*16th World Conference on Earthquake, 16WCEE 2017*

*Santiago Chile, January 9th to 13th 2017*

*Paper N° 1685*

*Registration Code: S-P1463118811*

# SEISMIC BEHAVIOUR OF GFRG - OGS BUILDING SYSTEM – A COMPUTATIONAL STUDY

Gouri Krishna S R [1], Dixon David [2], A Meher Prasad [3], Devdas Menon [4]

[1] *PhD scholar, Indian Institute of Technology Madras, India, e-mail: gouriksr@gmail.com*
[2] *Graduate Design Engineer, Walter P Moore and Associates, Inc., dixondavid100@gmail.com*
[3] *Professor, Indian Institute of Technology Madras, India, e-mail: prasadam@iitm.ac.in*
[4] *Professor, Indian Institute of Technology Madras, India, e-mail: dmenon@iitm.ac.in*

## *Abstract*

Glass Fibre Reinforced Gypsum, abbreviated as GFRG, is a light-weight load-bearing building panel, manufactured using gypsum plaster, glass fibre rovings and other special additives. In GFRG construction, the design demands all the walls to start from the foundation itself. The current demand from the housing sector for the urban community in India is open ground storey GFRG building (GFRG-OGS) in order to have parking space for vehicles at the ground or basement storey of the building. For this vertically irregular structure, columns can potentially collapse by soft storey mechanism with the formation of plastic hinges under the action of seismic forces. This paper analyses the performance of such building systems under gravity and lateral loads. The load path and the behaviour of the structure was studied by carrying out finite element analysis. The gravity loads were found to get transferred to columns by arching mechanism through walls. Lateral pushover analysis of the system revealed very less force demand on the beams. The hinges were in the elastic range owing to the higher number of columns given to utilize the arching mechanism for the Design Basis Earthquake (DBE) whereas for the Maximum Considered Earthquake (MCE), hinges went to the life safety level. The behaviour of the system was also verified by non-linear time history analysis incorporating material and geometric nonlinearities in the system and for seven different earthquake acceleration data. Based on this, a pushover load pattern different from the codal equivalent static load pattern was proposed for the analysis. The drift of the structure was found to be within the permissible limit. Hence the system behaviour is basically dictated in terms of strength based limit state. The results from the computational studies will be verified experimentally.

*Keywords: GFRG; Open ground storey (OGS); Finite element; Push-over; Time-history; Analysis*

## 1. Introduction

Glass Fibre Reinforced Gypsum panels were introduced as load bearing wall panels in Australia in 1990. These hollow panels, made of calcined gypsum and 13 micron glass fibre rovings of length 300 – 350 mm, are manufactured to a standard size of 12 m × 3 m with a thickness of 124 mm. Every metre of the panel houses 4 cavities of dimension 230 mm × 94 mm and can be infilled with concrete for enhanced strength and also can be used for accommodating electrical and plumbing service cables and pipes. The typical cross section of the panel is shown in Fig.1.

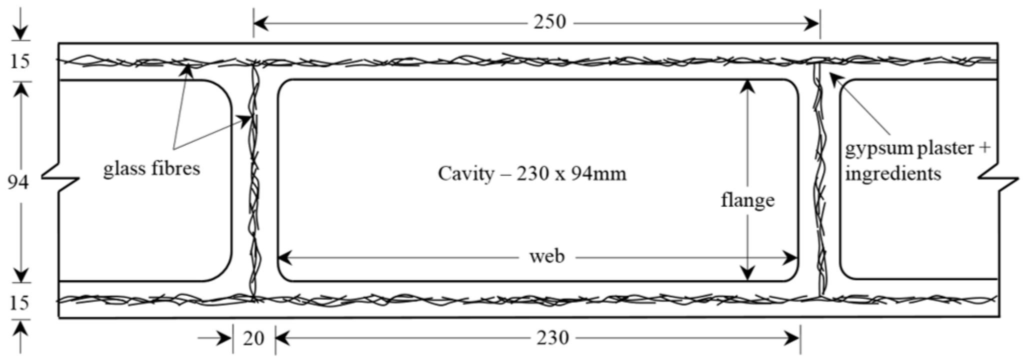



Fig. 1 – Typical cross section of GFRG panel

The panel has got the advantages of rapid construction, cost effectiveness, environment friendly, superior finishing, and reduced weight of the structure. These advantages helped in the promotion of GFRG as a sustainable solution for the rapid construction of affordable mass housing for the homeless, especially in India. The panels manufactured in India are made from industrial by-product phosphogypsum which again adds up the greenness of the material.

