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SEISMIC PERFORMANCE OF SCALED IBS BLOCK COLUMN FOR STATIC NONLINEAR MONOTONIC PUSHOVER EXPERIMENTAL ANALYSIS

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Graphical abstract

Abstract

This paper presents the seismic performance of the down scaled 1:5 model IBS block column with non-linear static analysis. The aim of this research is to access the ultimate capacity and structural behaviour of the IBS block column. This paper demonstrates the theoretical prediction of the full-scale prototype strength based on scaling factors at non-linear state. Besides, this research investigates the ultimate shear capacity, stiffness, bolt strength, inter-storey drift and block separation for prediction of seismic performance levels. Concrete material properties, mix specification and steel reinforcement detailing for scaled model are tabulated in this paper. The methodology of this research begins with full scale prototype design, scaling to the small model and followed by the scaled model fabrication. Theoretical lateral load prediction associated with scaling factors are also performed. The experiment test was carried out on the assembled scaled 1:5 IBS block column with proper displacement measuring equipment on test rig and graphical capture tools. The data of roof top displacement with base shear capacity, inter-storey drift and gap separations were tabulated for discussions. The tested ultimate roof top displacement was 128 mm with 3.1 kN base shear. The calculated elastic stiffness of the IBS block column was 0.137 kN/mm, followed by yielding stiffness of 0.033 kN/mm and 0.014 kN/mm plastic stiffness. The significant inter-storey drift was due to cracking and crushing of column blocks edges. The measured maximum separation gap was 24.4 mm located at 340 mm height due to the rocking of the column. Based on seismic performance levels indicator from FEMA 273 & 356, the column was in the state of immediate occupancy with 21 mm roof top displacement and 1.7 kN base shear. The life safety is limited at 65.27 mm roof top displacement with 2.4 kN of base shear. All scaled down data was then reverted to full scale prototype capacity according with the respective scaling factors. It concluded that the IBS blockwork column is capable of resisting the seismic event without falling of the blocks that endanger the occupant life at the maximum credible earthquakes of 1.3 g horizontal spectral acceleration equivalent to X+ Mercalli's scale.

Keywords: Pushover test, industrialized building system (IBS), reinforced concrete block column, scaling factor, seismic performance level

Abstrak

Kertas kerja ini menerangkan tentang prestasi seismik model berskala 1:5 IBS kerja blok statik analisis secara tidak lelurus. Tujuan kajian ini adalah untuk menilai kapasiti muktamad sisi dan kelakuan struktur kerja block IBS. Ia juga meramal teori kekuatan model dari kekuatan prototaip skala penuh kepada model kecil yang berkelakuan tak lelurus. Ia meramal kapasiti maksimum ricih, kekuatan bol, sesar antara tingkat dan pemisahan blok dalam meramal tahap prestasi seismiknya. Ciri bahan konkrit, spesifikasi campurannya dan tetulang keluli kecil di perincikan dari model prototaip yang besar. Kaedah kajian ini bermula dengan rekabentuk tiang prototaip berskala penuh ke perincian model berskala kecil dan diikuti dengan teori ramalan kapasiti sisi. Pengujian dilakukan pada model skala 1:5 IBS kerja blok yang dilengkapi dengan peralatan pengukur anjakan dan grafik di atas rangka ujian. Data sesaran aras bumbung dan kapasiti ricih, anjakan antara blok dan pemisahan blok juga dibincangkan. Pada had muktamad, anjakan aras bumbung adalah 128 mm dengan keupayaan ricih 3.1 kN pada aras asas tiang. Kekukuhan anjal IBS kerja blok adalah 0.137 kN/mm diikuti dengan kekukuhan alah 0.033 kN/mm dan kekukuhan pastik sebanyak 0.014 kN/mm pada model ujian. Sesaran antara blok adalah disebabkan oleh retakan and penghancuran tepian blok-blok tiang. Pemisahan tegak antara blok pada aras 340 mm tiang adalah 24.4 mm semasa model dianjakkan. Berdasarkan petunjuk prestasi seismic FEMA 273 & 356, struktur model berada pada tahap penghunian segera dengan sesaran bumbung sebanyak 21 mm dengan daya ricih 1.7 kN pada aras penapak. Tahap keselamatan kehidupan adalah apabila anjakan bumbung sebanyak 65.27 mm dengan daya ricih sebanyak 2.4 kN pada aras penapak. Data model skala 1:5 kemudiannya dibesarkan ke saiz sebenar prototaip dengan menggunakan sekala pembesaran. Ia memberi kesimpulan bahawa IBS kerja blok mampu menentang gegaran seismik tanpa kejatuhan block yang membahayakan penghuni bangunan dengan pencapaian 1.3 g pecutan melintang bersamaan skala Mercalli's X+.

Kata kunci: Ujian penolakan, sistem bangunan perindustrian, tiang tetulang konkrit blok, faktor skala, tahap prestasi seismik

1.0 INTRODUCTION

Multiple disasters such as serious flooding in Thailand, typhoon in Philippines and strong earthquake in Haiti happened around the world in year 2010 to 2014 have caused more than thousands of victims become homeless and the worst of all, people were killed during the disaster [1]. The largest earthquake with magnitude of 8.6 on the Richter scale was happened in Indonesia recently in 11th April year 2012 had triggers panic and injuries [2]. The consequences of earthquake natural disaster are loss of human life, private properties and outbreaks of infectious diseases in the aftermath of the disaster. Earthquake history of Indonesia in year 2004 has recorded a devastated tsunami triggered by tectonic plate shifting in the seabed had killed more than 170,000 people who live in coastal city Aceh Indonesia [3].

Due to these unpredictable catastrophic consequences, a natural disaster safe house shall be innovated to protect human lives and minimize the rate of casualties from earthquake natural disaster. The term "safe house" is defined as a fortified room installed in public or private structures to protect inhabitants from natural disasters and other unpredictable treats [4]. The concept of the safe house or block house is innovated from safe room of hurricane shelter developed by Federal Emergency Management Agency (FEMA) in United States [5].

The new innovative block house with industrialised building system (IBS) as shown in Figure 1 has capabilities to assemble or disassemble quickly before and after the earthquake disaster [6]. The damaged structural components such as beam, column and wall can be replaced rapidly right after the disaster. The IBS block house can be constructed internally for new building or placed externally for existing building. The IBS structure components are made of reinforced concrete blocks and designed as robust structural system. The IBS structure can be expanded vertically up to double storeys or horizontally for more protected rooms based on house owner needs [7].

Hence, the aim of this research is to obtain the scaled 1:5 IBS block house column system under monotonic lateral force that could possibly cause by earthquake horizontal load. Of course earthquake is coming with oscillation and creates dynamic effect to building in terms of P-Wave (Primary) and S-Wave (Secondary). However, the S-wave scenario, intense ground movements horizontally acting with the total mass of the structure may create largest base shear force concentrated at column base. Hence, the objectives of this research are to identify the strength, behaviour and seismic performance levels of IBS block work column structural model through experimental monotonic static lateral push over test beyond the earthquake dynamic loads to extreme level.

The following section begins with the illustration of the history of brick system, followed by pros and cons of clay brick system. Concrete block work structural system was then introduced subsequently for seismic resistance structure. Apart from that, a brief introduction of Buckingham and similitude law for scaled model was stated in following section. The section ends with monotonic pushover test for determining the structural seismic performances of IBS block column.

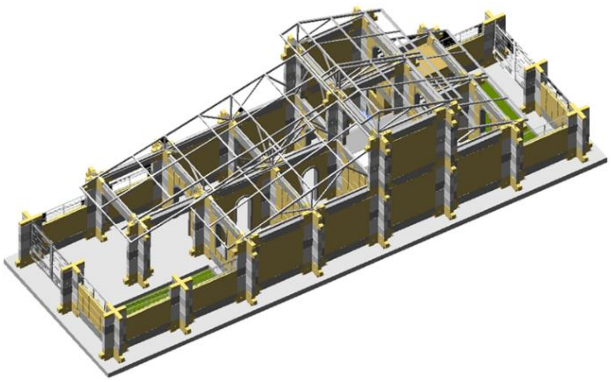


Figure 1 Innovative IBS Block House [6]

1.1 Brick System Structure

Back to 7000BC bricks are one of the oldest building materials discovered in southern Turkey. Bricks are excellent in resisting harsh weather conditions and absorbs any heat in day time as well as releases in any heat night time [8]. Besides, many historical structures such as St Basil Church in Moscow built in 1856, tallest Stupa (monument) in Sri Lanka built 1600 years ago and The Colosseum in Rome built over 2000 years ago are constructed by brick or masonry system.

These brick structures are wonders of the world and proven that brick is a durable construction material against unfavourable weather condition.

In modern age, bricks are still a popular construction material for various types of structures such as buildings, walls, bridges, foundations, arches, pavements and footpath. Bricks can be designed in different colours, shapes and orientations to form different surface designs for aesthetic purposes.

However, brick has disadvantages as well. Brick structure requires longer time to complete a construction and time consuming for mortar patching process.

Brick has extremely weak tensile strength. The brick product may break during the transportation and vulnerable toward massive vibration. Rough surface may promote growth of vegetation and cleaning the brick surface may not be easy.

Colour of the brick may change when aging as well. Brick structure cannot be used in high seismic zones [9]. This is because normal brick wall structure has poor seismic resistance, tensile strength, shear resistance, and ductility.

Mortar brick masonry is vulnerable in earthquakes, prone to cracks and often causes collapse of the whole structure [10]. Therefore, reinforced concrete block system comes into role to mitigate the weakness of masonry block system.

