is thus strength of the T-beam, while GFRG panel acts as a lost shutter. T-beam analysis done on this section (with specified reinforcement) showed that the RC T-beams are capable of carrying an ultimate load of 4.4 kN/m^2, whereas the normal live load on a slab is only 2 kN/m^2, for residential buildings, as per IS 875 (Part 2) : 1987 [9]. Large scale testing and studies are being carried out on GFRG-RC slabs. Studies revealed that GFRG slab panels could effectively span up to 4.5m in combination with RC.

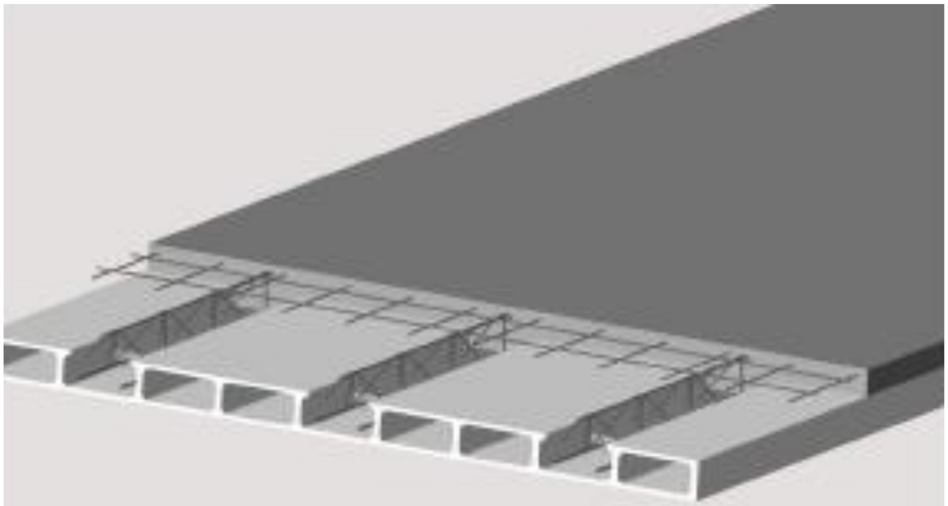

Fig. 2 - GFRG-RC composite floor slab

3. Need for the present study

From the review of literatures carried out on GFRG, it was found that, though extensive tests had been carried out on GFRG wall components, only very few tests were conducted on building system. Through components tests, it was established that GFRG panels have enough axial and shear carrying capacities and has higher ductility, when compared to similar RC shear walls; but this needs to be verified for building systems through tests. Unless a typical system comprising walls and slab is tested, the behaviour of a building cannot be predicted. Further, a building system test also shows the performance of connections provided in the system. Any failure in the connection will lead to total failure of the system in which case the capacity and characteristics of the system will be different from those of components. A building system comprising GFRG walls and GFRG-RC composite slabs was needed to be tested under gravity and lateral loads to assess the strength, performance of connections, mode of failure and ductility. Such a study on this proposed new system has not been done anywhere. The scope of this study is limited to wall to slab vertical joints and connections. Horizontal connection between the walls is assumed to transfer the entire shear till the ultimate shear carrying capacity of the wall panels is reached.

4. Preliminary study

A building system unit is representative of a typical room of a building, comprising four walls – two in the in-plane and two in the out-of-plane direction (in-plane and out-of-plane refers to the direction of earthquake force that is considered), and a floor / roof slab at the top. Considering only the in-plane strength of walls, and neglecting their out-of-plane strength contribution, the system unit can be abridged to that with only two in-plane walls connected by a slab. This is more representative of a GFRG system, as the GFRG slab is a one-way slab, integrally connected only with the in-plane walls. In order for the system test to be more realistic and representative of an actual case, a case study was done on a multistoried building and a typical room of this building was tested. The details regarding analysis and design of this building is given below.

Analysis and Design of an 8-Storeyed GFRG Building [3]

An 8-storeyed apartment building, which is planned to be constructed using GFRG panels in Mumbai, India, is taken as the case study building. The analysis of this building was done in the finite element software, ETABS. The steps followed for modeling and analysis of this building are given below.