Numerous research and development studies had been conducted across the world to explore the properties and behaviour of these panels under different loads. The effect of providing vertical reinforcement bars in cavities on axial and lateral load carrying capacities were also explored [1]. The experimental and numerical explorations of GFRG components and systems in India has a history of more than a decade. The studies done at IIT Madras resulted in the use of the panels for the construction of all building components such as slabs, staircases, parapet etc. Experimental investigations on full scale three dimensional models have also been performed in China and India. A 5 storeyed GFRG building model with GFRG walls and reinforced concrete (RC) slabs was tested under lateral cycling loading at Shandong University, China and satisfactory performance was observed [2]. Tests done in Structural Engineering Research Centre (SERC), Chennai studied the behaviour of single storeyed building models with different plan configurations under shake table loading [3]. The slabs of these buildings were GFRG – RC composite slabs. All the models survived the testing with minimal structural damage.

Open Ground Storey (OGS) buildings (buildings with no/few infill walls on the ground storey) are widely been in use for facilitating parking in ground floor of the building, despite its vulnerability to seismic forces. The demand for the same in GFRG buildings has posed a serious challenge as all the walls in GFRG buildings need to be started from foundation itself and the provision of OGS will require a hybrid system with an RC framed structure (comprising of RC columns, beams and solid slab) in the ground storey and the GFRG building system in upper floors. The present study deals with the performance evaluation of such systems under combined gravity and lateral loads.

The behaviour of GFRG building with OGS is much different from the normal shear wall structure. In the event of an earthquake, the panels behave as structural walls. In this system, the base shear is resisted entirely by the ground storey columns, causing relatively larger drifts at the first floor level. This large deflection further enhances the moments due to P-Δ effects. Plastic hinges forms in the ground storey; the upper stories remaining undamaged and moving as a rigid body. This is also called storey mechanism or soft storey collapse. In the present study, three types of analyses were performed to capture the behaviour of GFRG OGS systems (up to 6 storeys) under gravity and earthquake loads.

a) Finite element study to understand the load path and the demands on the structural elements
b) Non-linear monotonic pushover analysis to find the ductility and performance level of the structures under lateral loads
c) Non-linear time history analysis to capture component level behaviour for real earthquakes

The results and findings from these analyses are presented in this paper. Experimental verification of these observations are proposed to be conducted at a later stage of the research.

## 2. Behavioural study

A 3D building was modelled using finite element software to understand the behaviour of GFRG OGS system. The ground storey of the building consisted of only RC columns and beams and all the GFRG walls started from the top of the first floor beam. Tie beams were also provided in each floor to ensure the connectivity of all the walls.

### 2.1. Modelling details

Fig. 2 shows the plan and three dimensional view of the GFRG building modelled in finite element software. The GFRG walls of the building were modelled as shell elements. The GFRG-RC composite slab was modelled as membrane elements and were assigned as rigid diaphragms. The depth of the beam was considered from the minimum dimension requirement as per the recommendations for OGS buildings. The walls are assumed to act in a linear range and checked to confirm with the shear force demand from analysis. As there are no walls continuing to ground floor, all the lateral load demands need to be taken by the columns in ground floor itself. The stresses in the shells were plotted to find the load paths. It gives a better insight in the behaviour of different structural elements.