1.2 Concrete Block System Structure

Concrete blocks are pre-fabricated in factory under quality controlled environment. Pre-fabricated concrete block is excellent for a repetitive type of structure element such as column, beam and especially wall.

Apart from that, pre-fabricated concrete component under quality controlled environment can save cost and time, minimized human errors and size precision guaranteed. In construction phase, mortarless reinforced concrete block system or pre-cast system provides rapid erection via post tensioning technology to large numbers of concrete structure such as flyover, concrete pier, box girder and concrete beams for bridges [11].

Concrete block has ability to interlock with each other during installation and allow the reinforcement bars or tendons to be embedded in the block structures for post-tensioning technique [12].

The interlocking groove is excellent in distribute and resist seismic force across the structure element [13]. Besides, this interlocking block also provides hole for vertical and horizontal reinforcement to be embedded within it. Reinforced concrete block jointed together by post-tensioned tendons can be a shear wall element that resists seismic force effectively [11].

1.3 Buckingham and Similitude Theory

Small scale models have been frequently used by many researchers to investigate the behaviour of the full-scale model. However, there are always having issues between the ultimate capacities of down scaled model in comparison with full scale model.

Many researchers believe similitude theory may prove useful in investigating structural seismic performance and capacities through down scaled structural model. Due to insufficient testing facilities for full scale model, down scaled model was the only option and economically viable for performing an experimental test [14].

Similitude law is defined as a mathematical technique to deduce the theoretical relation of variable describing a physical phenomenon [15]. Similitude law requires dimensionally homogeneous relations in any equation.

The common fundamental dimensions in physical problems are length (L), force (F) or mass (M) and time (T). The relations are valid provided the equation is dimensionally homogeneous regardless of the units used for physical variables [15]. In short, the equations must be in equilibrium state.

Buckingham's *π* Theorem, any dimensionally homogeneous equation involving physical quantities. It can be expressed as an equivalent equation involving a set of dimensionless parameters [15]. For example initial equation $f(X_1, X_2, X_3, \ldots X_n)$ has X_i physical variables are equivalent to equation of dimensional parameters $g(\pi_1, \pi_2, \pi_3, \ldots \pi_m)$ with variables $\pi_i = X_{ka}, X_{lb}, \ldots X_{mc}$. In short, normal equations can be rewrite into other new equations for other application by changing its physical variables factor. Hence, with the combination of Buckingham's *π* Theorem and similitude law, the prototype structure (p) full scale and the scaled model (m) can be distributed into simple equation $\pi_i^p = \pi_i^m$.

Prototype and scaled model capacity is always influence scale factors S_i [15]. Scale factor S_i is defined as quantity in scaled model over quantity in prototype. The summary and useful quantified scale factors for engineering purpose are as shown in Table 1. To obtain scaled model capacity or prototype capacity, scale factors S_i in every equation must take into consideration. Scale factor *S* is related to dimensional scale factor such as height, thickness, width and length [16].

Table 1 Similitude relations for elastic model

Parameter	Scale factor
Dimension (h_p = Height or t_p = Thickness)	S
Area A_p	S^2
Volume V_p	S^3
Linear displacement U_p	S
Moment of inertia I_p	S^4
Frequency f	$S^{-1/2}$ or $(S/S_a)^{-1/2}$
Time	$(S/S_a)^{1/2}$
Density ρ_p	S_e/S_aS
Point load F_p	S_eS^2
Line load F_L	S_eS
Uniform distributed load P_p	S_e
Shear force V_p	S_eS^2
Moment M or Torque T	S_eS^2
Stress σ_p	S_e
Velocity V	$(S)^{1/2}$
Acceleration a	S_a or $S/S = 1$
Curvature C	$1/S$
Mass M	S_eS^2/S_a
Stiffness K	S_eS
Spectral Acceleration S_A	$S_eS^2/(S_eS^2/S_a)$

In structural material elasticity with scale factor S_e is equivalent to elasticity of $E_{prototype}$ over elasticity of E_{model} which defines the downscaled material strength effects [17].

Last but not least the scale factor in acceleration domain $S_a = [(1/S^{1/2})(S/S^{1/2})]$ = time multiplication with velocity dimension = 1.0 in constant gravitational environment [16]. Therefore, careful application of scale factors in conducting scaled specimen test to obtain structural behaviour and performance is feasible.

1.4 Monotonic Pushover Test for Structure

A monotonic pushover test was carried out in this research for IBS block structure system to access the structural ultimate capacity. An idealized structure with an assembly of components which can represent the nonlinear monotonic load-deformation characteristics is known as monotonic pushover analysis [17].

Pushover test is applying an invariant monotonic lateral load pattern towards the structure. The monotonic lateral load is applied together with the present of constant gravity load, dead load and imposed load. The test ends with large inelastic deformation occurs on the structure until the targeted strength is reached [17].

Monotonic pushover test is to push the structure to the expected maximum strength over recorded displacement. This test is known as force versus drift demand evaluation and component deformation assessment [17].

A maximum structural shear versus displacement capacity can be obtained through a standard monotonic pushover test. Apart from that, a basic seismic parameter such as inter-storey drift, column block separation, and internal steel tensile stress can be obtained as well [17].

This research was adapting non-linear static structural capacity analysis to assess the prototype structural performance levels. The non-linear static structural capacity analysis requires theoretical calculation of overall structural capacity from structural design codes such as European code 2 [18] and European code 8 [19] before conducting experiment.

Apart from that, downscaled model for laboratory test requires Buckingham laws and Similitude theory to support the theoretical capacity determination [20]. During the experimental test the structural model is placed on testing rig and tested beyond elastic limits.

Base shear force and roof top displacements must be recorded during the experimental test by linear variable differential transducer and load cells placed on the roof top of the test specimen.

The experimental test was stopped when the test specimen was having instability, loss of load carrying capacity and with excessive distortions [21].

Structural capacity curve can be plotted with adequate base shear versus roof top displacement data after the experimental test [21].

These analyses are performed to determine the structural capacity based on earthquake demand. Popular earthquake demand such as permanent drift, shear capacity, yield load, structural behaviours and performance levels can be obtained from tier 3 analyses [22].

2.0 METHODOLOGY

2.1 Specimen Specifications

Structural specifications of scaled 1:5 IBS column components are shown in Figure 2. Square blocks, rectangular blocks, T-blocks (small), T-blocks (big), L-blocks (small) and L-blocks (big) are used to construct IBS column for monotonic static pushover test.

There are six types of IBS block components were used to form column structure. All individual structural components were used to construct single storey column with 780 millimetres height, 240 millimetres width as shown in Figure 2. There are total of 28 components per column used to fabricate monotonic pushover test column specimen. The IBS reinforced concrete block column has four L-shape blocks placed on top of the column. The total width of the IBS column is 320 millimetres as shown in Figure 3.

Figure 4 shows the plan view of the IBS column block specimen with dimensions in millimetre. The L-block and T-block were built with double layer internal reinforcements. The spacing between both reinforcement was 20 mm. Square block and rectangular block have only single layer reinforcement located in the middle of each concrete block.

