Cyclic Pushover Behaviour on Industrialised Building System Lightweight Blockwork

Ding Kooi Kei, Abdul Kadir Marsono, Rosli Anang

[1]Faculty of Civil Engineering, Universiti Teknologi Malaysia, Malaysia

akadir@utm.my

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Abstract. The IBS is referred as advanced construction technique whereby construction components are fabricated in controlled environment and then assembled on site. It promotes faster, neater, safer, easier and cheaper construction works in future. Blockwork system is one of the IBS which has not commonly known in Malaysia. The key objectives of this research is to investigate the material characteristics and strength of lightweight concrete, in addition to study and compare performance and failure mechanism of lightweight concrete blockwork system in cyclic pushover experiment with numerical non-linear finite element analysis. 1:5 scale-downed sub-frame structure was built and performed cyclic pushover experiment and its results is used to make comparison with that in Finite Element Analysis, as well as IBS conventional concrete structure. From the research, IBS lightweight concrete blockwork system had relatively low strength and rigidity but more ductility and able to endure large deformation before ultimate limit state, when compared to IBS conventional blockwork system.

Introduction

IBS is a pre-fabricated system at which structural components are manufactured in factory, transported and assembled on-site. Not in doubt that it offers sustainability in term of reduced materials and wastage, reduced labour and machineries on-site, shorten construction process and the products are of controlled quality. To cope with current and future challenges, further researches and studies on IBS shall be always carried out in order to professionals as well as public develop level of confidence on implementation of this method in construction.

Problem Statement

Minimized usage of raw materials and optimized the use of construction materials, industrialization building production and minimized the post-maintenance cost of the structure are the key elements to achieve sustainable development in building industry. Gradually, non-technical issues such as economical issue and social development were started to be taken into consideration for sustainable development. However, the IBS implementation is still not popular in Malaysia construction field due to the poor and negative perception to IBS in the past.

Further researches and studies on IBS's failure mechanism and structural behavior should be increased so that the dark history will not be repeated and then the construction technique will be embraced by more construction professionals in Malaysia. In this research, failure mechanism of lightweight concrete blockwork system that can be assembled and dissembled with bolted connection when subjected to lateral loads is investigated.

Objectives

The objectives of this study are:

1. To obtain the material characteristics, properties and strength of lightweight concrete.
2. To obtain the performance and failure mechanism of IBS lightweight blockwork system in cyclic pushover analysis in laboratory test.
3. To study strength, ductility and failure mechanism of IBS lightweight blockwork system in numerical non-linear analysis.

Scope of Study

This research is carried out to study the structural behavior and failure mechanism of IBS blockwork system so that the IBS blockwork system can be implemented in residential building construction. A scaled down 1:5 model is assembled using autoclaved aerated lightweight concrete blocks and jointed using just a bolted connection. The model is loaded and tested in cyclic pushover test by applying lateral load monotonically up to collapse state. The robustness or ultimate strength of lightweight concrete blockworks is not investigated in this research. The experimental result will be compared with modelling results from numerical non-linear finite element analysis.

Literature Review

Industrialised Building System (IBS) is a construction technique in which the structure components are manufactured in a controlled environment either on-site or off-site, transported or assembled into a structure at construction site [1]. Malaysia had introduced IBS since 1960, however IBS survey 2003 indicated that only 15 percent of construction projects in Malaysia had implemented IBS method, and only 10 percent of complete projects involved IBS by 2006 [2]. The involvement of IBS in private sector is still at lack and conventional construction is still their preference due to: uniqueness of most of the new structure designs; low cost of unskilled foreign labour; lack of expertise in IBS; low IBS construction components available in the market; necessity of on-site specialized skills for assembly of components; lack of special equipment and machinery and deficiency of local Research and Development (R&D) on technologies.

Modular Coordination has been introduced as extension of IBS technology to facilitate IBS implementation to be more systematic and standardized in construction sector. It provides the general principles, room and storey height, and coordinating sizes for various building components including blockworks, dimensions of elements, components and spaces in building design. Modular Coordination is a coordination concept of dimensions and space, in which building components are dimensioned and positioned in term of basic module (1M) which is equivalent to 100 mm [3]. Standardization of dimension and space for building components have fully and effectively implemented IBS in construction. Furthermore, Modular buildings have been proven to be stronger than conventional buildings [4]. Each module is designed to withstand load independently and assembled together through connection to form stronger structural system.