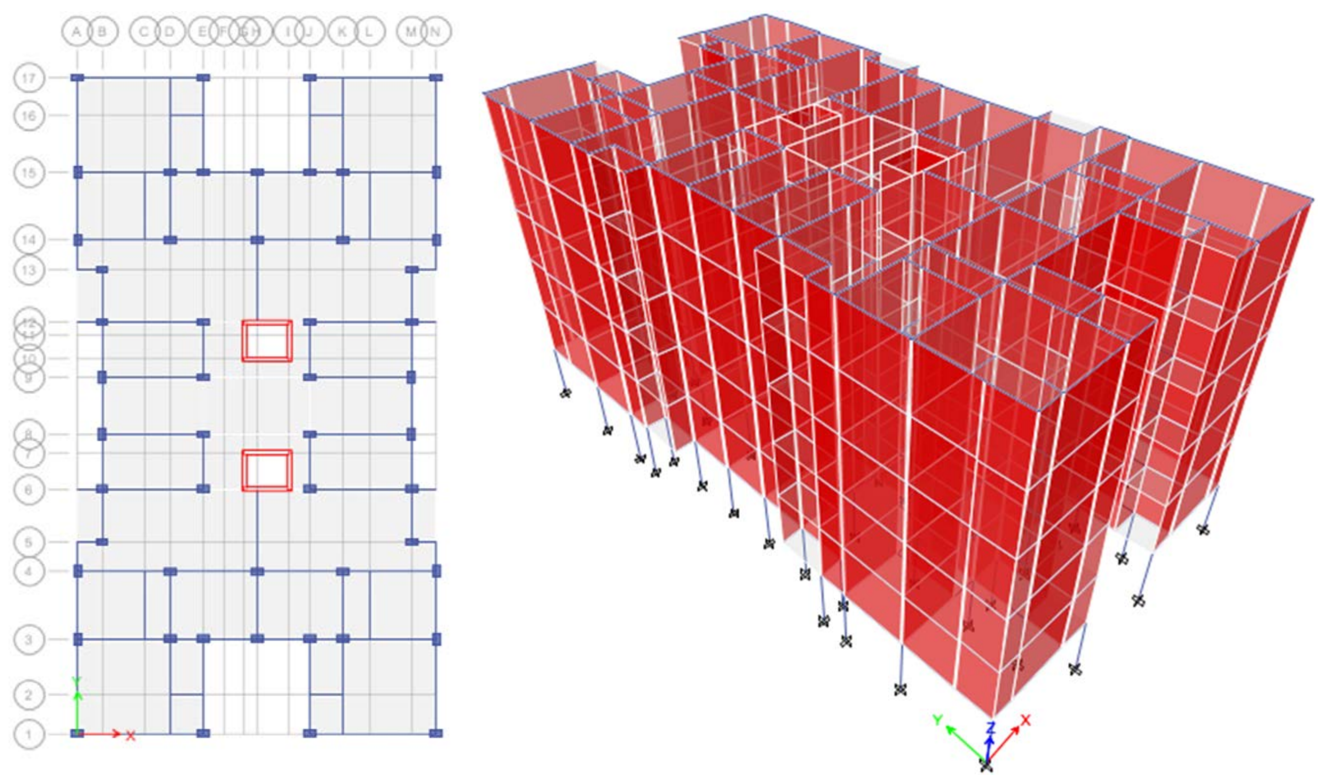



Fig. 2 – GFG OGS building modelled in Finite Element Software

## 2.2. Observations

Analysis of the finite element model of the building gave a maximum bending moment of 40 kNm and maximum shear force of 80 kN in the ground floor beam. The lower values of BM and SF can be attributed to the combined behaviour of beams and walls above. Thus the ground floor beams need not be designed considering uniform distribution of loads from the walls above, though there are no columns on the upper floors. By plotting the principle stresses from FEM analysis, it was observed that the load from the upper storeys are transferred through arching mechanism, directly to columns.as shown in Fig. 3. These beams also exhibited a tie behaviour. In this analysis, higher number of columns were provided to fully utilize the arching mechanism. Hence optimization of number of columns is required from economical and functionality point of view.

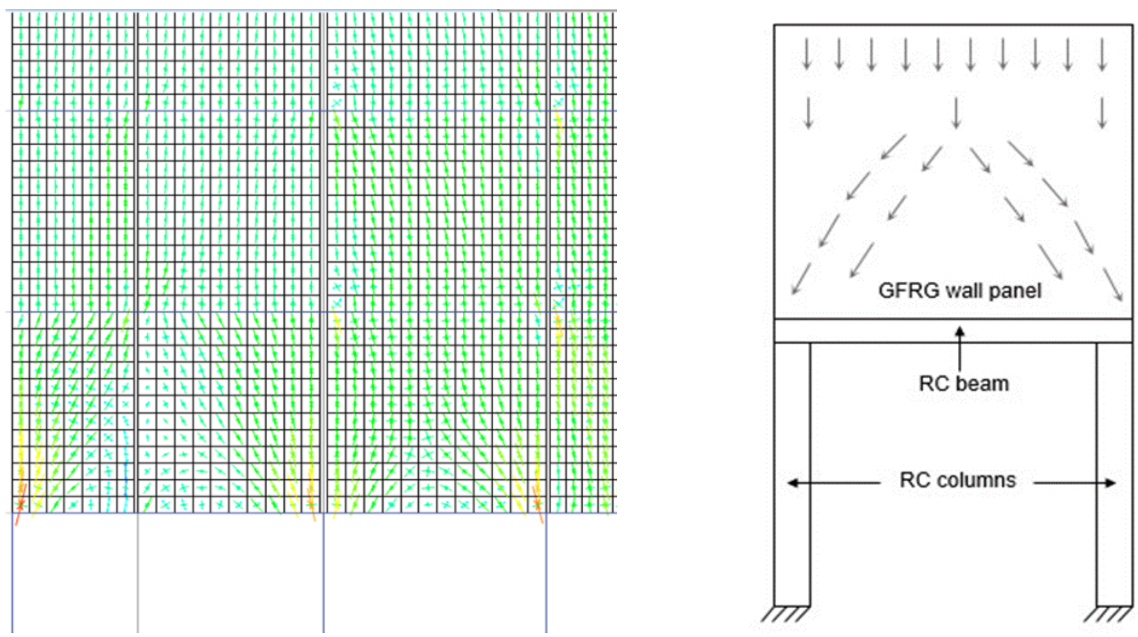



Fig. 3 – Load transfer by arching mechanism

# 3. Pushover analysis

A nonlinear static pushover analysis was conducted to study the performance of the building. Pushover analysis is a static approach in which the magnitude of the lateral loads is incrementally increased, in a predefined pattern through the height of the building until a collapse mechanism is formed. It thus helps in understanding the ultimate strength and the displacement capacity of the building as a whole. The building was designed for the lateral load demand due to seismic and wind actions including gravity loads. Nonlinear hinges (P-M2- M3 hinges for columns and M3 hinges for beams) were assigned to columns and beams as per FEMA provisions [2, 3]. The base shear versus roof displacement plot obtained by considering equivalent static load pattern for pushover analysis is shown in Fig. 4.