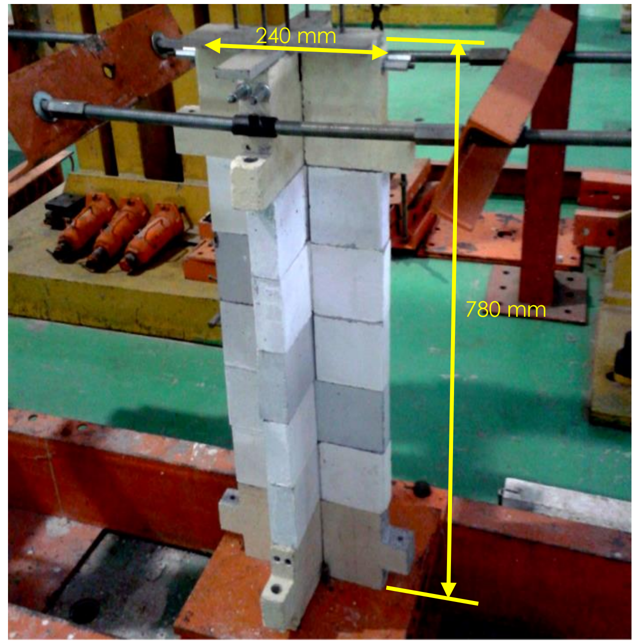


Figure 2 Isotropic view of IBS block column

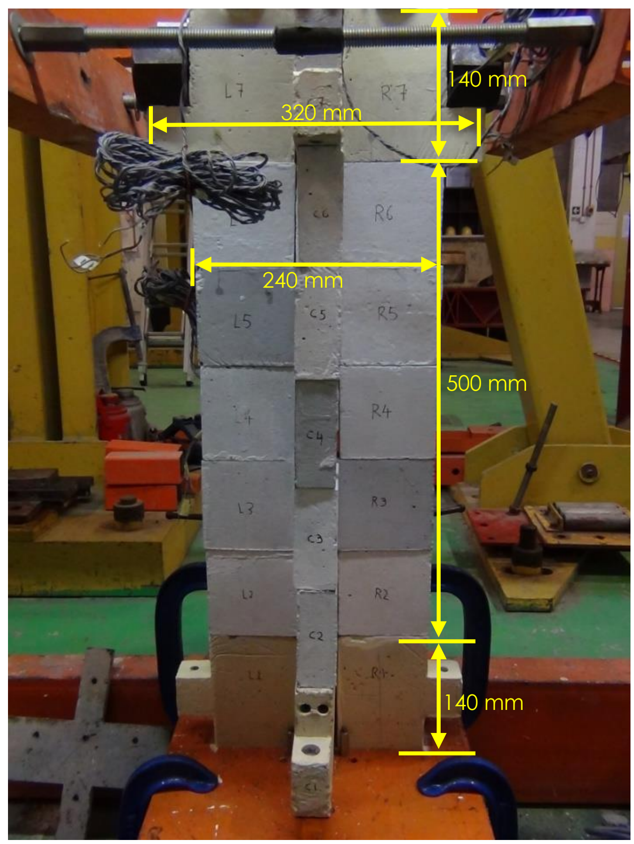


Figure 3 Front view of IBS block column

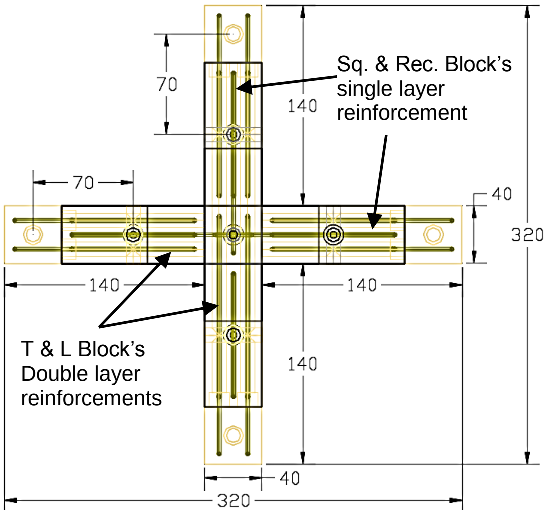


Figure 4 Plan view of IBS block column

Figure 5 shows the elevation view of the IBS block column. The arrangement of the internal reinforcements shown in the Figure 5 with minimal scaled 1:5 fire resistance concrete cover is 10 mm. The column bolt was placed in the middle of the of the concrete blocks to joint them together. Five of those bolts were eventually locked together by 10 mm thick roof top metal anchor plate to prevent them to fall apart.

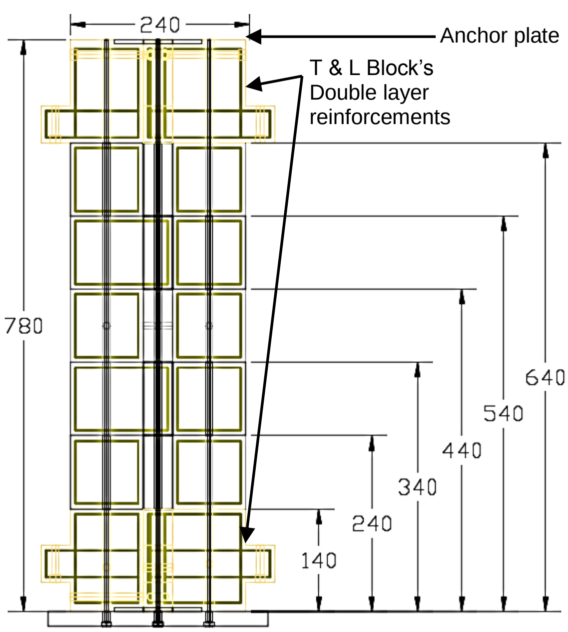


Figure 5 Elevation view of IBS block column

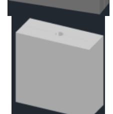
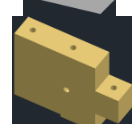
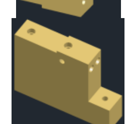
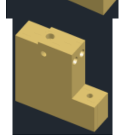
Those L-shape blocks are used to join the beam components. Five units of rectangular and fifteen units of square reinforced concrete blocks were placed in between L-blocks and T-blocks to form a 500 millimetres length of column specimen. The T-block and L-block have same height of 140 millimetres placed on top and bottom respectively. Similarly, each face of the column was aligned symmetrically.

The IBS concrete block column structure was clamped by 10 mm thickness column top plate and fastened by five 5 mm diameter bolts and nuts. In addition, all test specimens were locked on pushover test frame as fixed base connection.

Twenty-eight reinforced concrete block components were fabricated per column for this experimental test. The dimension and shapes of IBS reinforced concrete block components are shown in Table 2. Five rectangular blocks and fifteen square blocks were assembled to become IBS block columns. One T-Blocks (Big) and three T-Blocks (Small) were placed at foundation level connected to the test rig. Besides, T-Block is also function as support for ground beams.

One L-Blocks (Big) and three L-Blocks (Small) were placed on top of the four columns as support for the roof beams. The main function of L-Blocks is to provide supports for beam and slab. The column was fastened by five bolts with 5 mm in diameter clamped by column top steel plate with thickness 10 mm.

Table 2 Safe house structural component details

Description	Components Photos	Dimension (mm)	Required Components
Rectangular Block		100x140x40	5
Square Block		100x100x40	15
T-Block (Big)		180x140x40	1
T-Block (Small)		140x140x40	3
L-Block (Big)		180x140x40	1
L-Block (Small)		140x140x40	3
Total fabricated components per column			28

2.2 Reinforcements Specification

The full scale reinforced blocks were designed and checked with accordance to European code 2 [18]. By applying the Buckingham and similitude theory, the reinforcement and dimension of specimen were down sized to scale 1:5. Diameter of 3.0 mm and 5.0 mm reinforcements were used for components fabrication in this paper.

Reinforcement with 3.0 mm in diameter was used to fabricate square, rectangular, T and L blocks with specific dimension as shown in Figure 6. All dimensions shown in Figure 6 are in millimetre.

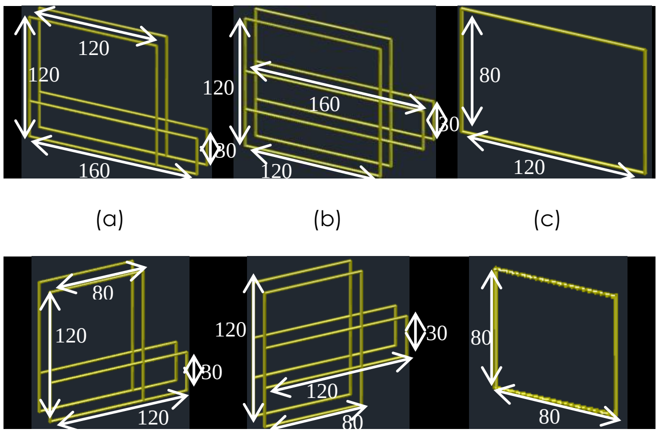


Figure 6 Reinforcement details (a) L-Big, (b) T-Big, (c) Rectangular, (d) L-Small, (e) T-Small and (f) Square [23]

Reinforcements for T-block, L-block, square and rectangular blocks were fabricated by several continuous loops and tighten by steel wire. All the components have concrete cover of at least 10 mm to protect the reinforcement from corrosion and fire attack.

The tensile strength of 3.0 mm diameter steel bar was tested in laboratory and the summary of the result is shown in Table 3.

Steel bar with 3.0 mm in diameter are having average yield load of 4.783 kN with yield stress of 676.7 MPa obtained from tensile test. The average ultimate load of 3.0 mm steel bar is 5.064 kN with maximum stress of 716.4 MPa.

The recorded average maximum strain is 0.03944 mm/mm with average modulus of elasticity of 217.4 GPa were obtained from universal testing machine equipped with extensometer.

Table 3 Material properties of 3 mm diameter steel bar

Reinforcement material properties	
Diameter (mm)	3.0
Average yielding load (kN)	4.783
Average yielding stress (MPa)	676.7
Average ultimate load (kN)	5.064
Average maximum stress (MPa)	716.4
Average maximum strain (mm/mm)	0.03944
Average modulus of elasticity (GPa)	217.4

2.3 Concrete Mix Specification

Concrete mix for grade C30 with super plasticizer admixture was shown in Table 4. The concrete mix was designed for characteristic strength of 30 N/mm^2 at 28 days with density of 2380 kg/m^3 based on the British Standard BS5328: Part 2: 1997 [24].

Water cement ratio for this mix is 0.42 and the mixture is fairy dry without super plasticizer. The workability of the mix improved after adding in the super plasticizer.

550 kg/m^3 of ordinary Portland cement was used to fabricate the components. 233 kg/m^3 of treated fresh water with room temperature was used in this concrete mixture.

511 kg/m^3 industrial grade fine aggregate (washed river sand) was used in the mixture. 1086 kg/m^3 of crushed coarse aggregate with size 3 to 5 mm in diameter was utilized in the concrete mixture.

The purpose of choosing such aggregate is to enable the fresh concrete evenly distributed in congested reinforcement such as T-block and L-block component.

Based on 1.2 % of cement powder, 6.6 kg/m^3 super plasticizer with brand Glenium ACE 388 was mixed with fresh concrete to improve the fresh concrete workability and early hardening strength.

Table 4 Mixture of concrete for IBS block house

Grade 30 Concrete Mix Per Cubic Meter	
Water / Cement ratio	0.42
Cement (kg/m^3)	550.0
Water (kg/m^3)	233.0
Fine Aggregate (kg/m^3)	511.0
Coarse Aggregate (kg/m^3)	1086.0
Density (kg/m^3)	2380.0
Admixture 1.2% (kg/m^3)	6.60

Total of twenty-one concrete cylinders with size 100 mm in diameter and 200 mm height were tested for concrete material compressive strength. The summary of tested result is shown in Table 5. There are eleven samples with 28 days strength and ten samples with more than 28 days were tested by concrete compressive testing machine. The average concrete compressive strength for 28 days strength and >28 days strength were 33.607 N/mm^2 and 53.827 N/mm^2 respectively. Based on the obtained average concrete compressive strength shown in Table 5, this grade C30 mixture with super plasticizer shows a very promising result to obtain desired strength by 28 days strength. Apart from that, the hardened concrete for C30 mixture can develop up to 53 N/mm^2 compressive strength after a year. This indicates the concrete mix is strong and reliable in the construction industry.

