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CLAMPING AND INTERLOCKING EFFECTS ON IBS BLOCK HOUSE SYSTEM IN COMPARISON WITH CONVENTIONAL HOUSE SYSTEM

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Graphical abstract

Abstract

Industrialised Building System (IBS) is a unique construction technique that has been implemented in many construction fields all around the world. However, its implementation in Malaysia is still slow and not effective. Through the research on IBS, some elements are found to be important and need to be improved in order to produce better quality components. One of the important elements is the design and innovation of IBS components by applying new interlocking configuration between blocks and by using a clamping bolted connection to the system. The main objective of this research is to determine the structural behavior of IBS block works sub-system under push over cyclic loading in comparison with conventional sub-system and to verify that the IBS interlocking geometry sub-system perform better than other sub-systems via laboratory tests. In this research, a block work assembly to form building sub-frame that integrated by two beams, two columns and infill system were built and tested to failure. Two types of IBS block work sub-systems with original geometry and interlocking geometry with scaled of 1:5 were tested with Push Over Cyclic Load Test. In comparison, a control model of Conventional Sub-System was also tested and analysed using the same methods. The results showed that the IBS geometry model with interlocking configuration performed better in terms of stiffness, ductility and flexibility of the models. The IBS original geometry model is ductile but lack structural stiffness while the conventional model is stiff but not ductile.

Keywords: Clamping and interlocking effects, ibs block work, push over cyclic test

Abstrak

Industrialised Building System (IBS) adalah satu teknik pembinaan yang unik dan telah dilaksanakan di kebanyakan bidang pembinaan di seluruh dunia tetapi pelaksanaannya di Malaysia masih perlahan dan tidak berkesan. Melalui penyelidikan IBS, beberapa elemen adalah penting dan perlu diperbaiki untuk menghasilkan kualiti komponen yang lebih baik. Salah satu elemen penting ialah reka bentuk dan inovasi komponen IBS dengan menggunakan konfigurasi saling mengunci antara blok dan juga menggunakan sambungan bolt kepada sistem. Objektif utama kajian ini adalah untuk mendapatkan kelakunan struktur IBS blok sub-sistem dalam *Push Over Cyclic Load Test,* kemudian dibandingkan keputusannya dengan sub-sistem konvensional. Selain itu, kajian ini juga mengesahkan bahawa sub-sistem IBS dengan geometri saling mengunci mempunyai prestasi yang lebih baik daripada sub-sistem yang lain melalui ujian makmal. Dalam kajian ini, rangka struktur yang mengandungi dua rasuk, dua tiang dan dinding telah dibina dan diuji. Dua jenis sub-sistem IBS iaitu geometri asal dan geometri saling mengunci dengan skala nisbah 1: 5 telah diuji dalam *Push Over Cyclic Load Test*. Sebagai perbandingan, sub-sistem konvensional sebagai model kawalan juga diuji dan dianalisis dengan kaedah yang sama. Hasil kajian menunjukkan model geometri IBS dengan konfigurasi saling mengunci adalah lebih baik dari segi kekukuhan, kelasakan dan fleksibiliti. Model IBS geometri asal adalah lasak tetapi kekurangan kekukuhan struktur manakala model konvensional adalah kukuh tetapi tidak lasak.

Kata kunci: Kesan pengapit and saling mengunci, ibs blok, push over cyclic test

1.0 INTRODUCTION

Industrialised Building System (IBS) is a construction technique that can be implemented with high precision construction technology with embedded high safety features [1]. It is a construction technique where components are precisely manufactured in a manufacturing plant and then transported, and assembled into a multirole building system [2-4]. However, the implementation of IBS in Malaysia is considered slow and not effective in spite of the government introducing multiple initiatives for the use of IBS [5]. This is due to the reluctance of construction parties to adequately deal with the risks in the IBS projects. Failure to keep within the cost estimate in the IBS projects is still common in Malaysia and it is one of the reasons that limit the development of IBS [6-7].

This paper reports on a new IBS model designed for residential building as shown in Figure 1. In this model the blocks are assembled and held together to form a solid structure by using a clamping bolted connection. Therefore the design of components, number of blocks, bonding between the blocks, the weight of the blocks, material and concrete mix design of blocks become important aspects to determine the stability and structural performance of the IBS block work models.