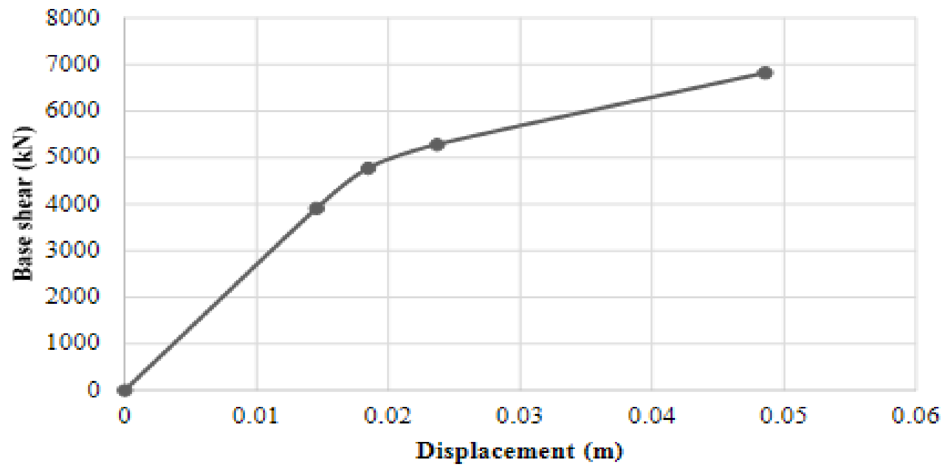



Fig. 4 – Base shear Vs. Displacement curve

The ATC-40 capacity spectrum method [4] was used to find the performance under Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE). The demand spectra was obtained using $C_a$ value of 0.24 and $C_v$ value of 0.33 as per the site condition, specified for the case study building. All the hinges were under life safety (LS) level and Collapse Prevention (CP) level for DBE and MCE respectively. The high amount of drift in the first floor relative to the upper floors confirms extreme soft storey behaviour. Very high stiffness is observed in the higher stories as the whole structure is modelled as shear walls. The ductility observed (1.6) was very less as the number of columns provided were very large. Estimated base shear was found to be higher than those predicted by conventional equivalent static method from code. The capacity curve and the demand spectrum at various levels of damping is plotted in the same graph in ADRS format (Acceleration Displacement Response Spectrum). The two curves meet at a point called the performance point and this gives an idea of the performance of the building at the corresponding earthquake loading.

The FEMA 440 [5] normalized plots are shown in Fig. 5 (a) and Fig. 5 (b).

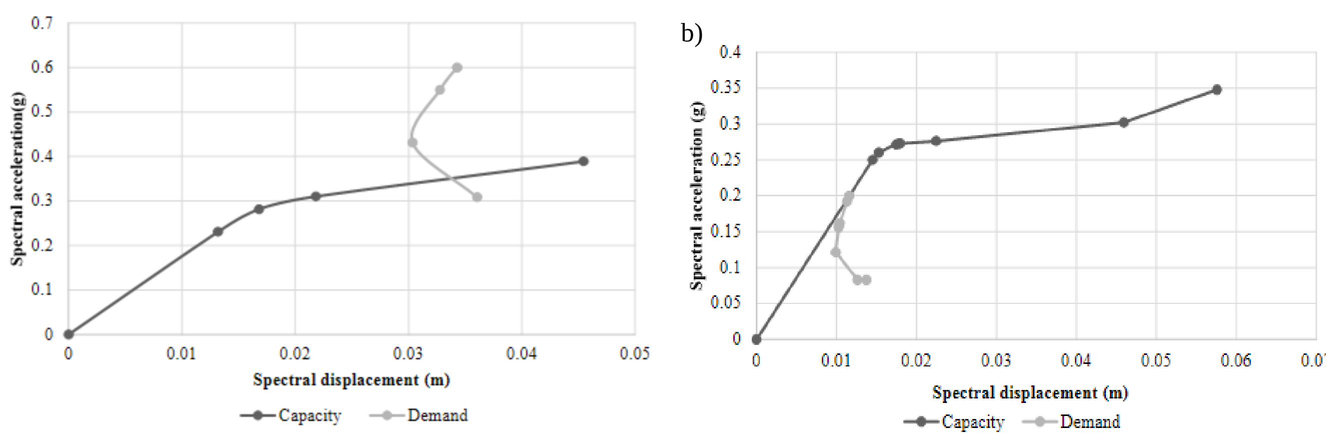



Fig. 5 – ADRS plot of demand and capacity for a) DBE and b) MCE

Table 1 gives the performance points under DBE and MCE. Though the hinges were in LS performance level under DBE, this behaviour cannot be generalised because of the higher number of columns given for the particular case study building.