The weight of each concrete cylinder is between range 3.6 kg to 3.7 kg. However, the weight of the cylinder does not have direct influence of the concrete compressive strength. The strength of the concrete is depending on curing, compaction and mixing process. Proper fresh concrete heat detention within 24 hours is crucial because of chemical reaction for fresh concrete to hardening process is depending on temperature of the environment. Favourable temperature environment enables the concrete undergoes full chemical reaction and complete hardening or bonding of material to form high concrete early strength before water curing.

Table 5 Tested 28 days concrete compressive strength f_{cu} of grade C30 concrete

28 days strength (11 Samples)	
Average Weight (kg)	3.707
Average Maximum load (kN)	263.9
Average Maximum strength (N/mm²)	33.607
>28days strength (10 Samples)	
Average Weight (kg)	3.688
Average Maximum load (kN)	422.8
Average Maximum strength (N/mm²)	53.827

Total of fifteen concrete cylinders with size 100 mm in diameter and 200 mm height were tested for concrete material tensile splitting strength. The summary of the result is shown in Table 6. There are six samples with 28 days strength and nine samples with more than 28 days were tested by concrete tensile splitting testing machine.

The average concrete tensile splitting strength for 28 days strength and >28 days strength was 5.124 N/mm^2 and 4.775 N/mm^2 respectively. Based on the obtained average concrete tensile splitting strength shown in Table 5, the grade C30 mixture with super plasticizer have meet the desired tensile splitting strength which is approximately 10% (3.0 N/mm^2) of grade C30 compressive strength by 28 days.

The concrete tensile splitting strength was dropped to 4.775 N/mm^2 afterward (>28 days) which is normal. This is due to brittleness of the material, the tensile strength of concrete decreases while its compressive strength increases. Therefore, the concrete tensile strength is still strong and able to sustain the serviceability loads from cracking.

Table 6 Tested concrete tensile splitting strength f_t of grade C30 concrete

28 days strength (6 Samples)	
Average Weight (kg)	3.726
Average Maximum load (kN)	151.1
Average Maximum strength (N/mm²)	5.124
>28days strength (9 Samples)	
Average Weight (kg)	3.658
Average Maximum load (kN)	122.0
Average Maximum strength (N/mm²)	4.775

Based on the grade C30 concrete mix design, the concrete cylinder sample was tested by Universal Testing Machine (UTM). The concrete cylinder was equipped with two strain gauges from left and right of the treated flat surface. The strain gauges and 500 kN capacity load cell were connected to data logger to record the applied loads and strains throughout the experiment. The specimen was loaded until ultimate capacity and the modulus of elasticity for 28 days of concrete cylinder sample was 37496.91 N/mm^2.

2.4 Operational Frame Work

This research began with the column block full scale model design check by utilising European code 2 (2002) [18]. The design check was included with determine axial load and bending moment in the column, slenderness ratio check with clause 5.8.3.2.1, slenderness limit check with clause 5.8.3.1.1, effective length check with clause 5.8.3.2.2 and determination of required shear reinforcement with clause 9.5.3. Design check from European code 2 (2002) [18] in IBS column block was adequate in every aspect.

The following stage was down scaled 1:5 model fabrication. The downscaled model was complied with the dimensional space stated in Buckingham Law and Similitude Theorem. Buckingham's Law and Similitude Theorem were supported Nam *et al*. [14] and Andreas *et al*., [15], with their research experience in down scaled 1:5 models.

The casting work was performed accordingly and the concrete blocks and cylinders were place into curing tank carefully for 28 days of curing.

Next stage was theoretical strength prediction and assumption for block column. The experiments for monotonic pushover tests were only carried out after the theoretical strength prediction with the aid of FEMA 440 [26] for none linear static seismic analysis procedures.

Data analysis was carried out after the experimentation of monotonic static pushover tests. Discussions of the tested specimens were aided by structure behaviour, charts and figures obtained from experimental results. This research was concluded with the seismic performance level of the column component based on FEMA 273 [25], 274 [27] & 356 [21] guideline.

2.5 Theoretical Load Prediction

Theoretical strength prediction of the down scaled 1:5 concrete block work column ultimate capacity had to carry out before experiment test with the aid of Buckingham and Similitude Theorem.

The design check was started from European code 8 (2003) [19] with parameter such as: structure piled on bed rock location with shear waves velocity of 900 m/s and storey height of 780 mm. In order to use European code 8 to check the theoretical capacity, the structural weight determination shown in Eq. (1) has to be done first. Regular structural weight (W) determination is multiplication of density (ρ), area (A) and height of the structure (H) or volume (V) directly. Theoretical density of the reinforced concrete was 2500 kg/m^3 with cross sectional area of the full-scale block column 0.44 m^2, clear height of 3.2 m and 0.08 m^3 of corbel support were used for weight determination. The obtained weight of full scale structure was 3720 kg = 3.72 tons per column.

$$W = \rho \times [(A \times H) + V] \quad (1)$$

In fact, full scale weight of the column has to be down scaled before applied into any calculation. According to Buckingham and similitude theorem, the scale factor for density (ρ) = S_e / S, Dimension = S, Stress = S_e, Area = S^2, Mass = $S_e S^2/S_a$ and Volume = S^3 have to be used in right equation and condition.

Based on the full-scale block mass measured from laboratory, each full-scale column has ± 3.7 tons of mass which is close to theoretical predicted mass 3.72 tons. The downscaled model has mass of 32.5 kg per column. The material property scale factor, S_e due to mass scale factors S_eS^2 can be obtain by 3700 kg divided with 32.5 kg with scale factor S^2 = 5^2. Therefore, scale factor S_e = 3720 kg / [32.5 kg x (5^2)] equivalent to 4.5.

Determination of downscaled structural weight *W* in Eq. (2) was formed based on substitution of all dimensional scale factors from Eq. (1). Given the theoretical density *ρ* of the reinforced concrete was 2500 kg/m^3, cross-sectional area *A* = 0.44 m^2, clear height *H* = 3.2 m, volume *V* = 0.08 m^3 of corbel support, dimensional scale factor S = 5 and stress scale factor S_e = 4.5 due to full scale weight 3.72 tons per column versus downscaled weight 32.5 kg per column measured from laboratory. The calculated theoretical weight *W* Eq. (2) of the reinforced concrete block column scaled 1:5 is 33 kg which is similar with 32.5 kg measured from laboratory. Hence, stress scale factor S_e = 4.5 and dimensional scale factor S = 5 were adapted throughout the experiment theoretical prediction.

$$W = \left[\rho \div \left(\frac{S_e}{S}\right)\right] \times \left[\frac{(A \times H) + V}{S^3}\right] \quad (2)$$

Similar process of determining the weight of each floor was performed for full scale double storey block house is shown in Table 7. The weight determination began with calculation of characteristic permanent action G_k and characteristic variable action Q_k for each floor level. Characteristic permanent action G_k for roof level consists of slab and beam with 11.28 kN/m. For 1st floor level, the characteristic permanent action G_k consists of slab, beam and wall is 23.28 kN/m. For ground floor with beam and wall components, the calculated characteristic permanent action G_k is 14.4 kN/m as shown in Table 7. The characteristic variable action Q_k for each floor is 11.1 kN/m. The characteristic variable action Q_k is based on life loads distribution for residential house 3.0 kN/m^2 specified by European code 2 and multiplied with floor width 3.7 m length.

The load distribution was followed by injecting the design action with safety factor of 1.35G_k + 1.5Q_k. The roof level, 1st floor and ground floor have factored distribution loads of 31.88 kN/m, 48.08 kN/m and 36.09 kN/m respectively. The factored distribution loads were further multiplied with the total floor beam length 5.55 m measured from prototype structure in major and minor directions to obtain the maximum concentrated load acting upon each individual column. The calculated total loads distribution from beam to column for roof, 1st floor and ground floor were 176.94 kN, 491.35 kN and 749.50 kN respectively as shown in Table 7. Hence, the load distribution from beam to column of each floor was obtained.

By adding the factored self-weight of each individual column, the total axial force acting on floor column was obtained as well. Given the dimensional scale factor S = 5, Stress scale factor S_e = 4.5 and force scale factor of F = S_eS^2, hence the scaling of force dimension was able to perform as shown in Eq. (3).

