

Structural Performance of Innovative Precast Hollow Concrete Walls for Buildings

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ABSTRACT: Depleting fossil fuels and the stringent conditions being imposed by the global community to reduce greenhouse gas emission, construction industry will be pushed to innovate energy efficient building systems. The conventional concrete building units are energy intensive firstly in terms of raw material manufacturing secondly during operation. Further, these buildings require extensive site preparation and construction time. Several ways have been proposed to tackle the problem of energy efficiency of buildings and each of those has shortcomings. The climate of Saudi Arabia is characterized by hot and arid because of which residential energy consumption for cooling is very high. A new hollow precast structural wall system is proposed which has multiple benefits including, energy efficiency and economy. In this paper, the structural evaluation of a two-storied residential building using the new wall system is presented. The building with hollow precast wall panel as structural load bearing walls, subjected to gravity, wind and seismic loading was investigated using finite element modelling. In-situ thermal performance of the constructed housing unit was investigated in addition to the full-scale load testing. From the results of structural evaluation, it can be concluded that the proposed energy efficient wall units offer a robust construction system for buildings and provides strong resistance to lateral and gravity loadings. Additionally, these wall units coupled with the hollow core slabs provide a fast track construction technique.

1 INTRODUCTION

In the future as the global requirement for the construction of new houses increases, there will be increasing demand for the concrete worldwide. Primary material utilized in the production of concrete is Portland cement. The production of Portland cement used in the construction industry is unfortunately associated with the emission of greenhouse gases such as CO₂. Every ton of Portland cement production contributes about a ton of CO₂ both directly, when calcium carbonate is burnt in the kilns, producing lime and carbon dioxide (CO₂) and also indirectly through the use of energy in the kilns, particularly if the energy is sourced from fossil fuels (Mehta 2012, Malhotra 2012). Therefore, the conventional concrete building units have multiple shortcomings in terms of energy consumption starting from the manufacturing of raw materials for the building components to the energy requirements during operation. In addition, these precast buildings require extensive site preparation, transportation and construction time.

To overcome these shortcomings associated with the conventional buildings, several methods have been proposed and utilized in the past. These include lightweight aggregate concrete and autoclaved aerated concrete (AAC). Also triple glazed glass façade and low volatile organic compound paints along with the low emission carpet tiles have been utilized in view of curtailing energy consumption of buildings. However, each of these methods has their own shortcomings. For instance, production of autoclaved aerated concrete requires special manufacturing plant in addition to its affordability. Also, AAC blocks are predominantly used to construct non-load bearing walls. Lightweight aggregate concrete (LWC) requires special aggregates and the strength of such a concrete is largely proportional to its unit weight. Generally, the strength of the LWC is much lower than the conventional concrete.

Owing to the depleting fossil fuels and the threat of global warming, lowering our energy consumption is an essential survival strategy. Minimizing the usage of materials, which are

energy intensive during manufacturing, transporting and installation, should be the way forward. Eco friendly design methodology can further reduce energy consumption by lowering energy inputs for heating, cooling and lighting.

A hollow precast structural wall system is presented in this paper which has multiple benefits including, energy efficiency, economy and ease in construction and adoption. The structural performance of the proposed wall system was investigated by developing a 3-D finite element model of a two-storied residential building, using the hollow precast wall panel as a structural load bearing walls and hollow core slabs as floor system. The structure was subjected to gravity, wind and seismic loading. The in-situ thermal performance of the building unit constructed using proposed hollow precast wall panel was also evaluated and results presented.