Table 1 – Performance points for an earthquake of PGA 0.24 g

| Considered earthquake level | Base shear (kN) | Displacement | Drift at | |
|---|---|---|---|---|
| | | | First floor | Top floor |
| Design Basis Earthquake (DBE) | 4963 | 18 mm | 0.53 % | 0.1 % |
| Maximum Considered Earthquake (MCE) | 6017 | 36 mm | 1.1 % | 0.12 % |

When the pushover was done incrementally, the beam hinges were formed in a later state to that of the column hinges. This was as per the observation of the load transfer mechanism explained using FEM analysis. Thus the same effect is found in the lateral load path also. The hinge formation in columns is illustrated in Fig. 6.

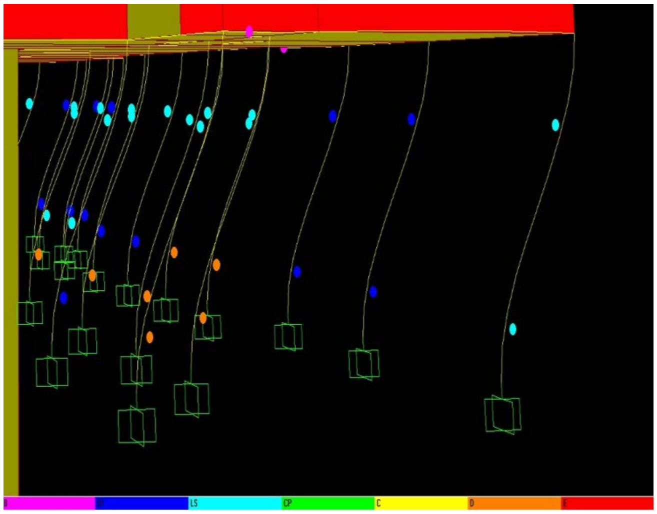


Fig. 6 – Hinge formation in columns

## 4. Nonlinear time history analysis

The nonlinear time history analysis was conducted using different time histories of recorded earthquakes selected as per FEMA P695 provisions [6]. Seven ground motion time histories were considered for the analysis. The average response spectrum of the studied time histories was scaled to codal response spectra by linearly multiplying with a scaling factor. The scaling factor is obtained by comparing both spectra for value corresponding to the natural period of the building. The time histories of considered ground motions and the corresponding scaled response spectra is depicted in Fig. 7.

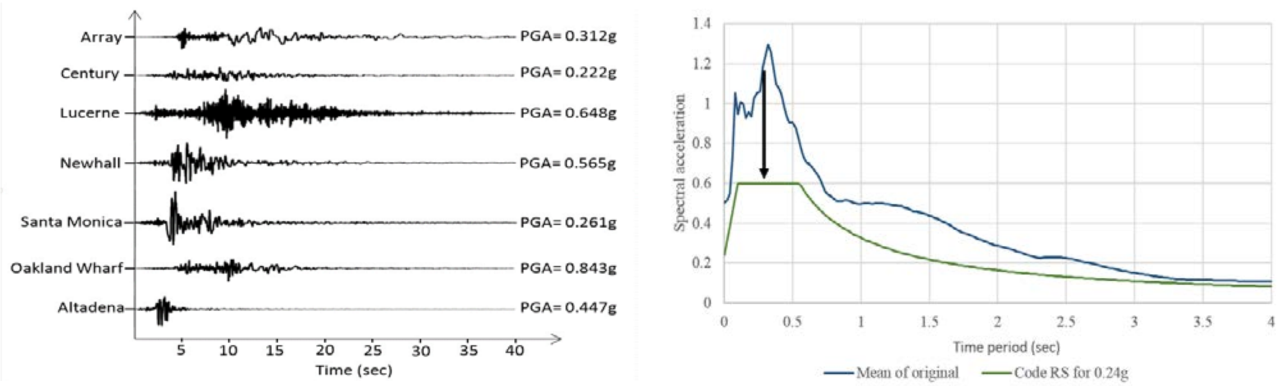



Fig. 7 – Considered ground motions and scaled response spectra

To consider the nonlinearity due to the GFRG panels acting in the system, the walls were modelled as layered shell elements in SAP2000v17. The layers of different materials were sandwiched, as shown in Fig. 8 and their properties were given as an input. The steel provided was also modelled as a thin shell layer element in perpendicular direction with a thickness of 0.2 mm (having an area equivalent to that of an 8 mm diameter bar in each cavity) The stress strain property of GFRG material is taken from the experiments conducted by Sreenivasa, 2009 at IIT Madras [7]. The Takeda model is used in the present study to model the hysteretic behaviour [8].