Besides, conversion of total axial force on column to 1:5 scaled mass acting on column shown in Table 7 can be determined by applying the Eq. (3) with some basic physics equation F =ma and m = F/a as well. Hence, the calculated maximum mass acting on the individual column on roof, 1st floor and ground floor are 199.5 kg, 488.1 kg and 666.2 kg

$$F_{model} = \frac{\text{Axial Force}_{prototype}}{(S_e)(S^2)} \quad (3)$$

Table 7 Structural axial force design summary for full scale double story block house

Actions	Roof Level	1st Floor	Ground Floor
	Slab + Beam + Column	Slab + Beam + Wall + Column	Beam + Wall
Characteristic Permanent Action, G_k (kN/m)	11.28	23.28	14.4
Characteristic Variable Action, Q_k (kN/m)	11.1	11.1	11.1
Combine Action $1.35G_k + 1.5Q_k$ (kN/m)	31.88	48.08	36.09
Total Load Distribution From Beams (kN)	**176.94**	**491.35**	**749.50**
Column Self weight $1.35G_k$ (kN)	47.52	57.92	N/A (Stump)
Total Axial Force Acting On Column (kN)	**224.45**	**549.21**	**749.50**
1:5 Scaled Weight (kN)	1.995	4.88	6.662
1:5 Scaled Weight (kg)	**199.5**	**488.1**	**666.2**

After obtaining all the floor weight, the determination of base shear F_b or known as ultimate column base shear capacity was performed with Eq. (4) stated in European code 8 [19] before monotonic column pushover test was performed. Determination of base shear F_b was complied with clause 4.3.3.2.2 in European code 8. Given the condition whereby shear wave velocity versus on hard rock with ground type A from clause 3.2.2.2 is 900 m/s. The ground Type A in Malaysia has parameter such as soil factor S = 1.0, elastic response spectrum $T_B(S)$ = 0.15, $T_C(S)$ = 0.55, $T_D(S)$ = 2.0, constant value C = 2.0 especially in West Malaysia and correction factor of λ = 0.85 were used to determine the base shear F_b.

$$F_b = S_d(T_1)m\lambda \qquad (4)$$

The annotations in Equation 4 are stated as follow and cited from European code 8 (2003) [19],

- $S_d(T_1)$ is the ordinate of the design spectrum at period T_1;
- T_1 is the fundamental period of vibration of the building for lateral motion in direction considered.
- m is total mass of the building, above the foundation or above the top of a rigid basement.
- λ is the correction factor, the value of which is equal to 0.85 if $T_1 \leq 2T_C$ and the building has more than two storeys, or λ = 1.0 otherwise.

Determination of fundamental period T_1 of the block structure shown in Eq. (5) was complied with European code 8 (2003) [19] clause 4.3.3.2.2 as well. The parameter such as constant C_t = 0.050 for other types of structure, height of scaled 1:5 column H = 780 mm or 0.78 m were used to determine T_1. Hence, calculated fundamental period T_1 was 0.04 sec for block column structure.

$$T_1 = C_t(H^{3/4}) \qquad (5)$$

Whereby the annotations shown in Equation 5 are stated as follow (European code 8, 2003) [19];

- C_t is 0.085 for moment resistant space steel frames, 0.075 is for moment resistant space concrete frame and for eccentrically braced steel frame and 0.050 for all other structures.
- H is the height of the building, in m, from the foundation or from the top of a rigid basement.

Determination of horizontal elastic spectrum S_dT_1 is similar with S_eT_1. Under European code 8 [19] clause 3.2.2.2 has four different equations with different application parameter to determine the horizontal elastic spectrum S_dT_1. In this case condition with 0 ≤ T_1 0.04 sec ≤ T_B was used to determine horizontal elastic spectrum S_dT_1 as shown in Eq. (6). Given the parameter a_g = 0.12g for return period of 2500 years, S = 1.0 for ground type A, η = 1.0 with ζ = 5 % of viscous damping and constant C = 2.4 for West Malaysia. Hence, the calculated S_eT_1 is 0.52g.

$$0 \leq T \leq T_B: S_e(T) = a_g.S.\left[1 + \frac{T}{T_B}.(\eta.2.5 - 1)\right] \qquad (6)$$

Whereby (European code 8, 2003);

- T is fundamental period of vibration of a linear single degree of freedom system.
- T_B is the lower limit of the period of the constant spectral acceleration branch.
- a_g is the design ground acceleration on type A ground.
- S is soil factor.
- η is the damping correction factor with a reference value of η = 1 for 5 % viscous damping.

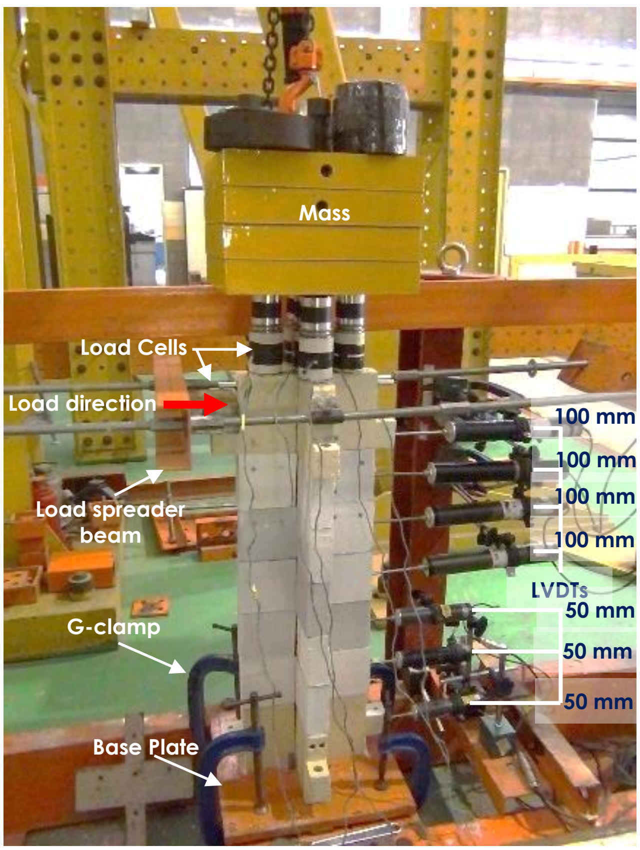
Ultimately, the base shear F_b can be calculated with input such as S_eT_1 = 0.52g, structural weight 6.662 kN and correction factor λ = 0.85. The calculated critical base shear force F_b was 2.94 kN.

The reinforced concrete column was then check for its shear capacity by applied design for shear force philosophy European code 2 (2002) [18] clause 6.2.3 together with the column bolts capacity design from European code 3 (1992) [27]. The formula was injected with Buckingham and Similitude Theorem to determine downscaled model shear force capacity as shown in Eq. (7). Given that $(b_w)(d)$ was cross section area with 6800 mm^2, concrete strength f_{ck1} was Grade 30, dimensional scale factor S = 5.0, and stress scale factor S_e = 4.5 were used to calculate the shear force capacity with angle of deformation θ = 22° or 45° stated in European code 2 (2002) [18]. The obtained shear force capacities with θ = 22° and 45° were 5.51 kN or 7.94 kN respectively. Both designed capacities 5.51 kN or 7.94 kN were greater than critical shear force 2.94 kN and therefore the column was safe.

$$V_{R.d\,max} = \frac{0.36\left(\frac{b_w}{s}\right)\left(\frac{d}{s}\right)\left(\frac{f_{ck1}}{S_e}\right)\left[1-\left(\frac{f_{ck1}}{S_e}\div 250\right)\right]}{\frac{\cos\theta}{\sin\theta}+\tan\theta} \quad (7)$$

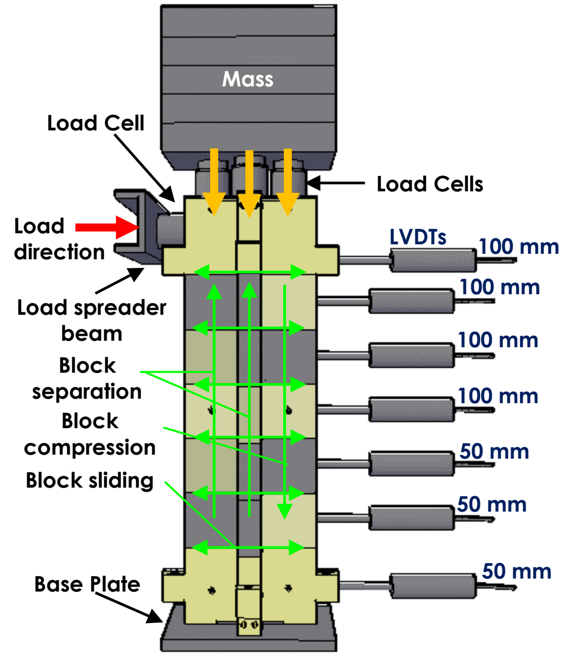
2.6 IBS Block Column Experimental Setup

The goal of monotonic pushover test was carried out to obtain the column's ultimate base shear capacity. Hence, the theoretical weight of 199.5 kg ≈ 200 kg from Table 7 was prepared in the form of metal mass block. The mass block was placed on top of the column as axial load as shown in Figure 7(a) during the experiment.



(a)

Figure 7 Block work column monotonic lateral load test (a) Real Setup, (b) Schematic front view setup & load path (continue)



(b)

Figure 7 Block work column monotonic lateral load test (a) Real Setup, (b) Schematic front view setup & load path

Seven linear variable differential transducers (LVDT) were installed to measure movement of every block and inter-storey drift with respective height of column in monotonic pushover test as shown in Figure 7(a) and (b). Four LVDTs with stroke 100 mm and three LVDTs with stroke 50 mm were installed during the experiment.

Five load cells with 10 kN capacity were installed on top of the column to measure the bolts tensile strength and additional 50 kN capacity load cell was installed for capturing column's lateral load. All LVDTs and load cells were connected to data logger for recording the loads and displacements results.

The expected load path was indicated by arrows as shown in Figure 7(b). The axial load was transferred vertically from mass into the column. The horizontal load applied by hydraulic jacking system was transferred through the load spreader beam from the test frame into the surface of the column laterally. The lateral applied load may cause the left and middle column block to separate and uplift while right column block in compression. Due to this behaviour, pre-stressed bolts in left and middle column experience tension in order to resist block from separation.