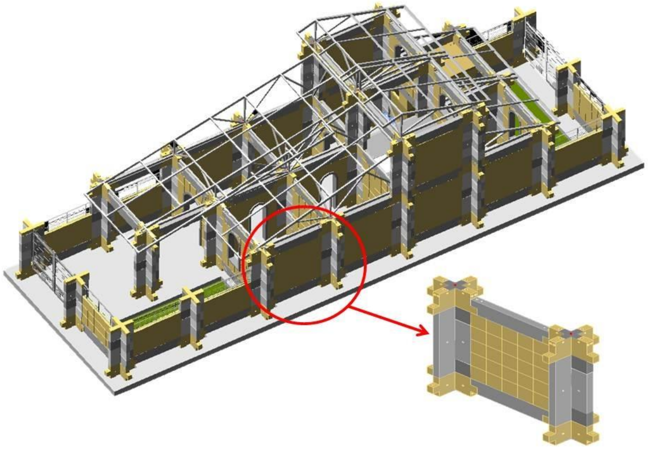

Figure 1 IBS Block Works Residential Building

However, the non-homogeneous assembly between the block works may cause water leaking and this would affect the durability of IBS block works [8-9]. Hence, another interlocking model has been designed to solve the problems of leakages. These new models were designed with consideration to overcome the problems of pre-fabrication and mass production. The standardization of the IBS model layout, components and parts are maintained so that the standardization of IBS system in Malaysia can be achieved in the future.

The objectives of this paper are:

1. To verify that the scaled 1:5 IBS interlocking geometry sub-system perform better in terms of structural behavior in comparison with IBS original geometry sub-system and conventional sub-system via laboratory tests.
2. To determine the scaled 1:5 structural behavior of IBS block works sub-system under push over cyclic loading in comparison with conventional sub-system.

2.0 METHODOLOGY

Three models were built and tested in laboratory. The first model is the originally invented geometry of IBS Block Work Sub Frame System which is called Original Geometry Model as shown in Figure 1(a). The second model is IBS Block Work Sub Frame System with interlocking configuration which is called Interlocking Geometry Model as shown in Figure 1(b). Figure 1(c) shows the third model which is Conventional Sub Frame Model. The original design and innovation was conceived at the Universiti Teknologi Malaysia since year 2012.