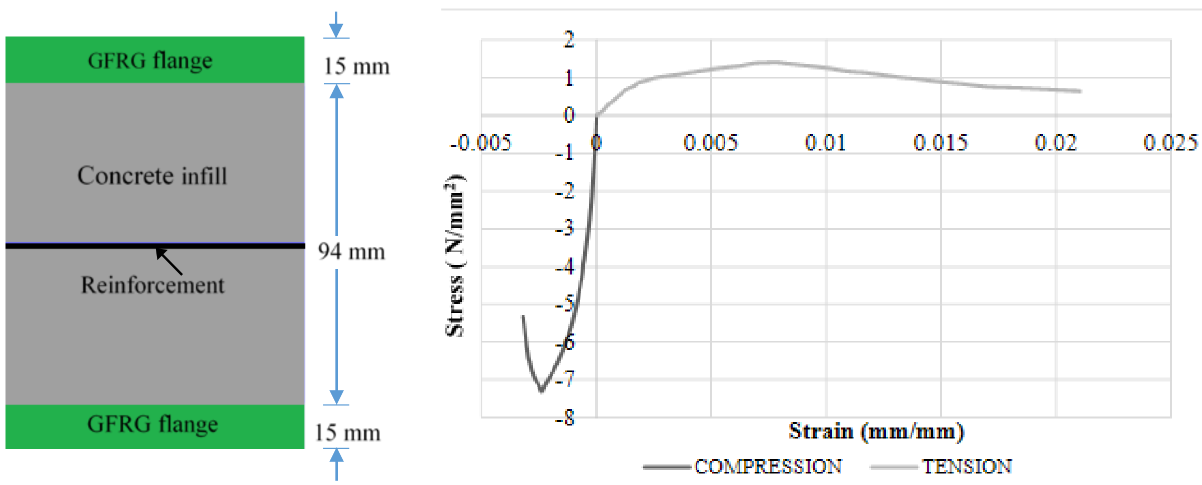



Fig. 8 – a) Modelling of GFRG wall as layered shell element b) Stress – strain curve for GFRG

The analysis was done on a representative bay of the case study building as performing time history analysis on the entire building was not viable. The response was studied for all the selected ground motion histories. The results are summarised in Table 2. It was observed that the maximum shear demand for all the walls are well within 60 kN/m which is the unit shear carrying capacity of infilled GFRG walls as specified in the GFRG design manual [9].

Table 2 Results of time history analysis

| **Earthquake** | **Original max (g)** | **Matched max (g)** | **Column** | | **Beam** | | **Avg. wall shear** | **Δ** | **Drift** | **Base shear** |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | **Outer** | **Inner** | **Shear** | **BM** | | | | |
| | | | **kN** | **kN** | **kN** | **kNm** | **kN/m** | **mm** | **%** | **kN** |
| **Array** | 0.312 | 0.177 | 19.16 | 21.97 | 52.60 | 25.35 | 10.26 | 4.88 | 0.027 | 126.2 |
| **Century** | 0.222 | 0.126 | 14.19 | 16.55 | 43.98 | 18.41 | 7.69 | 4.95 | 0.027 | 94.58 |
| **Lucerne** | 0.648 | 0.368 | 9.99 | 12.02 | 37.32 | 12.95 | 5.53 | 2.78 | 0.015 | 68.06 |
| **Newhall** | 0.565 | 0.322 | 45.71 | 49.99 | 153.72 | 62.44 | 23.69 | 15.2 | 0.084 | 291.39 |
| **Oakwhalf** | 0.843 | 0.480 | 32.75 | 35.80 | 108.79 | 44.26 | 16.97 | 12.6 | 0.070 | 208.7 |
| **Smonica** | 0.261 | 0.148 | 20.39 | 23.31 | 54.69 | 27.02 | 10.90 | 5.59 | 0.031 | 134.02 |
| **Altadena** | 0.447 | 0.254 | 26.80 | 29.30 | 89.41 | 36.35 | 13.89 | 8.16 | 0.045 | 170.8 |

The maximum and average displacements observed were 15.2 mm and 7.7 mm respectively. This implies the greater stiffness of the wall sections. The variation of inter-storey drift and displacement at each storey level along the height of building are represented in Fig. 9. The storey drift is very less in the GFRG wall region due to the very stiff shear wall sections compared to drift in OGS region.