2 DESCRIPTION OF HOUSING UNIT WITH HOLLOW CORE WALL PANELS

The hollow core structural wall panel has three vertical openings along the height of the panel and a dual parallel 70 mm thick solid element separated by a 160 mm cavity. These panels have an interlocking system to connect vertical joints of adjacent panels. Further, the wall panels also have vertical reinforcement projecting out at each level to connect the two walls one upon the other. The width of these panels ranges between 300 mm to 1550 mm depending on the architectural requirements with a standard height of 3200 mm and overall thickness of about 300 mm. The isometric view and cross section of the typical wall panel is shown in Figures 1 and 2. The structure has ground, first and penthouse floors. Ground floor precast wall panels are connected to the cast in place strip footing with dowel bars, by grouting up to a height of 250 mm. Figure 3 shows the construction stage where panels are being erected. Precast wall panels are tied together by horizontal reinforced cast-in place beam at each floor level along with the hollow core slabs acting as rigid diaphragms. The floor framing system also consists of transfer beams for some of the precast wall panels that do not continue from foundation to upper level. A model of the finished house is shown in Figure 4. The model house was constructed in 16 weeks time and its performance was investigated.

3 MODELING OF STRUCTURAL SYSTEM

The structure was modeled with 3-D load bearing precast walls and strip foundation as plate finite elements and hollow core slab as beam elements acting as floor framing. Figures 5 and 6 shows the side and top views, respectively, of the modeled precast wall panel showing the horizontal and vertical openings. Precast wall panel has been modeled as fabricated in the factory with 3 horizontal openings along the height of the panel and dual parallel 70 mm thick plate finite elements separated by a 160 mm thick vertical cavity along the width of the panel as described in the previous section.

4 PRIMARY LOADS AND LOAD COMBINATIONS

The 3D finite element modeled structure was subjected to 11 primary load cases, including dead, live, wind and seismic loads and 49 combinations of primary loads. A wind speed of 166 km/h, seismic factors including short period of acceleration (S_s) of 0.20 and 1 second acceleration (S_1) of 0.055 prevailing in Riyadh according to Saudi Building Code 301 was adopted in the analysis (Saudi Building Code 301, 2007).

5 IN-SITU MEASUREMENTS FOR THERMAL PERFORMANCE

The in-situ thermal performance of the building constructed using the hollowcore precast wall panels was evaluated by conducting thermal measurements on the two exterior walls. The exterior walls on North and East sides were instrumented from inside as well as outside with thermocouples, heat flux sensors and air temperature sensors. The monitoring was carried out

over a period of two months during a typical summer climate of Saudi Arabia. The standard procedures specified in international standards were adopted for the in-situ measurement of the thermal transmittance and resistance of the walls.

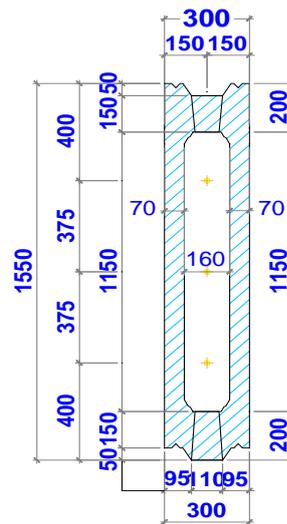
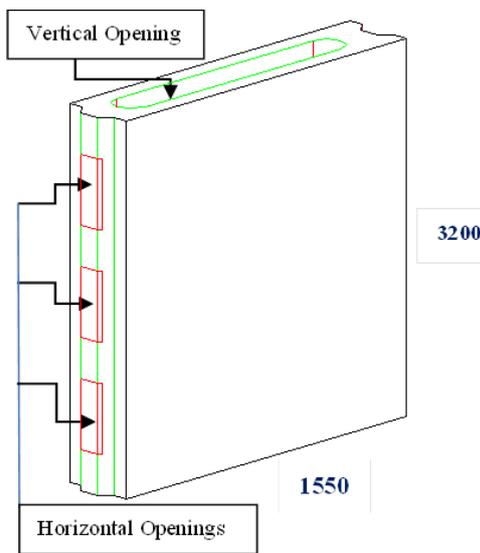


Figure 1. Isometric view of hollow wall panel

Figure 2. Cross section of hollow wall panel.



Figure 3. Stages of construction.

Figure 4. Completed and finished model house.