Besides, there are six possible height of the column block may experience sliding with no separations indicated by two ways arrow head. These places allow lateral load to be dissipate through the concrete friction resistance.

In order to secure the rigidity of the base, the specimen was bolted to the testing rig and clamped by four G-clamp. The monotonic load test begins with the application of lateral loads. Every displacement and load were recorded until the specimen collapse or seriously unstable. Monotonic lateral pushover test is to push the structure from one direction until it collapses or lose its resistance.

3.0 RESULTS AND DISSCUSSION

3.1 Ultimate Shear Capacity of IBS Block Column

Figure 8 shows six samples of IBS column ultimate base shear capacity tested under monotonic lateral pushover test. The ultimate base shear capacity was measured from the maximum roof top displacement with maximum applied loads on the roof top surface laterally.

Figure 8 (a) shows tested IBS column sample1 to 5 with reversed cyclic lateral load test. Sample 1 was tested up to elastic limit with 1.4 kN of lateral load and 10.1 mm roof top displacement. The load applied on sample 1 does not have any significant damage toward the structure. The second specimen was tested slightly beyond elastic limit of 2 kN lateral load with 20 mm roof top displacement. When the load was released the structure has ability to return back to the original position with a little permanent drift of 3.7 mm. No damage was found in this tested specimen.

Specimen 3 was tested up to 3.7 kN of lateral load with 40 mm roof top displacement. No significant damage was found in this test. However, when the load released a visible of 11 mm permanent displacement was formed due to the sliding of the blocks. The experiment continues with specimen 4 loaded up to 4.9 kN lateral load with roof top displacement 84 mm. The concrete block was cracked at load 3.7 kN at 50 mm roof top displacement had cause a sudden drop of strength as shown in Figure 8 (a). This is due to the concrete reached its respective tensile strength capacity. Specimen 4 has permanent drift of 40 mm after the load was fully released.

Due to repeated test and softening of the tested specimen. Specimen 5 has lower initial stiffness and the strength only started to pick up after 40 mm of lateral displacement. Specimen 5 has ultimate capacity of 5.5 kN lateral load resistance with 97 mm of roof top displacement. This test ends with a failure of the bolt at 100 mm of displacement. Although the load start to resist again after the failure of bolt but it does not contribute much of the lateral resistance. Therefore, reversed cyclic lateral load test is not suitable for representing the static ultimate lateral strength of the IBS column.

Sample 6 shown in Figure 8 (b) is a direct lateral load without any reverse cyclic load action. The obtained result in such condition is favourable under static condition. This is because no stiffness degradation happened in this test subject. The recorded ultimate base shear of IBS column 6 V_t was 3.1 kN and roof top displacement δ_t = 128 mm respectively. The IBS column behaves elastically up till 0.7 kN with displacement of 3.32 mm. The calculated initial stiffness K_i of this IBS column specimen was 0.137 kN/mm. The high initial stiffness indicates the structure is still behave elastically under certain amount of lateral loads.

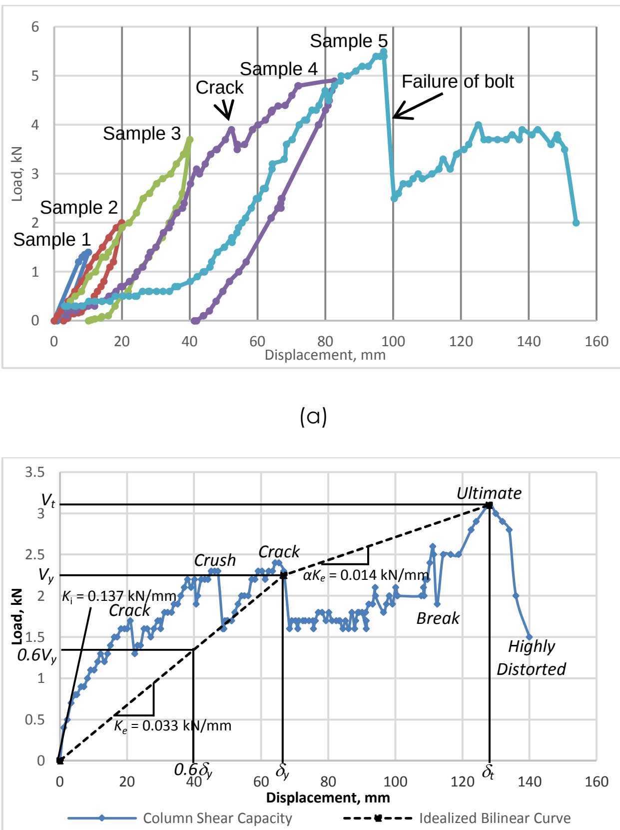
Beyond 0.7 kN of lateral load, the column stars behave plastically with directly proportional of loads increment over displacement. There is a sudden drop of load 1.7 kN at 21 mm displacement to 1.3 kN at 22.27 mm displacement due to crack initiation at block R3 as shown in Figure 12. Every crack formed on concrete block may reduce the overall strength of the structure.

The column continues to resist the lateral load up until 2.3 kN with 47.09 mm displacement. Then there is another sudden drop of load to 1.6 kN with 48.58 mm displacement due to crushing of R3 block cracked previously. The crushing of the concrete block indicates the compressive load has to distribute to other nearby component to further resist. Due to this reason, more nearby concrete block will begin to crack when applied load increases.

The column could take more lateral load up until 2.4 kN with 65.27 mm displacement and dropped to 1.6 kN with 68.50 mm displacement due to more cracks propagated from block R3 to block R2 as expected. The test was proceeded on with consistence lateral load resistance with increment of roof top displacement until 107.70 mm. From that point, the load was increased to 2.6 kN and a huge sound occurred due to sudden break of one bolt out of five supporting bolts of the column. That makes the column load resistance dropped further to 1.9 kN as shown in Figure 8.

The test continues with increment load up until ultimate capacity of 3.1 kN with 128 mm lateral displacement until one of the bolt from the remaining four column's bolts was broken with huge sound and thus the column lost it lateral resistance because of the crushing of the blocks R2 and R3. The test stopped at displacement 140 mm due to highly distorted structural element of the column.

To summarise the ultimate lateral load capacity of the column, an idealized bilinear curve is developed as shown in Figure 8. The idealized bilinear curve was developed based on the equivalent energy above and below the curve. The idealized bilinear curve describes the column's effective yielding stiffness and plastic stiffness capacity. The effective yielding stiffness K_e of the column is 0.033 kN/mm which is higher than the effective plastic stiffness αK_e = 0.014 kN/mm where by constant α is 0.425 as shown in the Figure 8. The reason is because the initial resistance of the column is higher than the later stage of the column with deformations. Any deformation such as cracking or crushing of the concrete block will ultimately lowering down the stiffness of the column. Based on the idealized bilinear curve shown in Figure 8 with equivalent energy under the curve, the yielding limit V_y is located at 2.25 kN with displacement δ_y at 67 mm. To be conservative a common practise of the effective yielding stiffness prediction is set to be 60% capacity of the yielding stiffness or known as $0.6V_y$. The calculated $0.6V_y$ is located at 1.35 kN shear force resistance with $0.6\delta_y$ at 40 mm roof top displacement. Stiffness reduction is equivalent to improvement of structural ductility. Therefore, improvement in ductility promotes the seismic energy dissipation.



(a)

(b)

Figure 8 Ultimate base shear capacity of IBS block column under lateral load test (a) Tested samples 1 to 5, (b) Adopted sample 6

3.2 Bolt Capacities of IBS Block Column

Figure 9 shows the measured tensile strength of five bolts in the column during the experiment. All five column bolts were equipped with load cells on top of the structure to measure the applied loads of the bolt due to monotonic push over test. The layout of five load cells LC1 to LC5 are as shown in Figure 9. Load cell LC2 with red colour was placed on top of the column facing the front of the experimental test while load cell LC1 with dark blue colour is measuring the direct lateral load applied on the column structure. In fact, the initial fastening load allows four out five structural bolts to have steady tensile resistance until 1.25kN measured by LC1 to LC4. Only LC5 bolts in compression zone increase steadily without been interfere by initial fastening load.

Based on the bolt strength measured by load cell LC1, the concrete block slides when load was applied towards the structure. The sliding movement between block ends in between 20 mm to 40 mm lateral displacement and the stabilized bolt in LC1 starts to pick up loads with 0.5kN slowly from 40 mm lateral displacement. For initial 40 mm lateral displacement, the bolt deflects toward right without any deformation. This is because the behaviour of the column bolt LC1 is similar with cantilever beam with fixed end and applied point load of force at the end. Therefore, the column bolt LC1 breaks due to bending after it reached the material limit strength at lateral displacement 112.47 mm with tensile of force 1.1 kN.

Bolt with load cell LC3 and LC5 loss its tensile strength due to the crushing of the concrete blocks in the column at 90 mm and 68 mm lateral displacement respectively. Therefore, the tensile stress in bolt LC3 and LC5 have been relieved earlier. However, the bolt LC3 located at the centre core of the column continues to take tensile stress generated by lateral loads until ultimate capacity of the column at lateral displacement of 128 mm.

At the end of the experimental test, only bolt in LC4, LC2 and LC5 still in good condition with minor bending. Based on percentage of the survival capability, 40% of the column bolts were damaged while 60% of the bolts are still functional. The column does not overturn in this test because the bolt in LC2 and LC4 are still functional with maximum loads of 2.2 kN and 1.3 kN respectively.