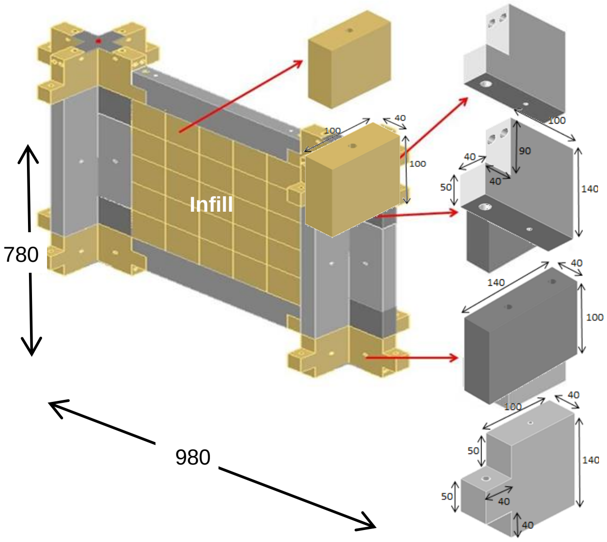

Figure 1(a) Original Geometry Model of IBS Block Work Sub Frame

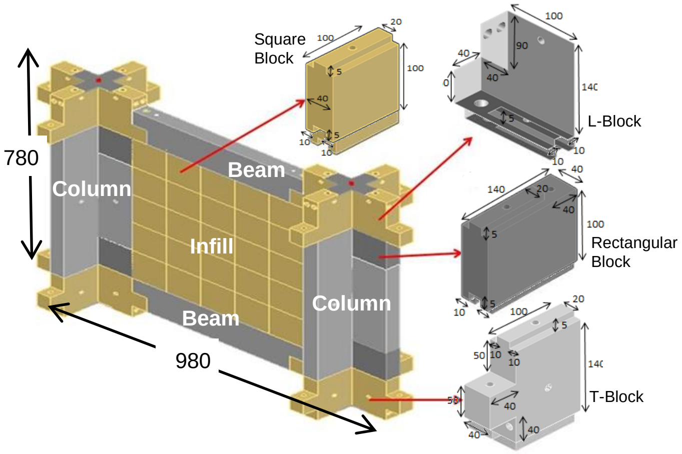

Figure 1(b) Interlocking Geometry Model of IBS Block Work Sub Frame

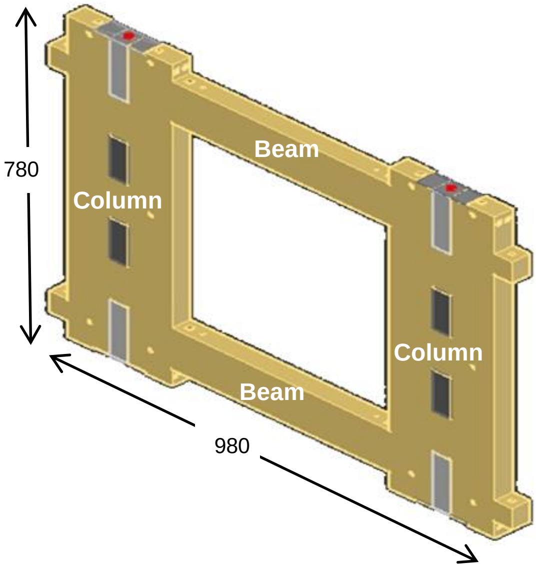

Figure 1(c) Conventional Sub Frame Model

Push over cyclic test is used in this study where the structure was pushed by an increasing lateral loads from both left and right direction alternately. The goal of this testing is to obtain a reliable cyclic strength that can be sustained by the IBS block work sub-systems to match a real world earthquake demand [10-11]. For instance, Yip (2016) performed push over cyclic test on reinforced concrete block system for two storeys safe house. The structural stiffness capacity, performance level, seismic energy dissipation and spectral acceleration were able to obtain through calculations from the hysteresis curves from the test [12]. The testing was performed and monitored with the assistance of a variety of instruments such as displacement laser meter, Linear Variable Displacement Transducer (LVDT), inclinometer, Demec Points, hydraulic jack, load cell and data logger. Figure 2(a) and 2(b) show the assembled block work sub-system with the complete set up of instruments on testing frame.

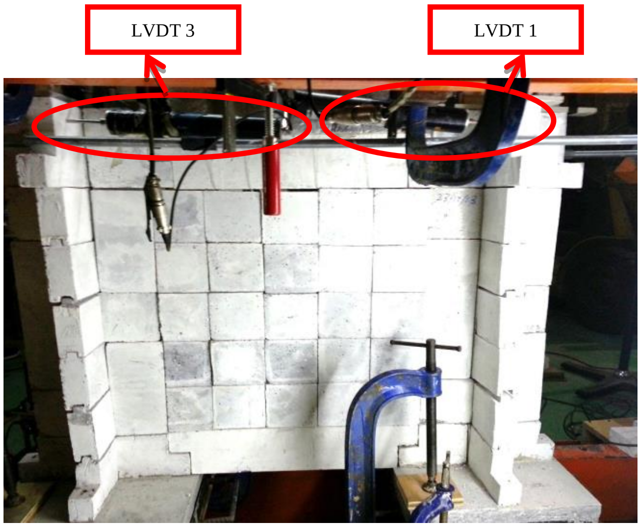

Figure 2(a) Instruments Set Up for Push Over Cyclic Test (Rear View)