IBS blockwork system is one of the building system in IBS technique developed by UTM inventor. Blockwork system with standardised properties, controlled quality and aesthetic in appearance have made the construction easier, faster, neater and safer. On the other hand, lightweight concrete is widely used in construction industry due to its characteristics of low density, low shrinkage, high heat resistance, high workability and high early strength. The application of lightweight blockwork system in main earthquake resisting components such as beams and columns has high potential due to its lightness, workability, thermal insulation properties and fire resistance. Its lightness reduces the seismic inertial forces with regards to other structural materials [5]. In order to study the seismic performance and resisting capacity of lightweight blockwork system, the response of mortarless AAC frame has been assessed through non-linear pushover analysis and finite element analysis in this research.

Buckingham Pi Theorem or similarity rule stated that the relevant system parameters must be identical and each dependent variable in model is proportional to the corresponding variable of the prototype by a scale factor [6]. In this research, the 1:5 scaled-down model from actual frame system is designed according to geometric similarity in Buckingham's Similarity Theorem. The model has proportional relationship to prototype in term of section dimension or fundamental unit of length, which will influence the test results in cyclic pushover analysis and also non-linear finite element analysis afterwards. The scale-down blockwork system is tested to verify and predict the actual plastic, ultimate and collapse behaviour of actual structural system when subjected to similar lateral loadings.

Beam-column joint is the most critical region in standard structure as there is the plastic hinge where vertical and horizontal shears meet and are being transferred to foundation. Seismic performance and structural integrity of a building are dependent on the ductility of beam-column joint [7]. In this research, corbel method is used to join the columns and beams of the frame modelling. Corbel is a bracket or cantilever block projecting from face of columns or other structural members to support a beam or other horizontal member. The bolt and nuts system creates an assemble-and-disassemble mode of construction as well as clamping the whole system of blockworks for strength against gravity and robustness against earthquake.

Earthquake load extend elastic state of the structure to inelastic behaviour that dissipates excess energy. However, structure with traditional design technique had been designed based on the assumption that buildings respond elastically to earthquake [8]. The seismic performances of IBS components need to be studied to predict its failure mechanism and the connection's behaviour at the maximum lateral load capacity. Non-linear static analysis based on the pushover analysis method has been widely used in practice to assess the seismic performance and inelastic behaviour of a structure more accurately. In cyclic pushover analysis, lateral loads are applied until a weak link of the structure is discovered. The failure mechanism of the model is observed and revised. A second iteration is then continued to study how the lateral load is distributed in the structure. With increment of the load and corresponding displacement, the accumulated base shear and top displacement are recorded. A graph of the load versus top displacement is obtained and plotted that would indicate any premature failure or weakness. With that pushover curve plotted, the structure's non-linear behaviour and progression of damage due to increasing ground motion can also be studied and analysed.

Finite element analysis (FEA) is a computerized method for predicting how a product reacts to real-world forces, vibration, heat, fluid flow, and other physical effects. Mesh generating technique divides a complex structure into small elements and study the behaviour of every single element for analysis purpose. A finite element model is constructed in ETABS software to predict the behaviour and failure mechanism of the blockwork system when subjected to gravity loads and lateral loads. By setting the material properties and dimensions of frame components, ultimate loads, maximum displacement and the cracking pattern of frame structure as well as its deformation shape associated to different displacements can be obtained from the analysis software through complex numerical analysis. However, computational modelling is a structural analysis under ideal condition. It assumes that the beams-columns joint and column component joints are in perfect bonding. Besides, assumption that there is no any imperfection when preparing model or original imperfection of materials.

Methodology

The main objective of the research is to study performance and failure mechanism of lightweight blockwork in push over test and non-linear finite element analysis. In addition, failure mechanism of lightweight concrete structure in cyclic pushover experiment was compared with that of conventional concrete structure as well. This research methodology consisted of 4 key activities: lightweight concrete blockworks preparation, material test on lightweight concrete samples, cyclic pushover experiment, and finite element analysis.

Lightweight Concrete Blockworks Preparation

The small model of IBS system was fabricated into 1:5 scale of full scale model, and a frame which includes two columns and two beams was produced from industrialized autoclaved aerated concrete which is 600 mm x 100 mm x 200 mm in size. Each column was formed by 4 T-shaped blocks, 4 L-shaped blocks, 5 rectangular blocks and 15 square blocks. Mortarless system was implemented in this research in which the blockworks were jointed using steel bolts and nuts, without reinforcements and mortar.