Bolt in LC5 was still in good condition and it does not contribute much tensile stress due to crushing of the concrete blocks and compressive action in that geometrical area. Therefore, seismic force comes in all direction will be resisted by front line defence of perimeter bolts in LC1, LC2, LC4 and LC5 or reinforced by each other vice-versa. Bolt in LC3 will be the core resistance of cruciform type of column configuration. Based on the ultimate base shear force 3.1 kN presented in previous section distributed into five bolts, theoretically each bolt shall experience at least 0.6 kN of shear force. However, 0.6 kN bolt in shear force is lower than the recorded tensile force. Therefore, this type of there structure tensile force was dominated by bolts while the shear force was taken by reinforced concrete block due to friction.

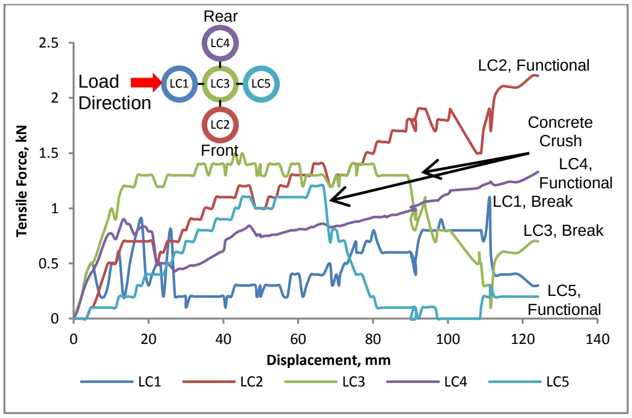


Figure 9 Bolt tensile strength versus displacement

3.3 Inter Storey Drift of IBS Block Column

Figure 10 shows the inter-storey drift of the IBS block column with monotonic lateral push over loaded on rooftop of the column. There are seven LVDTs were installed during the experiment test and each of them was located at the centre of each concrete block with respective height as shown in Figure 10. The movement of the column was recorded by LVDTs that installed on each level of the column.

Based on Figure 10, for the initial 5 mm roof top displacement, the entire column slides to the right evenly. After the displacement was loaded till 10 mm, block in level 4 does not have any significant movement and remains at 5 mm lateral displacement. This is the initiation of differential inter storey drift due to lateral loads.

The roof top displacement was further loaded to 20 mm while the level 4-block movement was still 10 mm left behind. Obviously, a cantilever behaviour can be observed from this point of view.

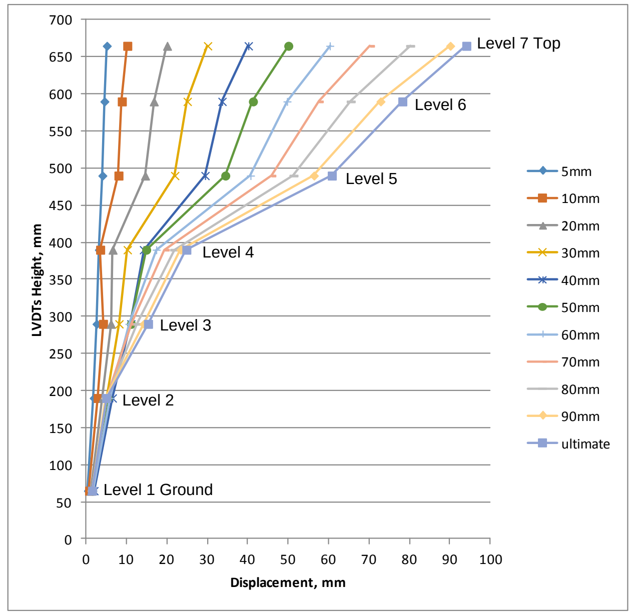


Figure 10 Inter-storey drift of the IBS block column

When applied load on roof top displacement of 30 mm, the differences between block level 4 and level 5 become obvious. This behaviour was continued gradually until ultimate lateral capacity of the column. The large movement of column in level 4 to 7 is because of the crushing of column block in level 3 and followed by column block in level 2. Therefore, any crushing of the column block will ultimately cause the upper floor to have greater storey drift.

3.4 Block Separation of IBS Block Column

Figure 11 shows the block separation due to lateral displacement with respective to height of IBS column. The separation of block at each level of column was due to load applied laterally with displacement controlled experiment. All the gap separation was measured by digital calliper manually.

Based on Figure 11, no concrete block separation was found in initial 5 mm of roof top displacement. The concrete block separation begins when roof top displacement was loaded up to 20 mm. Concrete block at height of 340 mm experience separation with gap 3.5 mm because of the initiation of crack in other side of the concrete block. The rest of the concrete block remains at 1.5 mm and 2 mm without much separation. The gap at height 340 mm propagates to 5.7 mm after the roof top displacement loaded to 30 mm. This is mainly due to the crack propagation at the other side of concrete block.

This behaviour continues until 50 mm roof top displacement. The separation of block increased tremendously to 17.3 mm because of the crushing of concrete block from the other side. Afterward the gap at height 340 mm continues to increase from 17.3 mm to maximum of 24.4 mm at roof top displacement of 94 mm. Apart from that, the concrete block at base of the column was lifted up 8.8 mm above the ground due to the broken bolts at the end of the experiment.

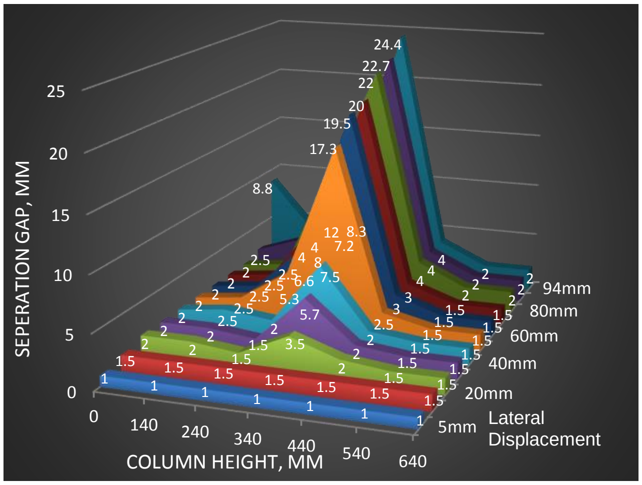


Figure 11 Separation of block in IBS column

3.5 IBS Block Column Structural Behaviour

Figure 12 shows the ultimate behaviour and deformation of the tested IBS reinforced concrete block column. The tested specimen experienced cracking, crushing, block sliding, block separation, bolt fracture and bending of entire column specimen.

Initially, the column blocks experience sliding effect with the applied lateral load on the rooftop in stabilization process. Afterward, the concrete column starts to resist lateral loads and the first crack was happened at block R3 as shown in the Figure 12. When the crack happens the other sides of the concrete block starts to have gap with block separation.

When the lateral applied load increases, the crack at block R3 propagates and the gap opening at the opposite side increases simultaneously. The concrete block R3 in Figure 12 crushed at 1.6 kN of lateral load with 48.55 mm roof top displacement. With the crushing of the concrete block R3, the column starts to experience bending behaviour such as cantilever beam.

Due to the crushing of concrete block R3 the lateral force was transmitted to concrete block R2. R2 starts to crack when the applied load exceeded the concrete tensile strength of grade C30 of concrete mix. With the cracking of block R2 the stiffness of the column reduces and the column's bolt begins to take the action from lateral load. The first column bolt in the plane of L1 to L7 as shown in Figure 12 has failed at 111.2 mm roof top displacement with 2.6 kN of load.

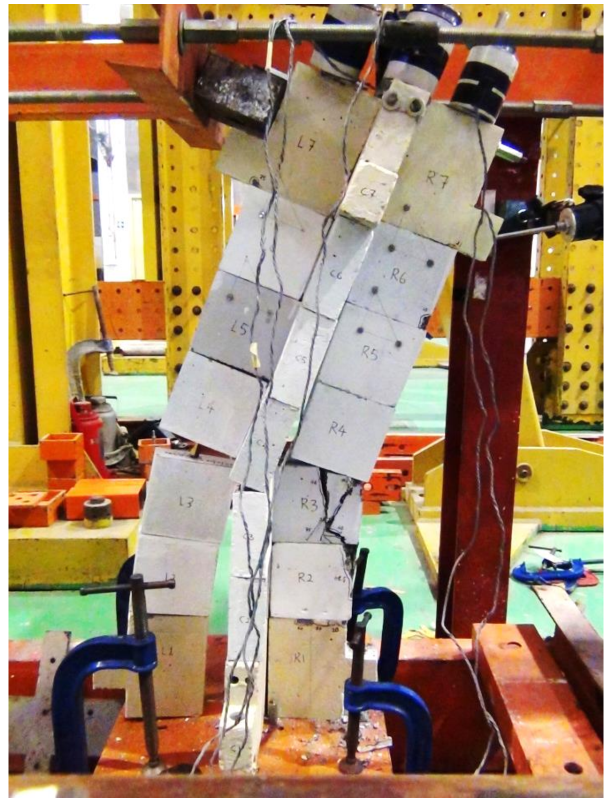


Figure 12 IBS Block Column Deformation

The fracture of the first column bolt was happened at the ground floor. The consequences of this failure was creating a huge gap with approximately 20 mm detached from the main element as shown in Figure 12. This deformation had caused the base of the column block become semi-rigid. This is because the failed bolt allows the column to bend along the load direction. This deformation had disabled the ¼ lateral load resistance of the column. Because the rest of the ¾ part of the column would take over those applied loads and axial load to provide further resistance. The experiment ends with the second fracture of the centre bolt that caused great reduction of the lateral resistance of the column with distorted shape.