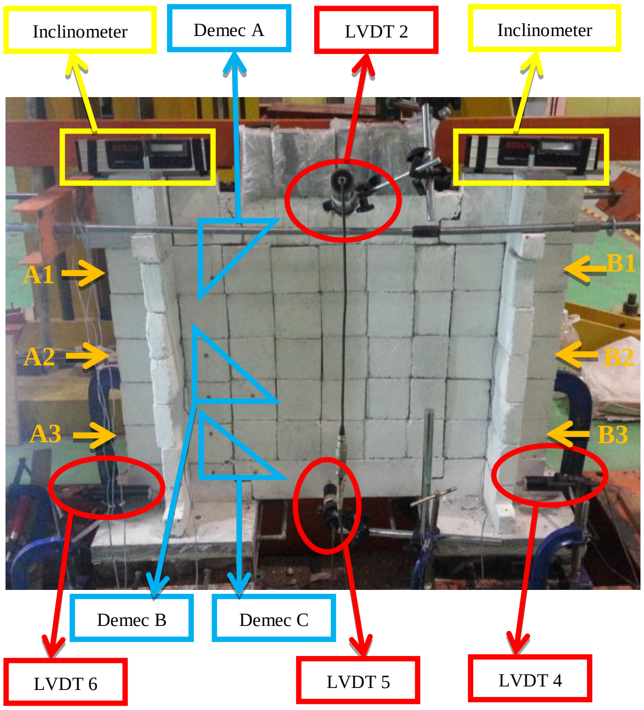

Figure 2(b) Instruments Set Up for Push Over Cyclic Test (Front View)

An estimated load weight with 20 kg was placed on the upper beam surface to indicate the self-weight of down scaled slab. LVDTs were used during the laboratory test at specific locations to record the displacements and deflection of structural movement. The LVDTs were connected to data logger so that the data were recorded and saved automatically to personal computer via data logger.

Laser Distance Instruments were placed on an independent testing frame and the lasers are pointed at the model frame. A profile graph of deformed column was obtained by using the displacement from the laser instruments pointed to the column.

Inclinometers were installed at the top of both columns to observe the degree of inclination or rotation of the columns when the lateral load was applied. The obtained results are important to analyze the ductility and shape of failure of the structure. A reading of inclination of the column shows whether the column structure is having a strong bonding between blocks or otherwise. The bending of column gives a value of inclination because the blocks of column sustain the loads in a rigid body state without sliding action.

Demec Systems were installed on the structure at the designed locations. The purpose of Demec System installation is to observe the movement between IBS block works. The Demec Systems are installed in the shape of right angle triangle with two side lengths of 100 mm. The data of Demec triangle obtained during every cycle of test will show the friction that create sliding bond between the blocks. The angle of Demec triangle will change when the component is rotated during test. The size or length of triangle changes when the component was tilted during the test.

The clamping bolt is the long threaded steel bar with the bolted end for clamping together all blocks in the column component. A total of 5 clamping bolts were used in each column components. In order to measure the strain built-up in bolt, a load cell was attached on the bolt at the column's top and then connected with data logger to obtain the strain reading of bolt during the push over test of the structure sub-system.

After all the structure and instruments were prepared, the structure was tested with push over cyclic load. The lateral force was applied by the hydraulic jack and was measured by load cell. Essentially, cyclic testing involves loading and unloading horizontally to obtain the performance of IBS interlocking block work system at various displacement limits and direction. This provides a more accurate idea of how the IBS system will perform in the real world, as most of the IBS products can be used for an extended period of time with various building roles [13-14].

3.0 RESULTS AND DISCUSSION

3.1 Load and Rooftop Displacement Relationship

For IBS block work sub-systems, four cycle tests were conducted by using hydraulic jack to apply a continuous increment of displacement at rooftop location of the frame. For conventional sub-system, there were only three cycle tests conducted due to the major failures of the sub-system.

Figure 3(a) shows the load and rooftop displacement for all three sub-systems at the first cycle of test. At first cycle, it can be clearly seen that the rooftop displacement increased when the load increased and the rooftop displacement decreased when the load is released for both IBS block work sub-systems and conventional sub-system. For IBS original geometry, the highest loading for original geometry is 0.7 kN, which is 7.8 mm. The curve of original geometry is smooth and the model is nearly back to its initial position when the load was completely released. This is because the lateral load reacted to the tied system homogenously with the rooftop displacement.

For interlocking geometry, the load that was sustained by the model is larger than the load sustained by original geometry model due to its interlocking effect. The highest loading for interlocking geometry is 1.8 kN, which is during the maximum rooftop displacement of -7.8 mm. The model does not return back to its initial position when the load was released completely because of the interlocking effect that increased the structural stiffness of model. At the rooftop displacement of 7.8 mm and -7.8 mm, there is a sudden drop of load and rooftop displacement. This is because of the high structural stiffness of model that resists the returning to its initial position until the hydraulic jack was released completely. In order to continue the test, the model was push from reverse direction until it is back to its initial position. Hence, there is a reading of load -0.5 kN and 0.3 kN at the rooftop displacement of 0 mm.