6 RESULTS AND DISCUSSION

6.1 Structural Performance

Figure 7 shows the layout of combined ground, first and second floor precast wall markings with the grid lines along the horizontal and vertical directions, which will be referred in the discussion of results. The results of some important walls are presented in this section. Based on the analysis results, higher stresses are associated due to combination of dead, live and wind loadings. Riyadh is in very low seismic zone as per SBC-301 hence it does not govern. Figure 8 and 9 illustrates the stresses S_x and S_y in the exterior wall panels along the grid line 1 (Figure 7) for the load case $DL+LL+LR+WLX$. The vertical stresses are compressive in nature with lower stress at the top increasing gradually towards the bottom. There is a stress concentration at the corner wall panels. Tensile stress of the order 0.26 MPa exists in the edges of the wall.

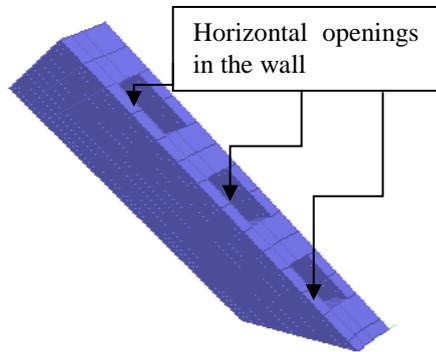


Figure 5. Side view of wall panel.

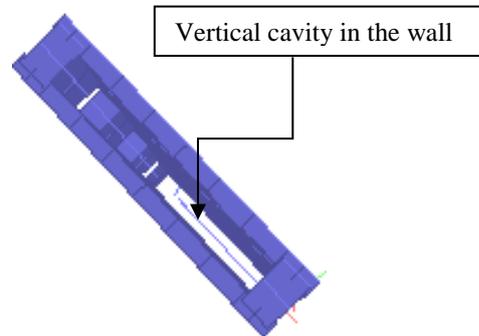


Figure 6. Top view of wall panel.

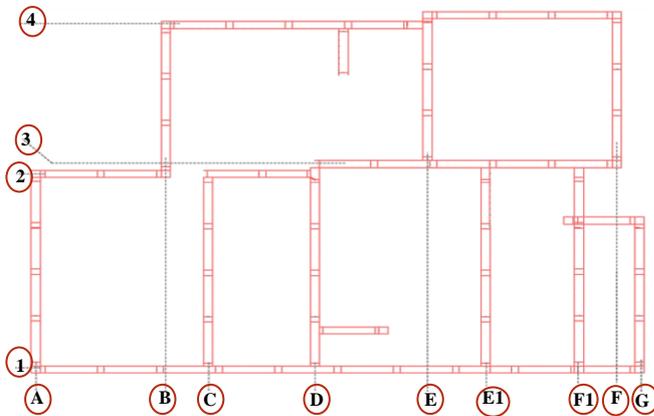


Figure 7. Combined ground, first and second floor precast wall marking layout with grid lines

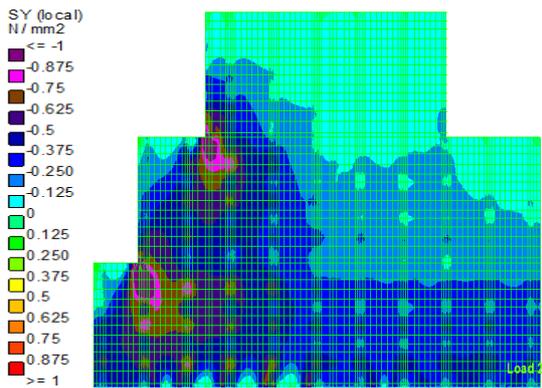


Figure 8. Plate stress contour (S_y) in the wall panels along grid 1 for load DL+LL+LR+WLX.