Surprisingly there are only two blocks were damaged and three bolts are still functional out of five after massive lateral load applied on to the column structure without overturning. Therefore, the structure itself is durable and those blocks can be replaced easily with minimal cost after the earthquake disaster.

3.6 IBS Column Performance Level

Based on standard guidance of FEMA 273 & 356, the performance levels of the monotonic lateral push over IBS column's base shear versus displacement curve is shown in Figure 13. According to the experimental test, the column has an Immediate Occupancy (IO) performance level at storey drift of 21 mm with base shear of 1.7 kN as shown in Figure 13. In Immediate Occupancy stage, the IBS column had suffered light damage such as minor break off of the concrete cover in fragments, without serious permanent drift up to that level, retained original strength and stiffness. Only minor cracks on facades of square and rectangular blocks were discovered without crushing of the concrete block. All structural components were still functional and able to reoccupy even after an earthquake disaster. Some minor repair may need to be done to restore the durability of the structure after the disaster by this level of performance.

After the immediate occupancy performance level, the column entered the damage controlled parameter up to limit of Life Safety (LS) performance level with storey drift of 65.27 mm and 2.4 kN of the base shear as shown in Figure 13. In damage control range with Life Safety performance level, moderate damage on column block such as rectangular and square blocks were occurred throughout the monotonic lateral load test. The damages were including with minor break off of concrete block cover, increased in crack opening and crack length in the rectangular concrete block. Permanent inter storey drift was formed in this stage due to the degradation of structural stiffness and crushing of one of the rectangular concrete blocks. A minimal repair on damaged structural and replacement of the damaged structural part was essential in damage control range to protect and preserve the column from further degradation after earthquake. The safety of occupants within the building is protected by the main element of structure such as IBS column so that occupants will not suffer from any injuries or harms caused by the falling debris. Only one out of four planes of the IBS column was damaged under life safety performance level. Therefore, occupants of the building have sufficient time to evacuate from the building before major deformation.

The final limit of Collapse Prevention (CP) performance level was recorded with maximum storey drift of 128 mm with maximum base shear of 3.1 kN as shown in Figure 13. In this performance level, there is very limited safety to protect the occupant from falling hazard. The IBS column still surviving and resisting lateral loads, however crushing of column blocks by excessive compressive load and distorted column due to failure of column bolt may post falling hazard toward occupant. Propagation of concrete cracks, severe spalling and concrete block separation were formed up to this performance level. The stiffness capacity of the column was further degraded by excessive damage.

Although stiffness of the column was degraded as well as broken bolts, the column was still protected by other internal steel bolts as anchor. Thus, the remaining bolts were preventing the column from overturn completely. The steel bolts acting as anchor to pull all the blocks together as final defence from completely detached and undamaged plane of blocks still able to withstand the compressive actions from other direction cause by earthquake. This column is still able to protect occupant evacuate from the structure within certain amount of time. This structure has tendency to collapse in this performance level due to distorted column behaviour.

Beyond Collapse Prevention performance level, the column will collapse due to failure of remaining anchor bolts as last line of defence. In this collapse stage, the IBS column loses its stiffness capacity with incremental storey drift without any additional resistance.

The column collapses due to the crushing of the column base and failure of the column's anchor bolts. However, the founding of this study is the remaining concrete blocks are still functional and able to take loads, even if one out of five column's vertical planes is completely crushed without overturning effect. This is because IBS column for IBS block house was designed based on strong column weak beam theory.

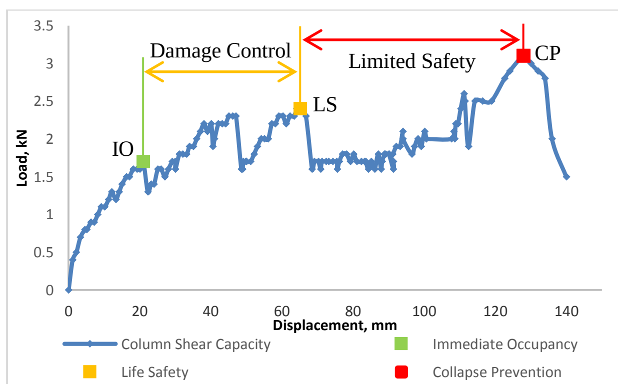


Figure 13 IBS column qualitative performance levels based on storey drift

Hence, the extreme lateral displacement tests have proven that this column has excellent performance in taking any earthquake ground movement that cause massive displacement of the building. Even if client demand higher column stiffness with less displacement, it can be done through optimized post tension force applied towards the column bolts or the post tension tendons.

3.7 IBS Column Buckingham and Similitude Theorem

Table 8 shows the similitude theorem with conjunction of Buckingham's relations of IBS block column. The dimensional scale factor for scaled model is 0.2 and 1.0 for full-scale prototype. The non-homogeneous material strength scale-factors that measured from laboratory were 0.22 for scaled model and 1.0 for full-scale prototype.

Based on the scale factor conversion, the full-scale prototype has ultimate roof top displacement, δ_t of 640 mm with ultimate base shear force capacity V_t of 348.7 kN. The IBS block column has yielding displacement δ_y of 333.5 mm with yielding strength V_y of 253.1 kN. The bilinear capacity curve shows the 60% effective capacity of the IBS column has 200 mm roof top displacement with 151.9 kN base shear force resistance.

The full-scale prototype of the IBS column has initial stiffness 3.08 kN/mm. The effective stiffness K_e of the column was having 0.74 kN/mm based on equivalent energy under the base-shear capacity curve. The calculated plastic stiffness of the IBS column block αK_e for full-scale prototype is 0.31 kN/mm.

The total mass of the tested sample is 2320 N with ultimate base shear of 3.1 kN. The total mass of full-scale prototype is 261600 N with ultimate base shear of 348.7 kN. The earthquake spectral acceleration is measured by ultimate base shear in unit kN divided with weight in unit Newton N of the structure ends with the gravitational unit g as shown in Eq. (7). The gravitational unit g is represented as lateral acceleration. The obtained scaled 1:5 and full scale prototype horizontal spectral acceleration both are 1.3 g. This has proven the similitude theorem and Buckingham's law is valid. According to Mercalli's earthquake scale 1.3 g is equivalent to X+ intensities with extreme shaking with very heavy potential structural damages.

$$Sa = \frac{(V)g}{W} \tag{7}$$

Each structural component has its unique scale factor. Therefore, extensive measurement of material strength is vital for obtaining representable scale factor to fabricate scaled model for any experimental test.

Table 8 Similitude relations for IBS block column model

Parameter	Scale factor	Scaled 1:5	Full Scale
Dimension	$S = 5.0$	0.2	1.0
Material strength	$S_e = 4.5$	0.22	1.0
Gravitational Acceleration, a (m/s^2)	$S_a = 1.0$	9.81	9.81
Ultimate displacement, δ_t (mm)	$S = 5.0$	128	640
Yielding displacement, δ_y (mm)	$S = 5.0$	66.7	333.5
60% displacement, $0.6\delta_y$ (mm)	$S = 5.0$	40	200
Ultimate Shear force, V_t (kN)	$S_eS^2 = (4.5)(5.0)^2$	3.1	348.7
Yielding Shear force, V_y (kN)	$S_eS^2 = (4.5)(5.0)^2$	2.25	253.1
60% Shear force capacity, $0.6V_y$ (kN)	$S_eS^2 = (4.5)(5.0)^2$	1.35	151.9
Initial Stiffness, K_i (kN/mm)	$S_eS = (4.5)(5.0)$	0.137	3.08
Yielding Stiffness, K_e (kN/mm)	$S_eS = (4.5)(5.0)$	0.033	0.74
Plastic Stiffness, αK_e (kN/mm)	$S_eS = (4.5)(5.0)$	0.014	0.31
Spectral Acceleration (Sa = Vg/W) = g	$S_eS^2/(S_eS^2/S_a)= (4.5)(5)^2/[(4.5)(5)^2/1.0]$	1.33g	1.33g
Mercalli's Scale	-	X+	X+

4.0 CONCLUSION

The down-scaled 1:5 IBS column model has ultimate capacity of 3.1 kN base shear force with 128 mm of roof top displacement. Behaviour of the IBS block column was identified from the monotonic lateral pushover experimental test that included with sliding and separation of concrete blocks. Structural damages such as cracking, spalling, crushing of concrete block and bolt fracture were part of this model behaviour as well.

Three bolts out of five were in good condition after the experimental test. Two bolts fracture due to excessive lateral loads. Two from the remaining three bolts continues to perform as anchor to take lateral loads and prevent the column from overturn. The other bolt loses its tensile strength after crushing of the column block in the column.

The recorded significant inter-storey drift for the column happened at height of level four to level seven. These inter-storey drift is because of the cracking and crushing of block located at level two and level 3 respectively.

Highest block separation recorded was 24.4 mm located at column height of 340 mm due to the fracture of the bolt and crushing of the concrete block. Apart from that, 20 mm gap separation from other column component was formed by the end of the experiment due to bolt fracture as well.

The seismic performance level of IBS column with Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance level were presented based on respective base shear and roof top displacement.

The ultimate finding of this paper is IBS block column model has high initial stiffness. The model is able to reach yielding stiffness and form plastic stiffness after yield. IBS column has high stiffness capacity without failure and transform into ductile behaviour due to lateral load from earthquake.

This concludes the IBS column block is strong and durable to protect occupants without falling hazards up to 1.3 g horizontal spectral acceleration equivalent to X+ Mercalli's scale. IBS column block has ability to withstand massive lateral loads generates by earthquake hazard and dissipate seismic energy through semi-rigid joint without total collapse.

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