For conventional sub-system, the highest loading for conventional structure is 8.3 kN, which is during the maximum rooftop displacement of 7.8 mm. Due to the high stiffness of the model, it can be seen that the curve does not monitored back to the original load path when the load is released. Therefore, the frame was forced to return back to its original position by pushing from opposite direction with the loading of -2.4 kN and 1.5 kN.

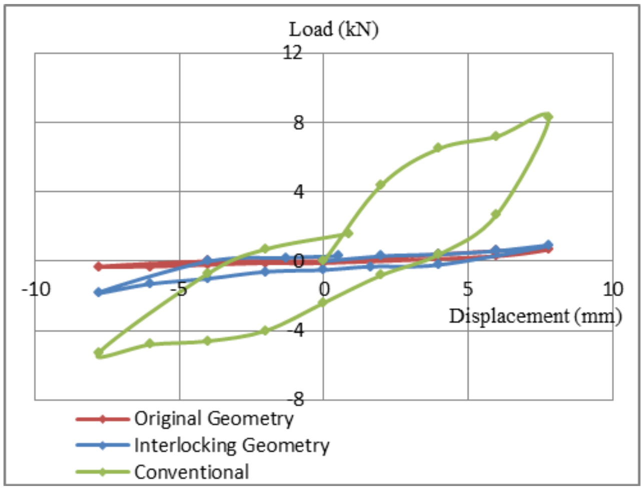

Figure 3(a) Load and Rooftop Displacement at First Cycle

Figure 3(b) shows the load and rooftop displacement for all three sub-systems at the second cycle of the test. For the original geometry model, the highest loading is 1.4 kN, which is during the maximum rooftop displacement of 15.6 mm. The lateral load reacted homogenously with the rooftop displacement and there is no sudden crack created in this cycle, hence the curve is smooth. However, there is overlapping of curves at the displacement of -10 mm. This is because of the over releasing of load by the hydraulic jack during the testing.

For interlocking geometry, the load that is sustained by the model is larger that is 2.6 kN during the maximum rooftop displacement of 12 mm. As shown in Figure 3(b), the highest loading for the model occurred at the rooftop displacement of 12 mm. As a result, the loading that push the model to displacement of -15.6 mm becomes smaller. Similar to the first cycle, the model did not return back to its initial position when the load was released completely. At the rooftop displacement of 15.6 mm, there is a sudden drop of load and rooftop displacement due to its larger structural stiffness of model that resists returning to its initial position.

For conventional sub-system, the highest loading is 9.2 kN at its maximum rooftop displacement of 15.6 mm and 7.1 kN for opposite direction. It is observed that the loading that can be sustained by the conventional sub-system is increased for every cyclic but the increment of load is small due to model damages during the first cycle of load. There was shear cracks discovered at the connecting parts of column and beam in the first cycle of test.

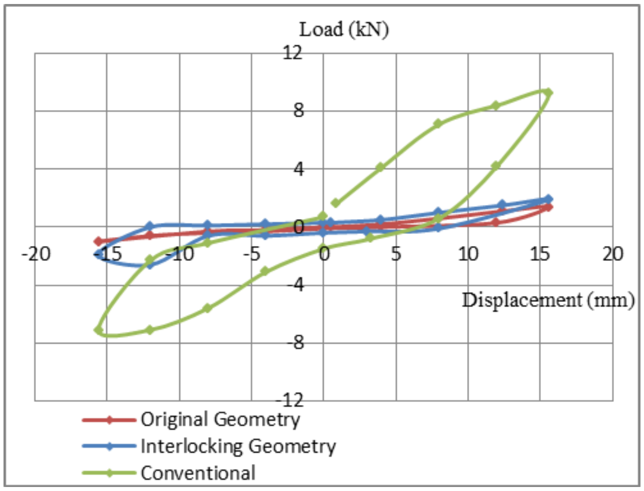

Figure 3(b) Load and Rooftop Displacement at Second Cycle

Figure 3(c) shows the load and rooftop displacement for all three sub-systems at the third cycle of test. For original geometry, the shape of curve is still smooth and similar to the shape of curve at previous cycle. This proves that the push over test was conducted smoothly and the load is applied homogenously to the rooftop displacement. For third cycle of load, the highest loading for original geometry is 2.8 kN, which is during the maximum rooftop displacement of 31.2 mm.