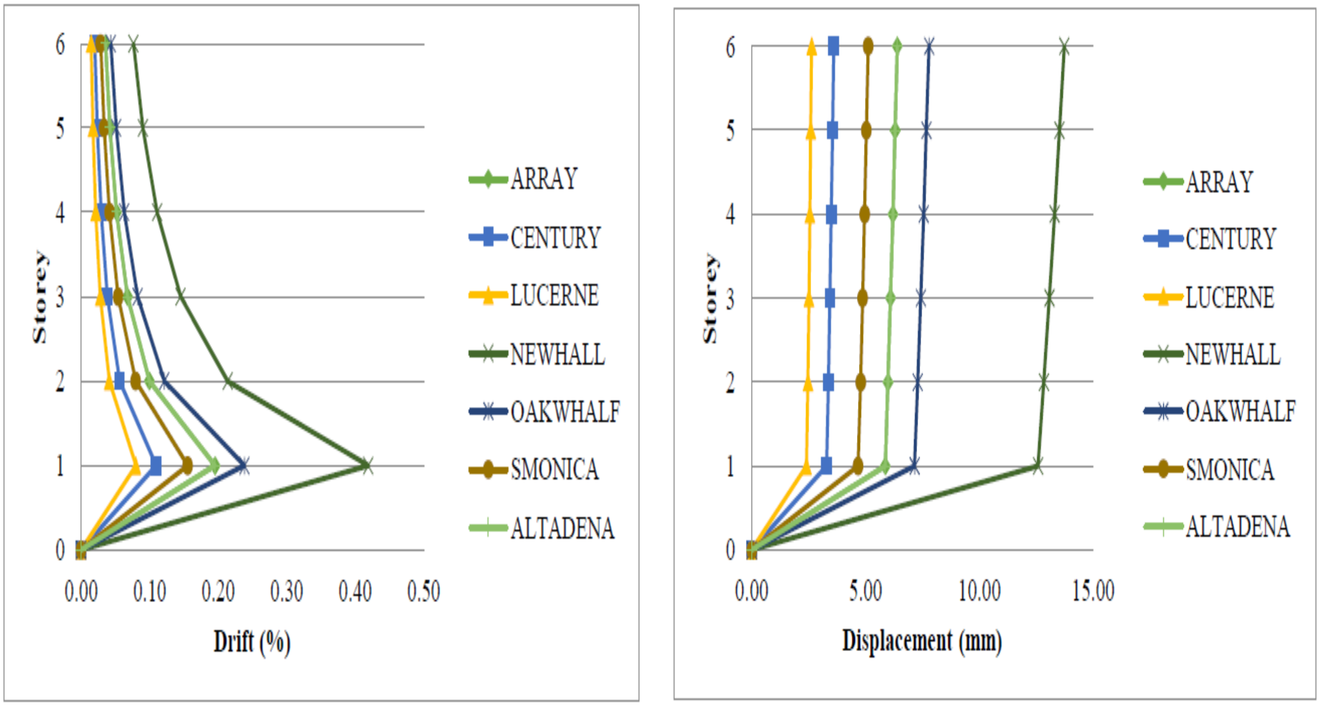
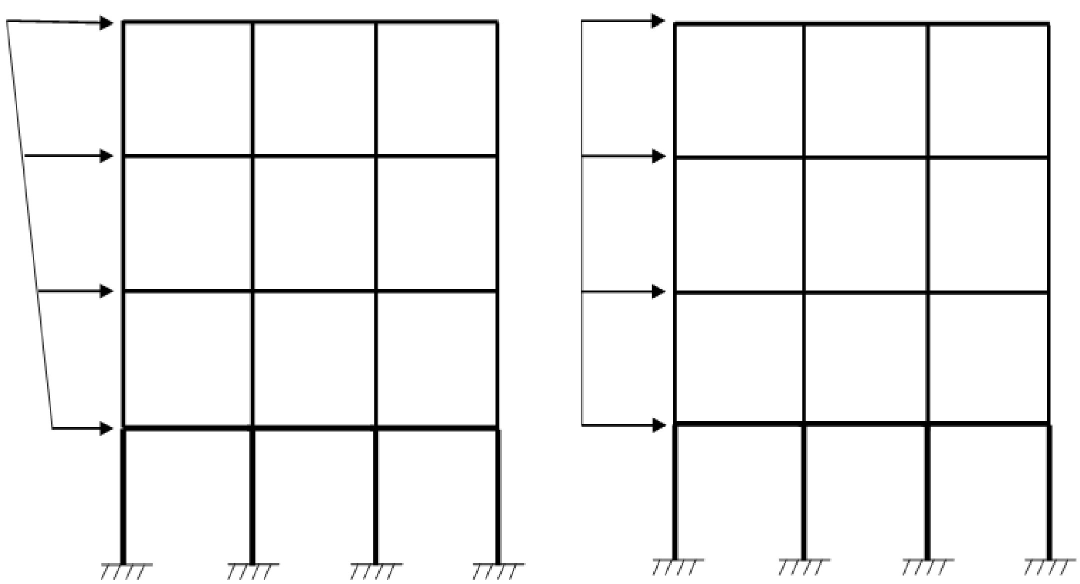