Lightweight Concrete Characteristic Test

Cube Compression Test. Compression test is used to measure the compression strength, F_{cu} of a concrete. Three cubes of size 100 mm was trimmed from the autoclaved aerated concrete blocks, and placed in the Compression Testing Machine. The load was applied at a constant rate of 0.2kN/m²/s until the concrete cube failed. The average maximum load of three samples was recorded as compressive strength, F_{cu}.

Young's Modulus. Young's Modulus, also known as modulus of elasticity is a measure of material's stiffness. It is used to estimate stress and the corresponding deflection of concrete structure within elastic limit state. The higher Young's Modulus represents the stiffer the concrete is. By assuming that the concrete cube samples had the same strain as the normal concrete Grade 20 at the yield strength (20N/mm²). By projecting 0.000931 mm/mm strain at 20N/mm² from standard concrete, a Young's Modulus line was drawn from the origin to the intercept of compression strength of lightweight concrete samples and its projected strain for lightweight concrete cube samples. The Young's Modulus was calculated from gradient of the stress-strain curve obtained from compression test.

Splitting Tensile Test. The high cracking susceptibility of concrete is due to the relatively low tensile strength compared to its compressive strength and also its brittle nature. The splitting tensile strength is essential in lightweight concrete member design to evaluate the shear resistance of concrete and to determine the maximum load causes cracking. There is no a standard test method for direct tensile strength determination of concrete. The indication of tensile strength can be obtained from splitting tensile test. A concrete cylindrical specimen of 200 mm x 100 mm diameter is placed horizontally between loading surfaces of Compression Testing Machine, and a compression force is applied diametrically until it fails. The tensile stress at which failure occurs is defined as the tensile strength of concrete.

Water Absorption Test. High durability is one of the priorities in material selection of construction field, and water absorption is considered as a relevant parameter in the concrete durability estimation. Water absorption value are used to determine the porosity of the concrete blocks which offers an indication of the potential for calcium chloride penetration problem leading degradation of concrete strength after construction. The test was carried out by immersing a 100 mm concrete cube in water for 2 days after weighting the initial weight of specimen in dry condition. After 2 days, surface of the concrete block was dried and it is weighted again. The water absorption, W by immersion is expressed by following equation:

$$W = \frac{saturated\ weight\ - dry\ weight}{dry\ weight}$$

Cyclic Pushover Experiment

Cyclic pushover analysis is conducted to evaluate the seismic displacement of the frame structure. This analysis provides a fundamental relationship of base shear versus lateral displacement of the structure from elastic state to the ultimate failure and predicts the seismic demands on inelastic response of the structure based on the test result. A scaled 1:5 model of IBS frame which consists of two columns and two beams, was constructed and tested to investigate the failure mechanism of the model when subjected to cyclic lateral loads. The results obtained from cyclic pushover test are load versus corresponding rooftop displacement, interlocking between blocks and degree of rotation of the structure. The cyclic pushover test is displacement-based, a which target displacement of 4 mm, 8 mm, 16 mm and 32 mm has to be achieved with amount of lateral load for each cycle respectively.

Finite Element Analysis
Integrated Building Design Software (ETABS) is one of the finite element software used for analyzing the building performance under gravity loads and lateral loads applied on a structure using dynamic analysis via stimulation. It produces the failure mechanism and pattern of a structure in ideal condition where the material is in perfect condition, the joints of structural elements are rigid and tightly bonded, and no any flaw in the system. The scaled model of frame structure was first modeled in ETABS software as same as that in experimental pushover test at which 1:5 scale to actual dimension was formed. It was followed by defining the section properties of each structural element based on the autoclaved aerated concrete properties. The virtual pushover test was then performed with loading on lateral loading plate to the structure. ETABS finite element analysis was performed by running stimulation and responding displacement results was obtained.

Results and Discussion

The results of material properties of lightweight concrete blockworks and experimental cyclic pushover test on 1:5 small-scaled frame model until collapse state was obtained. The material properties were used to define the lightweight concrete material, and the properties were inserted into ETABS software for Finite Element Analysis modelling. The results of cyclic pushover experiment was used to compare with results of non-linear Finite Element Analysis from ETABS software modelling, and compare with results of experimental pushover test on conventional concrete blockwork system in term of failure mechanism, deformation shape, crack pattern and stress in structure.