For interlocking geometry, the load that is sustained by the model is larger which is 8.7 kN during the maximum rooftop displacement of -31.2 mm. As usual, there is a sudden drop of load and rooftop displacement at the rooftop displacement of 31.2 mm and -31.2 mm due to the model that resists returning to its initial position. The model was then pushed from reverse direction until it is returned to its initial position.

For conventional sub-system, the highest loading for the model is 9.5 kN at the rooftop displacement of 31.2 mm. The push over testing on conventional sub-system ended at the third cycle because the frame model has suffered major damages which the shear cracks are expanding until the beam elements are separated from the structure. The frame is then pushed to another direction until the maximum rooftop displacement that can be sustained by the model, which is 45 mm with load 7.5 kN laterally.

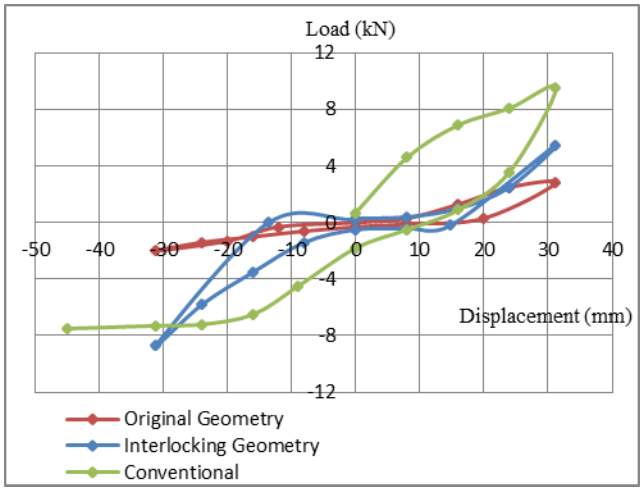

Figure 3(c) Load and Rooftop Displacement at Third Cycle

Figure 3(d) shows the load and rooftop displacement for both IBS block work sub-systems at the fourth cycle of test. For original geometry model, the highest loading for original geometry is 4.0 kN, which is during the maximum rooftop displacement of 62.4 mm.

For interlocking geometry, the curve is not smooth at the rooftop displacement of 32 mm. This is due to the limited length of cylinder of hydraulic jack. Therefore, the jack was released to readjust its cylinder length and was installed back to the testing frame. The testing was then continued by reaching the targeted rooftop displacement of 62.4 mm. During the loading of reverse direction, the model was pushed until -80 mm and the data were recorded. The highest loading is 12.5 kN, which is during the maximum rooftop displacement of -80 mm.

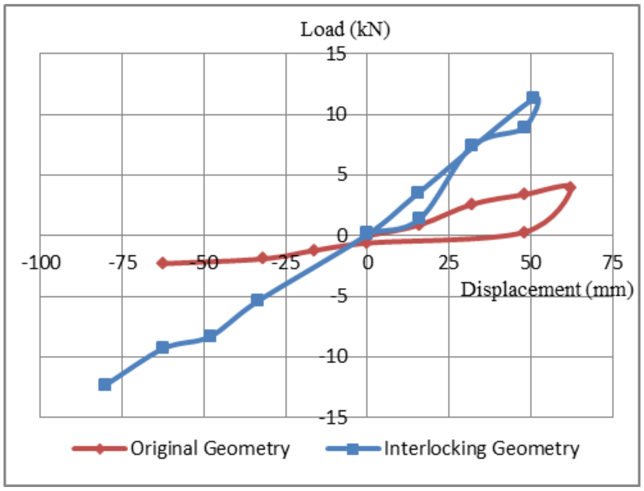

Figure 3(d) Load and Rooftop Displacement at Fourth Cycle

The stiffness, *k*, of a body is a measure of the resistance offered by an elastic body to deformation. For an elastic body with a single degree of freedom, the stiffness is defined as which is defined as $k = \frac{F}{\delta}$, where *F* is the force applied on the body and δ is the displacement produced by the force along the same degree of freedom (DOF) [15]. Therefore, the value of structural stiffness can be obtained from the gradient of stiffness curve.