1.) The building was modelled using shell and membrane elements representing concrete filled GFRG wall and slab panels respectively, for which the material properties were defined using values from the test results, given in Table 1. Modelling was done strictly with wall panels of widths varying from 1m to 3m at increments of 0.25m (with a very small gap in between), for which the P_u-M_u interaction curves are already available. This makes the design much easier. Walls were not modelled at openings and at locations of doors and windows. A typical floor plan of the building, modelled in ETABS, is shown in Fig. 3a.

2.) The gravity loads, viz., dead and live loads were applied as per IS 875 Part 1 & 2 respectively [8,9]. The lateral loads, viz., wind and seismic loads were also applied. Wind loads were applied as per IS 875 (Part 3) : 1987 [10], considering a wind velocity of 44m/s for Mumbai. Seismic loads were applied as per IS 1893 (Part 1) : 2002 [11], considering a zone factor of III (moderate seismic zone of India) for Mumbai.

3.) Rigid diaphragms were assigned to slabs in all floors in order to distribute the lateral loads. If the composite action of GFRG and RC T-beam is not considered or if it is lost, the RC T-beam alone is sufficient for ensuring rigid diaphragm action of the floor / roof slab in GFRG building. Static analysis was done for gravity, wind and seismic loads, in order to obtain forces on the structure.

4.) The base shear obtained due to both wind and seismic loads were compared, after analyzing the model, and it was found that the base shear due to seismic loads governed the design. The distribution of seismic base shear of the building in the X-direction and the resulting deformed shape are shown in Figs. 3b and 3c respectively.

The forces generated in the walls - axial load, in-plane bending moment and lateral shear force, were extracted. Structural design of GFRG building is, at arriving the number of hollows of the panel that need to be reinforced, number of bars and diameter of bars to be put inside the hollows. Using the P_u-M_u interaction curves given in the GFRG Structural Design Manual [3], it was required to provide 2 numbers of 12mm diameter bars with M20 concrete fill inside all the cavities of the wall panels, from ground to second stories. On the upper floors, on account of reduced axial force and bending moment in the walls, the diameter of the bars were reduced considerably. Hence, at the 3rd story and from fourth to top stories, 2 numbers of 10mm diameter bars and 2 numbers of 8mm diameter bars, filled with M20 concrete, were only needed to be provided.

It was checked whether the provided reinforcement provided was sufficient to resist the lateral shear on the wall panels, by comparing with the shear strength values given in Table 1.