Material Characteristics
- Unit weight : 6.573 kN/m^3
- Compression strength : 4.021 N/mm^2
- Young Modulus, E : 4319 N/mm^2
- Tensile strength : 0.693 N/mm^2
- Water absorption : 0.596 or 59.6%

The lightweight concrete blockworks had small unit weight but lower compression and tensile strength than conventional concrete blockworks. Lightweight concrete blockworks had smaller Young's Modulus of elasticity than conventional concrete, which showed lightweight concrete was less stiff than conventional concrete. Besides, lightweight concrete had high water absorption characteristic which made it not suitable to be used in the high humidity or high water exposure condition.

Push Over Test
Load versus lateral displacement. This experiment was displacement-based pushover test, thus target displacement was set and load to reach the target displacement was recorded in experiment. In the first cycle, the structure was applied by lateral load using hydraulic jack to reach a roof top displacement of 4 mm and unloaded. The following cycles were achieved by pushing the structure to roof top displacement of 8 mm, 16 mm and 32 mm. The maximum displacement of the frame model can sustain from the pushover test was 42.43 mm at the loading of 6.8 kN. The target displacements of the frame system at both directions were measured by LVDT 1 and LVDT 2 at rooftop of the structure.

From graph of load versus lateral displacement, the lightweight concrete blockworks had deflected when load was applied incrementally, and it did not return to its original position (deflection = 0 mm) after the load was released. It indicated that the lightweight concrete blockworks had reached its inelastic region with loading of 0.30 kN in the first cycle and undergone permanent deflection. Rigidity of the frame system had decreased, so did strength of the frame system. In the following cycles, the deformation of frame system was more significant, larger displacement occurred at the moment of load released. Besides, less applied load was required to achieve the same displacement in the next cycle.

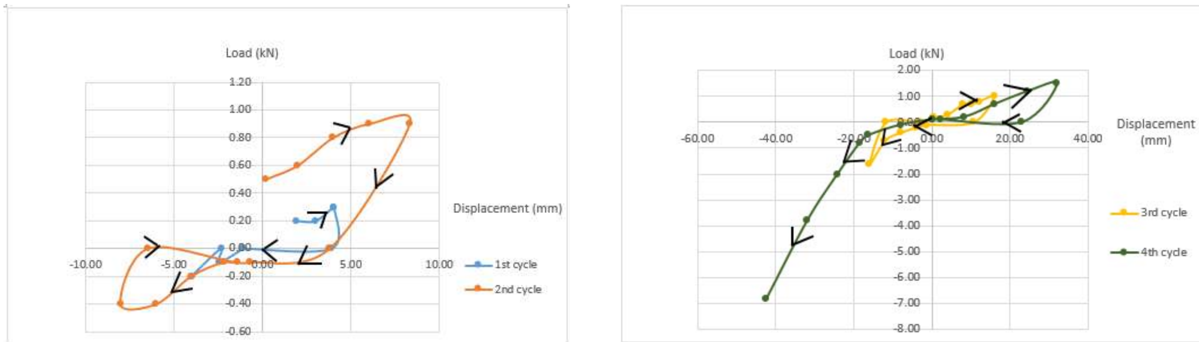

Figure 1: Graph of load versus lateral displacement for four cycles of push over test

Rooftop Rotation of Columns. During the first part of first cycle, a lateral load was applied to the frame model in order to reach target rooftop displacement of 4 mm to the left. The columns were displaced to left and caused rotation of 0.1º anticlockwise on both columns. And the lateral load was applied from right to the frame model during second part of first cycle, rotation of 0.1º clockwise was induced on both columns. In second cycle, rotation of 0.5º anticlockwise was induced on column B while rotation of 0.1º clockwise on column A. Larger degree of rotation on columns in second cycle compared to that in first cycle was mainly caused by the larger rooftop displacement of columns in second cycle, and the rigidity of frame model was decreased with formation of plastic hinge from first cycle.

The cracks were appeared first at the corbel connection and joints between beams and columns, and then on the blocks located at centre of columns. . It revealed that weak links was joints between blocks and load transferring point, and lateral force was transferred to columns as compression force. Surprisingly, lightweight concrete blockwork was able to endure very large displacement of 42.43mm due to its ductile property.

Structural Lateral Inclination. Laser measures named as 1, 2 and 3 were used to measure deflection of left column along its height while laser measures 4, 5 and 6 were used to measure deflection of right column. When lateral load was applied to one column, columns deflected in the same direction of the lateral load. The deflection of column also increased with cycles, which the rooftop displacement was rose with the lateral load. The displacement of column was a straight line (linear) until 290 mm height of column, column displaced as a curve shape beyond the height which has the similar deform shape as cantilever column. The increase of displacement along column height in each cycle was similar except for fourth cycle, as the frame system had reached its ultimate load and failed thus the deflection increased dramatically.