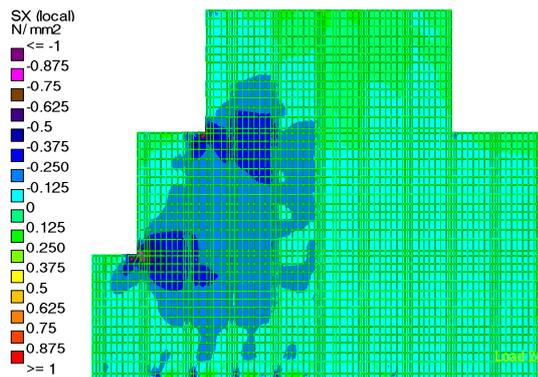


Figure 9. Plate stress contour (S_x) in the wall along grid 1 for loads DL+LL+LR+WLX.

Figures 10 and 11 show the stress contours S_y and S_x in the precast wall elements along the grid 1 for seismic load combination (DL+0.525EQZ+0.75LL+0.75LR). The stress S_y is compressive having a magnitude of -3.00 MPa and a localized tensile stress exists of about 1.25 MPa in the same direction. The maximum tensile and compressive stresses were observed in these plate elements in the x direction (S_x) were of the magnitude -1.45 MPa and 1.42 MPa, respectively.

The wall on grid 4 has a large number of openings. Significant compressive stresses S_y are present around the openings. Figure 12 and 13 shows the stresses S_x and S_y in the wall on grid 4

due to gravity and wind loads. Tensile stresses of small magnitude are present (both S_x and S_y) near the openings. The maximum compressive and tensile stress in the plate elements of the wall on grid 4 are -1.27 MPa (S_y) and 0.63 MPa (S_x), respectively. The magnitude of maximum and minimum principal stress is 1.46 and -2.73 MPa.

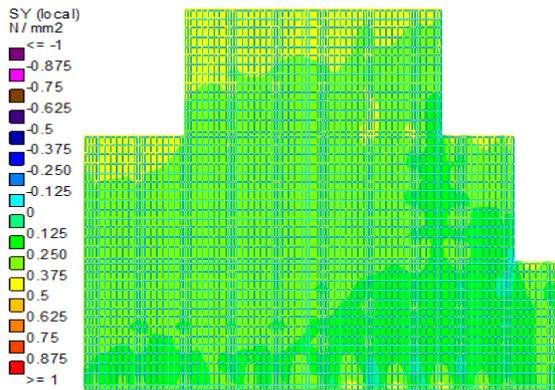


Figure 10. Plate stress contour (S_y) in wall panels grid 1 for loads $DL+0.525EQZ+0.75LL+0.75LR$.

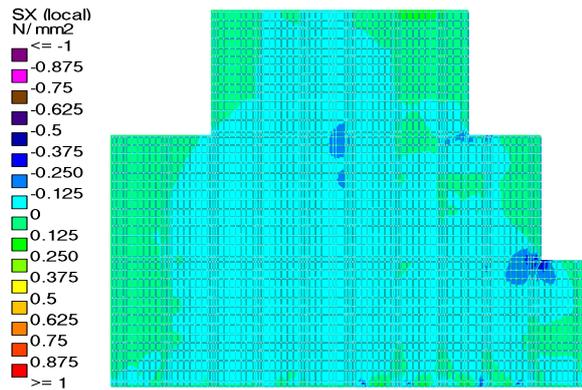


Figure 11. Plate stress contour (S_x) in wall panels grid 1 for load $L+0.525EQZ+0.75LL+0.75LR$.

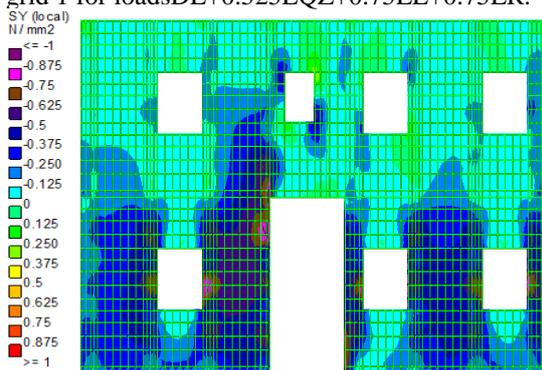


Figure 12. Plate stress contour (S_y) in the precast wall panels along grid 4 ($DL+LL+LR+W LX$).