Fig. 9 – Variation of inter-storey drift and lateral displacement along height

Based on the displacement profile, it is proposed to consider a 1D push (as shown in Fig. 10) rather than the codal equivalent static load pattern push for the analysis of these buildings.



a) Load pattern based on code b) Proposed 1D load pattern

Fig. 10 – Load pattern for pushover analysis

The displacement values obtained from the analysis was also compared with elastic displacement calculated by assuming double curvature of columns. This is depicted in Figure 11. The difference can be attributed to the nonlinearity considered in the analysis.

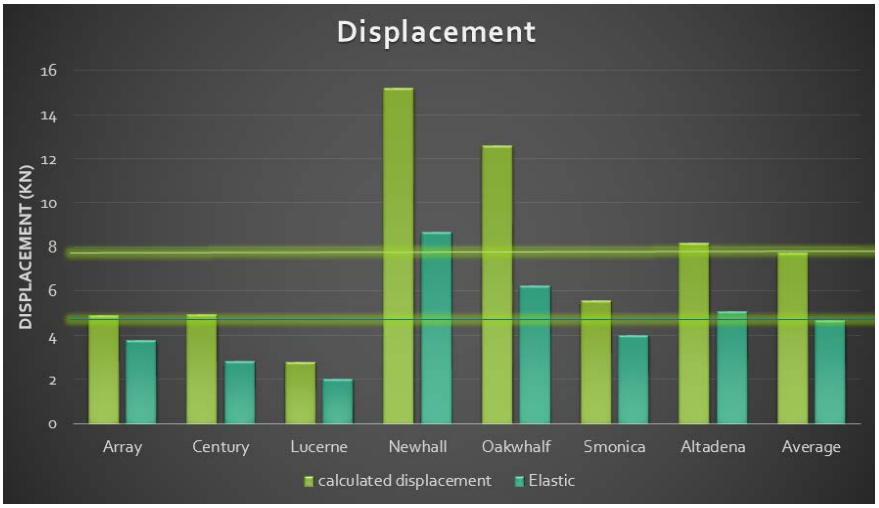



Fig. 11 – Comparison of displacement from analysis with elastic displacement

## 5. Conclusions

The performance of GFRG OGS systems under vertical and lateral loads was evaluated in the present study. In the finite element analysis, it was observed that the gravity loads are being transferred by arching mechanism through walls to columns and resulted in very less force response in beams. Based on the nonlinear time history analysis performed on a typical bay of the case study building, it was concluded that a one dimensional push is more appropriate than codal equivalent static load pattern for performing pushover analysis. Also, it is found that the estimated drift from the numerical study is lesser than the maximum permissible drift limit. Hence the system behaviour is basically dictated in terms of strength based limit state.

## 6. References

[1] Wu, Y. F. and M. P. Dare (2004) Axial and shear behavior of glass fibre reinforced gypsum wall panels: Tests, Journal of Composites for Construction, ASCE, 8 (6): 569-578.

[2] FEMA 273 (1997) NEHRP Guidelines for the seismic rehabilitation of buildings. Federal Emergency Management Agency, Washington DC, USA.

[3] FEMA 356 (2000) NEHRP recommended provisions for seismic regulations for new buildings and other structures. Federal Emergency Management Agency, Washington DC, USA.

[4] ATC 40 (1996) Seismic evaluation and retrofit of existing concrete buildings. Redwood City (CA): Applied technology council.

[5] FEMA 440 (2005) Improvement of Nonlinear static seismic analysis procedures. Federal Emergency Management Agency, Washington DC, USA.

[6] FEMA P695 (2009) Quantification of building seismic performance factors ATC-63 Project report.

[7] Sreenivasa R L, Strength and behaviour of Glass Fibre reinforced gypsum wall panels. Ph.D. Thesis. Indian Institute of Technology Madras, India, 2009

[8] Takeda, T., M. A. Sozen, and N. N. Nielson (1970) Reinforced concrete response to simulated earthquakes. Journal of the Structural Division; ASCE, 96: pp2557–2573.

[9] GFRG/Rapidwall Building Structural Design Manual, by BMTPC and IIT Madras, India

[10] Dixon David, Seismic Performance of Open Ground Storey GFRG Buildings. M. Tech. Thesis. Indian Institute of Technology Madras, India, 2009

[11] SAP 2000 NL Manual, Integrated software for Analysis and Design, computers and structures, Inc., Berkeley, California, USA.

[12] ETABS 2013 Manual, Integrated software for Analysis and Design, computers and structures, Inc., Berkeley, California, USA.