Figure 4 shows the structural stiffness of both IBS block work sub-systems and conventional sub-system. From the structural stiffness curve, it shows that the stiffness of original geometry remains the same from first cycle to third cycle but the stiffness started to decrease in the fourth cycle. The situation is different for interlocking geometry where the stiffness is increasing for every cyclic due to its interlocking effect. It can be concluded that the structural stiffness of interlocking geometry is stronger than original geometry.

For conventional sub-system, the structural stiffness is very large at first cycle load when compared to IBS block work sub-systems. However, when shear cracks started to appear on conventional sub-system at the first cycle, the stiffness of conventional sub-system decreased drastically for the following cycles. This shows that the conventional sub-system is stiff but not ductile. Hence, the interlocking block work sub-system is better in terms of stiffness and ductility when compared to conventional sub-system and original block work sub-system. Table 1 shows the value of structural stiffness for all three sub-systems in every cycle that obtained from Figure 4.

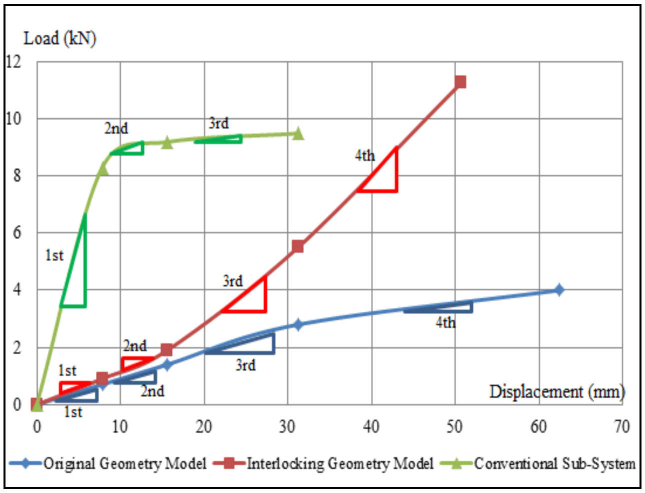

Figure 4 Structural Stiffness of both IBS Block Work Sub-systems and Conventional Sub-system in Every Cycle

Table 1 Structural Stiffness value of IBS Block Work Sub-System and Conventional Sub-System

Type of Sub-systems	Structural Stiffness (kN/m)			
	1st Cycle	2nd Cycle	3rd Cycle	4th Cycle
Original Geometry	89.74	89.74	89.74	38.46
Interlocking Geometry	115.38	128.21	230.77	295.77
Conventional	1064.10	115.38	19.23	-

3.2 Load, Horizontal Laser Distance Measurement and Damages

Figure 5 shows the profile graph for all three sub-systems models for all the cycles of loading. The profile graph shows the lateral displacement of the sub-system deformations corresponding to its height. For conventional sub-system, it has the largest deformation when the lateral load is subjected on it. Conventional sub-system that is casted in a continuous plane has large stiffness but lack flexibility. The whole sub-system can only deform in a plane where there is no block movement to resist load. Therefore, it has the largest profile curve and shear cracks would easily form on the conventional sub-system.

On the other hands, it can be seen that both of the IBS block work sub-systems has smaller profile curve when compared to conventional sub-system. However, the original geometry has larger deformation than interlocking geometry for every load cycle. This is because the bonding between original geometry blocks is weaker which causes the blocks to deform more due to the lateral load that subjected on it. As for interlocking geometry, it has the least deformation due to the system has the most suitable stiffness, ductility and flexibility to resist the lateral load applied on it. This proved that its interlocking effect between blocks gives better structural performance.