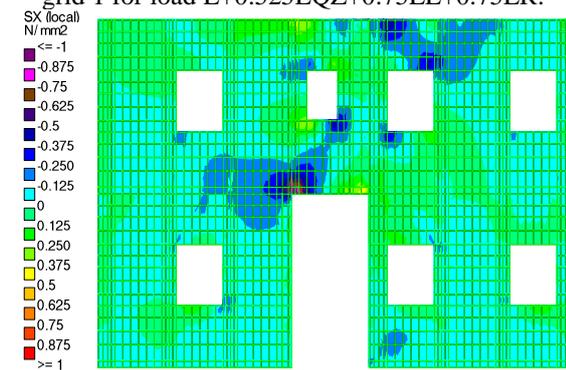


Figure 13. Plate stress contour (S_x) in the precast wall panels along grid 4 ($DL+LL+LR+W LX$).

Figures 14 and 15 show the stress contours for S_y and S_x in the wall elements on grid A. The stress S_y is mostly compressive with a maximum value of -0.88 MPa, with low tensile stresses. The stress contours S_x show low magnitude tensile stress. The maximum and minimum principal stresses ($+1.20$ and -1.65 MPa) are significantly lower than the allowable values.

The wall on grid line B has significant tensile stress at the lower left corner having a magnitude of 0.95 MPa in y -dir. Other than that the stresses are generally compressive with magnitudes around -2.04 MPa. Figure 16 shows the stress S_y in the wall on grid B. The stress S_x in this wall is shown in Figure 17. The stresses both compressive and tensile are low, ranging from 0.2 to 0.4 MPa in the x -direction. The maximum and minimum principal major stresses in the plate elements of wall along the grid line B are of the magnitude 2.29 and -3.87 MPa, respectively.

The stress envelope in the building shows maximum stress in the hollow precast wall panel is 3.27 MPa in compression and 1.53 MPa in tension. These stresses are substantially lower than the allowable stresses of 12.6 MPa in compression and 3.17 MPa in tension. There is a significant stress concentration at the corners and at the door and window openings. This is reported in several studies previously conducted (Saheb and Desayi 1990, Lee 2008, Ganesan et. al 2009). However, these values are lower than allowable compressive and tensile stresses. At

some locations near openings, loads are transferred through narrow solid wall elements, which resulted in high stress on the elements.

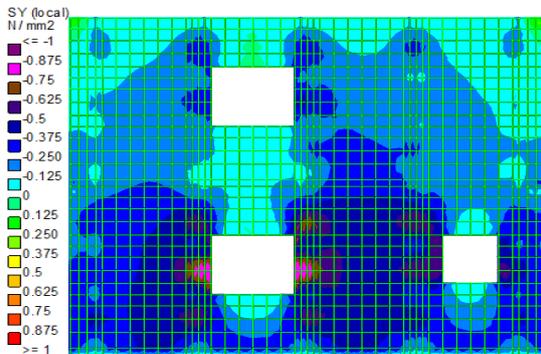


Figure 14. Plate stress contour (S_y) in the precast wall panels along grid A (DL+LL+LR+W LX).

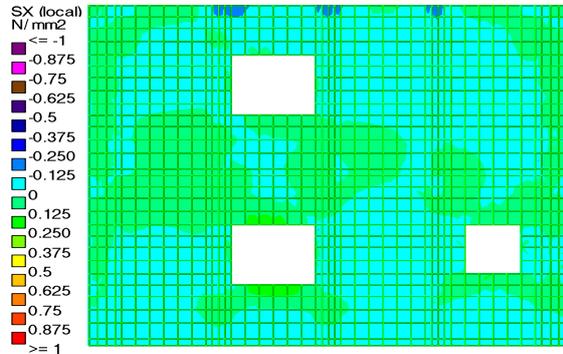


Figure 15. Plate stress contour (S_x) in the precast wall panels along grid A (DL+LL+LR+W LX).