Figure 2: Deformation shape of model at collapse state

Finite Element Analysis

Load-Displacement relationship. The result of Finite Element Analysis were different in magnitude, but both of them have the similar deformed pattern which was linear relationship between applied lateral load and its displacement. When 0.3 kN of lateral load applied to the frame model, the lateral displacement of 0.1 mm to right was obtained, whereas displacement of 4 mm to right was obtained with the same loading in push over test. In second cycle, 0.5 mm lateral displacement was obtained when subjected to lateral load of 0.9 kN while 0.4 mm lateral displacement was obtained when lateral load of 0.4 kN was applied afterward. The theory of lose in strength and weak line deformation in the frame model caused less force required to achieve larger displacement was verified.

However, the lateral displacement of structure in Finite Element Analysis was much different when compared to that in push over experiment. It was because of ideal condition of materials and connection between blocks of the structure in software analysis, while there was imperfection and fracture of materials and block connection in reality. Porous nature of blockwork material caused void and microcrack in the material which leaded to lose in strength to resist against lateral load. Besides, the rough and uneven surface of concrete blocks due to manual trimming reduced interlocking between blocks and transfer of load in structure during push over experiment. Materials in software analysis were assumed to be in perfect condition and uniformly distributed strength over concrete blocks. The load was transferred and distributed proportionally to blocks. Hence, poor condition of structure in push over experiment had leaded to larger deflection of structure compared to in Finite Element Analysis.

From Figure 3, the largest deflection occurred in blue colour zone while smallest deflection was showed by purple zone. Finite Element Analysis showed that the deflection at right column A always larger than deflection at column B, and the maximum stress was located at joint connection of beam and column. Besides, the displacement increased along column height and became maximum at rooftop of column. The failure mechanism in Finite Element Analysis was similar to push over test.

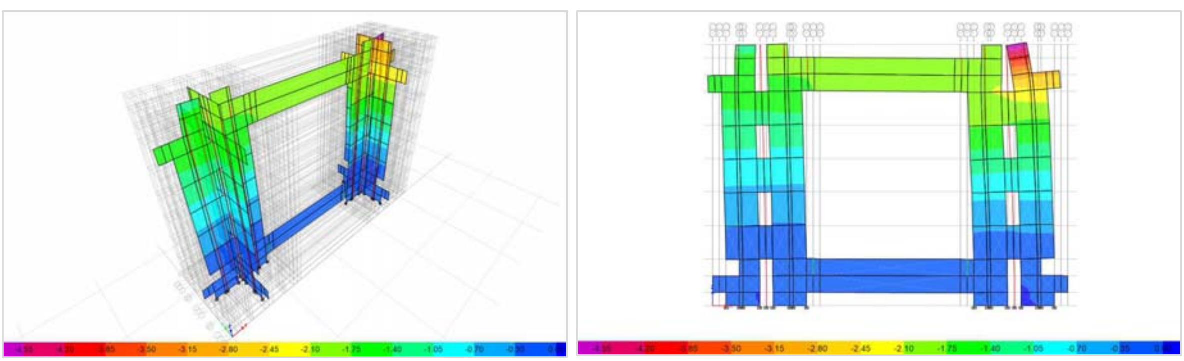

Figure 3: Lateral deformation shape of structure in Finite Element Analysis

Structural Lateral Inclination. Both experimental and Finite Element Analysis results showed inclination of columns in the structure as the blocks in the structure was bonded with each other as a frame structure through vertical clamping bolts. The bonding between blocks enhanced strength and rigidity of structure against lateral loads and it resisted the blocks from sliding out from structure. The steel bolts connection had also resist the sliding and bending by providing tensile strength to the structure. Hence, columns in the structure undergone bending effect and showed a degree of inclination against lateral load.

Stress in Structure. From Figure 4, the stress level was high at the four corbel connection between beams and columns, and also the second intermiddle blocks from top and bottom. The results could be correlated with the displacement generated from applied load, where the high stress location had the highest displacement and cracks was occurred at those location before others. The second intermeddle blocks experienced high stress due to load transferred from beams, to L blocks, then to those rectangular block which was located at the centre of columns. It proved that the load was transferred from beams to columns via the corbel connections and through centre of columns to the base.