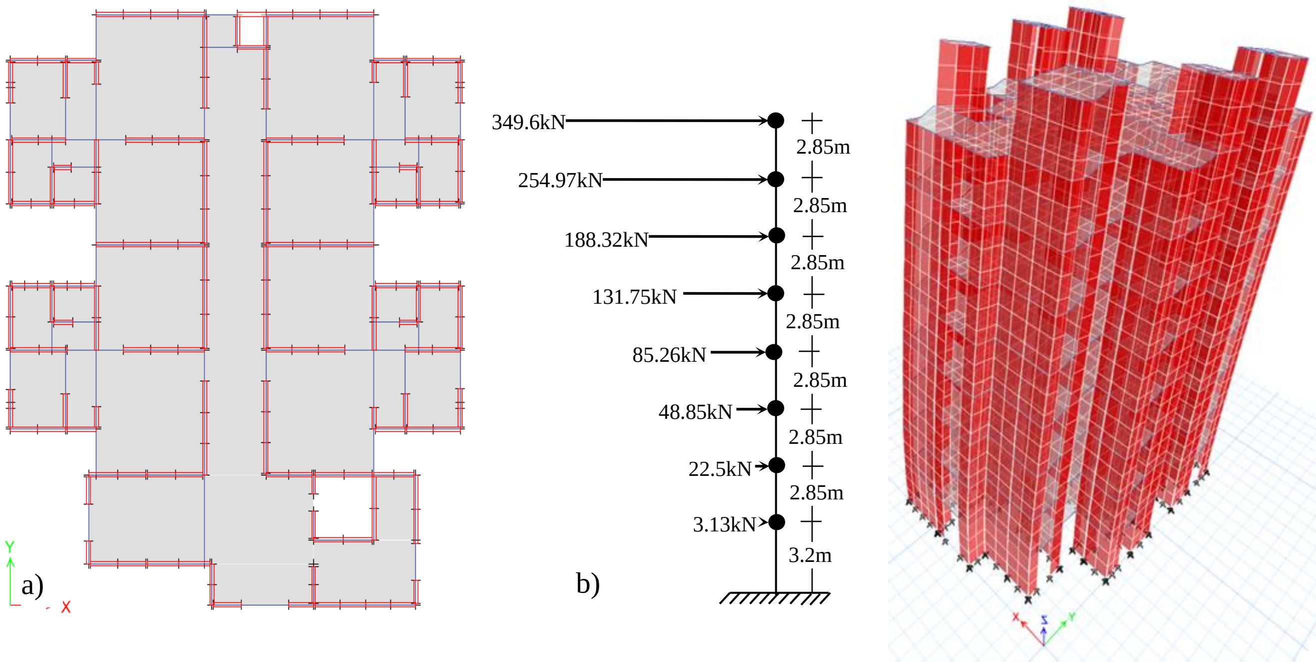

Fig. 3 - a) Typical floor plan b) Seismic base shear distribution in X-direction c) Deformed shape

5. System unit study

Typical room of this case study building has a size of 3m × 3m. Due to space constraint in the laboratory, it was decided to perform the test on a 2m × 2m GFRG system unit specimen. The system unit test set-up is shown in Fig. 4. As the primary aim of this test is in establishing the performance of connection, so as to facilitate transfer of forces from floor to walls, emphasis is given here on the type of connection to be provided between the wall and the slab, and also design of this connection in order to obtain adequate strength without causing failure. The interface shown in Fig. 4 is identified to be vulnerable to failure during the transfer of shear from slab to wall. The proposed connection is shown in Fig. 5. Two numbers of 10mm diameter bars are made to run throughout the outer length of walls connecting all the vertical rebars. In every third cavity, where the slab is reinforced, C-bars (special bars) of 10mm diameter are provided, where the closed end is hooked and tied to the two 10mm diameter bars and the open end is tied to the top and bottom reinforcement of slab. From the interface, a length of at least the development length of bar is made to go inside the GFRG slab, so as to develop full tension in the bar at this interface in the likelihood of a failure. The strength of this connection has been evaluated according to interface shear friction concept, which is shown below.

Considering the interface shown in Fig. 4, the lateral force acting on this joint is only the shear transfer from slab to wall, and does not depend on the cumulative shear transferred from walls in upper stories to those below. At the bottom story, the axial load from the walls on the top stories enhances the shear strength of this interface, while at the top story, this enhancement does not occur. As the maximum seismic force on the slab acts on the top most story (Fig. 3b), the interface considered for this study will be most critical at the eighth floor. Figures 4 and 5 shows only three cavities of walls and slab in order to avoid muddling up; but a 2m panel will have 8 cavities, of which all the wall panel cavities are reinforced with 2 numbers of 8mm diameter bars; in case of slab, only the end cavities and two middle cavities are reinforced (details of slab are explained in section 2.3) and filled with M25 concrete.

The shear carrying capacity of reinforcement = $\mu A_{vf} f_y$

where μ is the co-efficient of friction for concrete to concrete interface (taken as 0.6), A_{vf} is the area of reinforcement resisting the shear and f_y is the yield strength of steel. From the tension test done on reinforcement (of grade Fe500), f_y has been obtained as 511 MPa.

Considering a 10mm diameter C-bar put in every third cavity, shear carrying capacity corresponding to one concrete filled cavity = $0.6 \times \frac{\pi}{4} \times 10^2 \times 2 \times 511$ = 48.16 kN

A total of 5 such cavities of the slab have been reinforced with the inclusion of C-bars; hence total shear carrying capacity along one full interface = 240.8 kN

Considering both the interfaces, the designed connections can take a total load of 481.6 kN applied laterally on the slab. Quasi-static cyclic lateral load test was conducted on the system unit specimen.