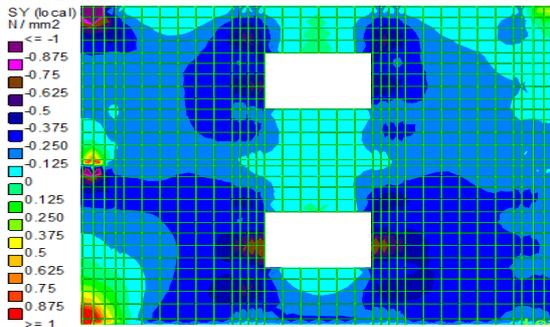


Figure 16. Plate stress contour (S_y) in the precast wall panels along grid B (DL+LL+LR+W LX).

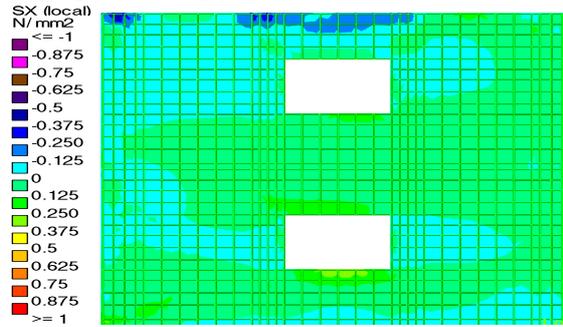


Figure 17. Plate stress contour (S_x) in the precast wall panels along grid B (DL+LL+LR+W LX).

The maximum bending moment for the whole villa in the x direction for the factored load cases ranges from -6.32 kN m/m to 4.80 kN m/m. For the y-direction it ranges between -10.24 kN m/m to 10.26 kN m/m. The maximum bending moment in the walls occur mostly in the transverse elements connecting dual parallel 70 mm thick plates together. Only minimum reinforcement is required in the longitudinal and transverse directions for the dual 70 mm thick parallel plate of hollow precast wall panel.

The maximum vertical displacement under service loads in the slabs is 3.8 mm which is less than the allowable. Maximum horizontal displacement under wind and seismic load combinations is 3.58 mm in y-direction which is small and within allowable limits. The displacement of the wall panels is small indicating that the hollow precast wall panels have the ability to resist lateral loads due to wind and seismic. A full-scale load test on a room constructed using the wall panels was carried out. After a sustained load of 12 months, replicating the load from five stories there was no settlement and cracking in the walls.

6.2 Proposed Connections

The construction and detailing of joints in the precast industry is the most important aspect, in order to transmit forces between the structural components. Joints provide strength and transmit lateral loads, predominantly due wind and seismic loading, to shear walls through the roof and floors acting as horizontal diaphragms. The diaphragm action transmits these applied horizontal forces to the foundation. In order to avoid progressive collapse and provide structural integrity, horizontal and vertical joints must be fully tied. The function of these ties is to transmit the

7 CONCLUSIONS

The structural model consists of plate finite elements representing hollow precast wall panels were used to develop a typical housing unit and subjected to 11 primary load cases and 49 load combinations according to ASCE. Based on the numerical analysis of the structure, the following are the findings:

- The maximum compressive and tensile stress under various load combinations in the plate elements of hollow precast wall panel are within the specified limits based on the compressive strength of 28 MPa.
- There is a significant stress concentration at the corners and at the door and window openings. However, these values are lower than allowable compressive and tensile stresses.
- At some locations near openings loads are transferred through narrow solid wall elements which resulted in high stress on the elements. It should be ensured that stress in these elements is kept within limits for various structures.

Based on the numerical analysis it can be concluded that the proposed Hollow core wall units provides a robust construction system for housing units and provides strong resistance to lateral and gravity loadings. The wall units coupled with hollow core slabs will provide a fast track construction technique. In addition, the proposed system, in terms of thermal performance, is either comparable or even better than the hollow blocks widely used in the construction industry.

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