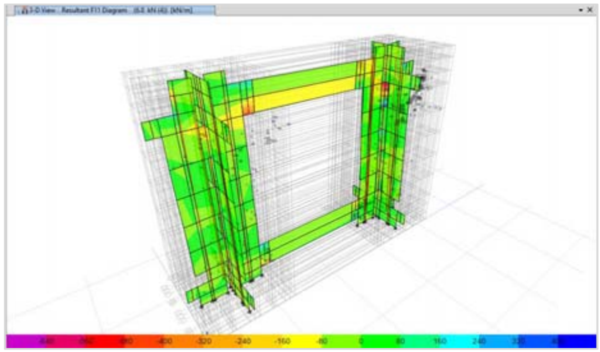

Figure 4: Lateral deformation shape of structure in Finite Element Analysis

Comparison of Conventional Concrete Blockwork and Lightweight Concrete Blockwork

Figure 5 had presented the difference in graph of load versus displacement between conventional concrete blockwork and lightweight concrete blockwork [9]. The graph indicated that larger force required to deform the conventional concrete frame than that in lightweight concrete frame. Conventional concrete blockworks was much stiffer and higher strength of 6.5 kN to restraint the target displacement of 4 mm in first while lightweight concrete blockworks required only 0.3 kN to achieve same displacement. The phenomena was also found in lightweight concrete blockwork system, it showed that both concrete materials had similar behavior and deformed shape but the lightweight concrete blockwork was less stiffer than conventional concrete blockwork. Lightweight concrete blockwork had smaller Young's Modulus of elasticity than that of conventional concrete.

IBS lightweight concrete blockwork endured more deformation than IBS conventional concrete blockwork at collapse state. It is because of conventional concrete had high strength but brittle nature while lightweight concrete had low strength but ductile nature. Lightweight concrete frame could deform more after yield point until total rupture, while conventional concrete was more rigid and high strength to resist against deformation.

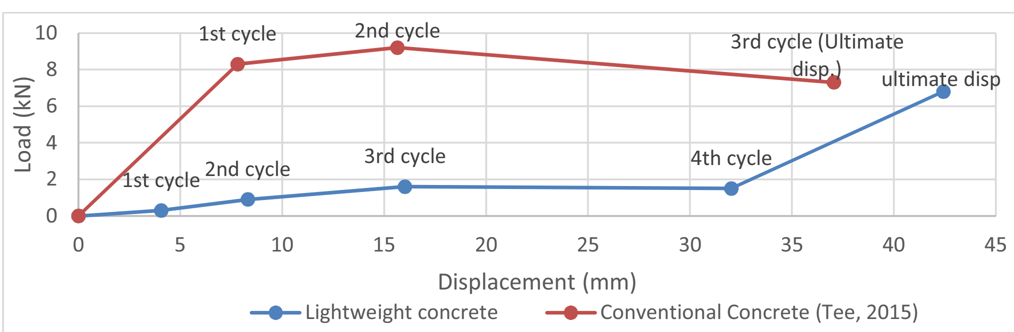

Figure 5: Graph of load versus displacement between conventional concrete and lightweight concrete IBS blockworks

Conclusion

This research presents the material characteristics and failure mechanism of IBS lightweight concrete blockwork system under push over test and Finite Element Analysis.

1. From the material tests which included compression test, Young's Modulus test, splitting tensile test and water absorption test, the lightweight concrete blockworks had small unit weight but lower compression and tensile strength than conventional concrete blockworks. Besides, lightweight concrete had high water absorption characteristic which made it not suitable to be used in the hot and humid condition.
2. From cyclic push over experiment, lightweight concrete blockwork system showed low resistance against lateral load as it required small load to achieve target displacement. It reached plastic state since the first cycle as it did not returned to original position after load was released and permanent deflection was formed. However, lightweight concrete structure proved that its ductile properties through endure large deformation before it totally failed.
3. It had lower strength but more ductile when compared to IBS conventional concrete blockwork as lightweight concrete blockwork needed less force to reach the displacement but able to endure larger deformation before failure.
4. Both structures from push over experiment and Finite Element Analysis performed similar failure mechanism with similar deflection shape and stress location but frame model from FEA performed much less displacement than model from pushover test at the same loadings. It was due to imperfection of material, friction and interlocking condition between blocks and uneven strength of blocks in experiment in contract to ideal condition of materials and bonding between blocks in Finite Element Analysis.

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