5.1.Lateral load test on system unit specimen

A destructive test was performed on the system unit specimen constructed inside the Structural Engineering Laboratory of IIT Madras. All the cavities of the wall panels were reinforced with 2 numbers of 8mm diameter bars (Fe500 grade of steel) and were filled with M20 grade of concrete. The 28 day cube strength was obtained as 20.22 MPa. The yield strength of steel was 554.38 MPa. Wall panel concreting was done to a height only up to 250mm below the wall panel top. Later after erection of the GFRG slab and completing the laying of slab reinforcement and providing the proposed connection, concreting (using M25 grade) was done monolithically over the wall top, wall-slab junction and GFRG slab including the 50mm screed concrete over the GFRG slab top. The 28 day cube strength was obtained as 27.86 MPa. The vertical reinforcement was taken 250mm above the slab top to provide the required development length. Considering the fact that the GFRG slab acts as a rigid diaphragm, the load was applied uniformly over the entire slab using specially fabricated steel beams on both ends of slab, connected together using large diameter bars. The weight of the beams along with the bars were equivalent to live load that had to be applied on the slab, hence live load on the slab was not applied separately. The entire test set-up is shown in Fig. 6.

The cyclic displacement pattern for the system unit test was fixed as per the test method B, also called ISO 6670 protocol or ISO displacement schedule, specified in ASTM E2126 [12]. Displacement controlled loading was applied on the test specimen which involves giving the displacement cycles incrementally. In order to arrive at the displacement pattern and amplitude of displacement, the ultimate displacement (displacement corresponding to failure load) of a similar specimen had to be known in advance. This was obtained by conducting a monotonic test on a similar specimen. The width of wall, reinforcement pattern and grades of steel and concrete used for the monotonic test specimen were the same as that used for the system unit specimen. The lateral load was applied as displacement loading at increments of 0.25mm till failure. This test yielded an ultimate displacement of 57.61mm. Based on this ultimate displacement, the load cycles were fixed which is shown in Fig. 7.

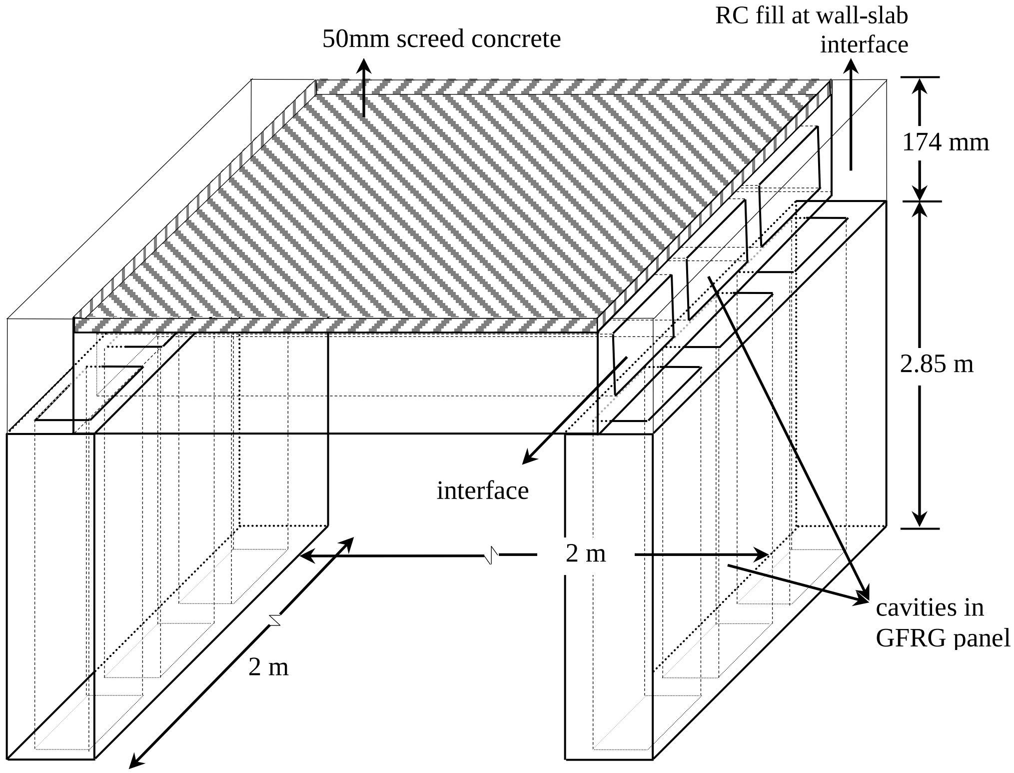

Fig. 4 - System unit test-up

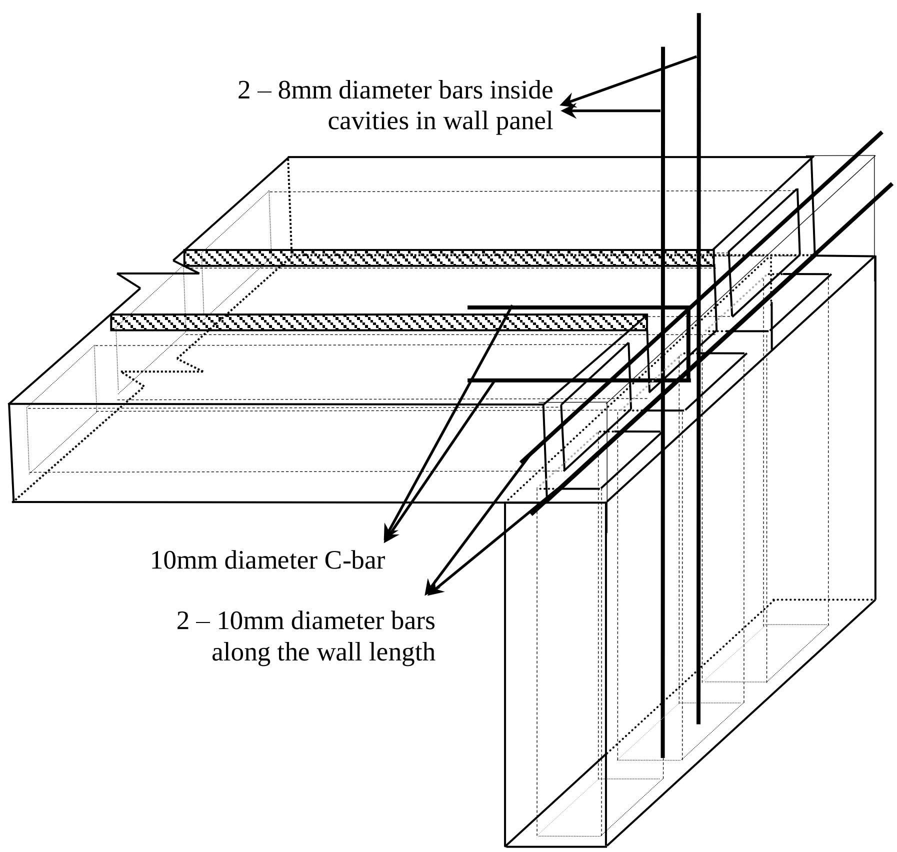

Fig. 5 - Wall-slab connection – C-bar in the third cavity of GFRG slab

Fig. 6 - Test setup

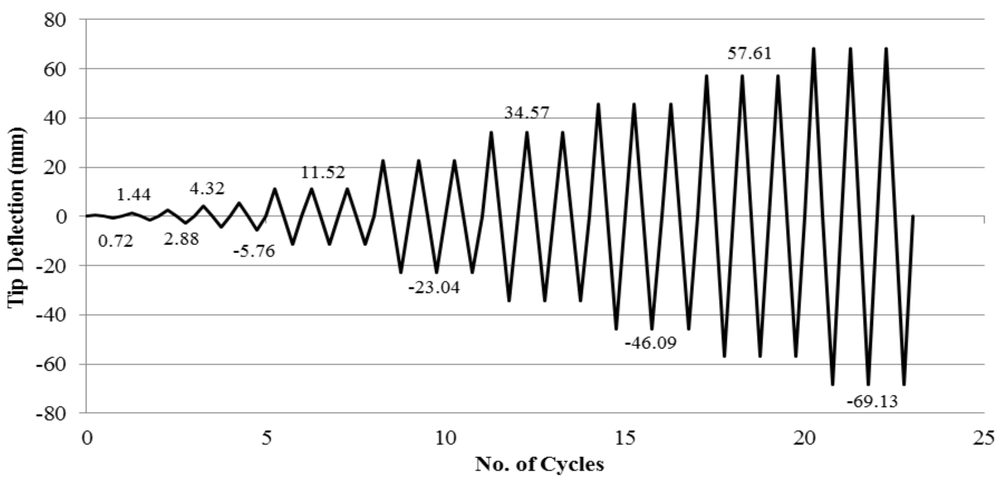

Fig. 7 - Load cycle

6. Observation

During the test, at about 50-60% of the ultimate load, loud sounds were heard from the wall panels due to tensile breaking of glass fibers. Local shear cracks in the form of diagonal cracks started appearing on the panel at the web-flange interfaces at around 75-80% of the ultimate load. Just after the peak load was attained, first vertical (longitudinal) shear crack was formed at the center of wall panels at the web-flange interface. Subsequently, more number of vertical cracks were formed at the interfaces accompanied by gradual reduction in load carrying capacity of the system. Gradual failure by formation of vertical shear cracks is a unique mode of failure observed in GFRG panels. The testing was stopped when the longitudinal cracks were formed at all the interfaces due to considerable loss of stiffness of wall panels, after which the system became unstable. Till the ultimate failure occurred in the walls, no cracks were formed at the wall-slab interface and the connections suffered no damage. Till yielding, the panel and the concrete fill behaved together in resisting the lateral load. At yield, diagonal shear cracks were formed, and at peak load, there was slip of concrete fill against the panel. The cyclic response of the system unit test obtained in the form of hysteresis curve is shown in Fig. 8. The peak load in the positive cycle was obtained as 144 kN and that in the negative cycle was 172 kN, at approximate displacements of around 57 mm (Δ_u). In order to arrive at the ductility, equivalent energy elastic plastic curve (EEEP) curve was plotted as per ASTM E2126 [12]. From the EEEP curve, as shown in Fig. 9 for the negative cycle, yield displacements (Δ_y) of 11.37 mm was obtained.

$$\text{Displacement ductility} = \frac{\Delta_u}{\Delta_y} = 5.06$$

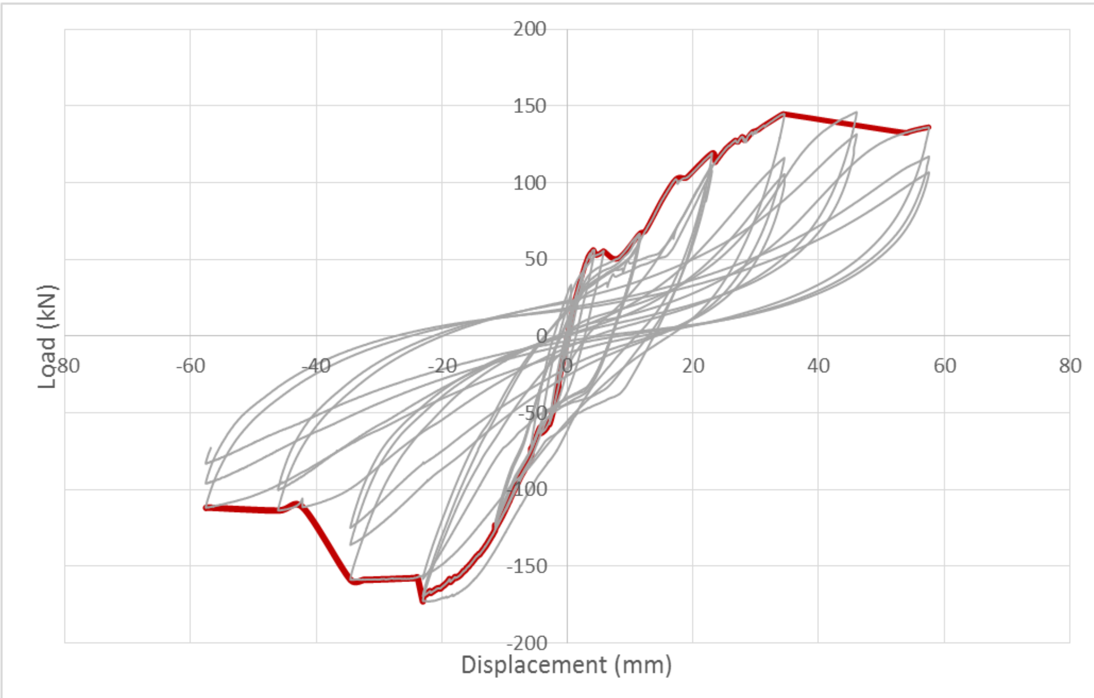

Fig. 8 - Cyclic response and envelope curve from system unit test

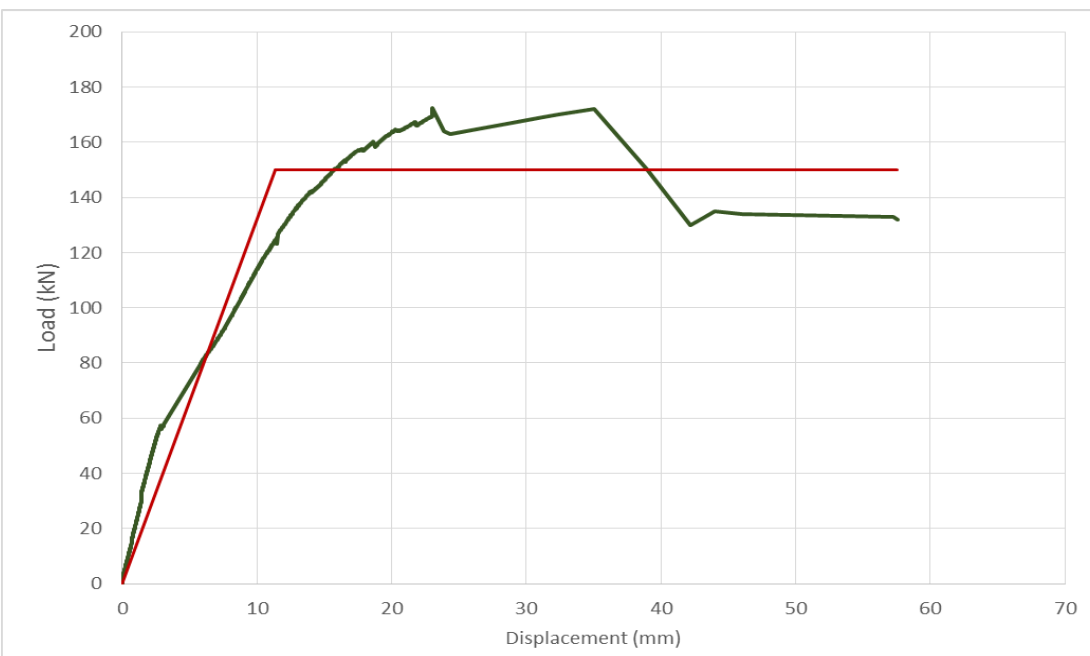

Fig. 9 - Load-deflection curve and EEEP curve (negative cycle)

7. Conclusion

A typical room, representing a GFRG building system unit, of a 8 storeyed GFRG building was tested under cyclic lateral loads. The performance of GFRG building system and the connection between GFRG wall and GFRG-RC composite slab in particular have been evaluated in this study. The performance of system was studied by assessing the system strength, mode of failure and ductility. It was seen that, based on the strength requirement, the cavities of the wall panels can be adequately reinforced in order to improve their moment and shear carrying capacities. The proposed wall-slab connection behaved satisfactorily in effectively transferring the lateral loads from slab to wall panels without causing any failure, till the ultimate capacity of the unit was reached. The failure of the unit was by formation of vertical shear cracks at the web-flange interfaces of the walls, a unique failure mode observed exhibited by GFRG. The formation of longitudinal cracks is due to slip of concrete inside the cavities of panel. Due to this distinctive failure mode, the ductility of the system is higher when compared to those of conventional systems.

8. Acknowledgements

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