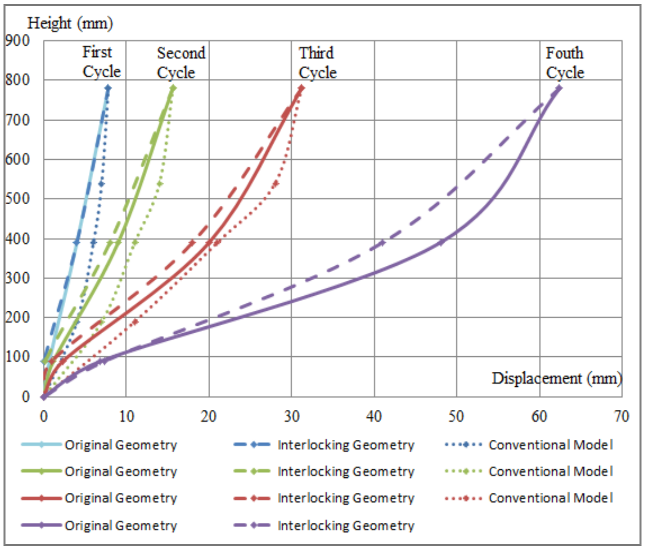

Figure 5 Profile Graph of both IBS Block Work Sub-systems and Conventional Sub-system in Every Cycle

3.3 Load, Inclinometer and Damages

Figure 6 shows the comparisons between lateral load and degree of inclination of column at the third cycle between both IBS block work sub-system and conventional sub-system. From the graph curve, it can be seen that the interlocking geometry has the larger degree of inclination when compared to original geometry. This is because the bonding between blocks for interlocking geometry is stronger than original geometry. The contact surface between blocks for interlocking geometry is larger compare to original geometry due to its interlocking effect. This would increase the friction between blocks and then form a stronger bonding between blocks. Therefore, the action of sliding between blocks for interlocking structure becomes lesser and the columns are subjected to more bending to resist the lateral load.

However, the degree of inclination for both IBS block work sub-systems is smaller than the degree of inclination for conventional sub-system. This is because the conventional sub-system was casted in one continuous plane which has the strongest concrete bonding. Ductility is reduced with increasing height-to-width ratio of the frame [16]. Hence, this proves that the IBS block work sub-systems have the better ductility and flexibility than the conventional sub-system. As a result, the interlocking parts between blocks for interlocking geometry block work sub-system not only gives the stronger bonding to the column but also the ductility and flexibility behavior between the interlocking blocks to resist lateral load.

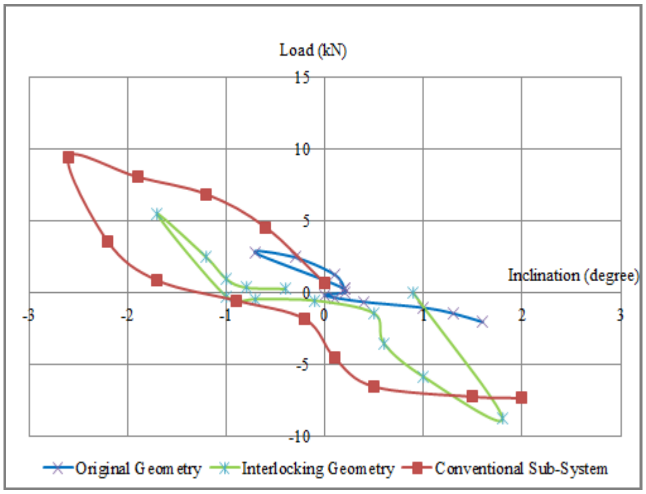

Figure 6 Comparison of Load and Degree of Inclination at Third Cycle

3.4 Load, Demec Displacement and Damages

There are three Demec Systems installed on the IBS block work sub-systems and four Demec Systems were installed on conventional sub-system. The position of Demec Systems installation is shown in Figure 7(a) for IBS block work sub-systems and Figure 7(b) for conventional sub-system.

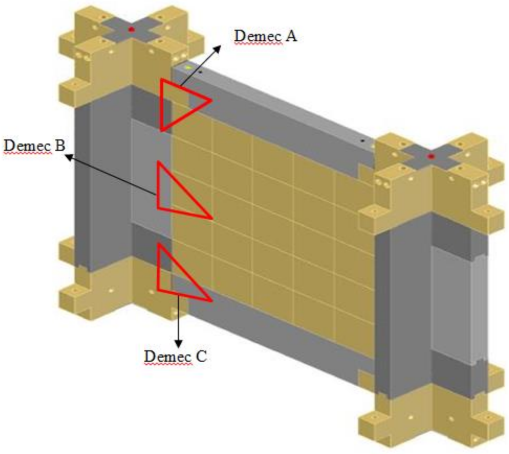

Figure 7(a) Position of Demec Systems for IBS Block Work Sub-systems Model

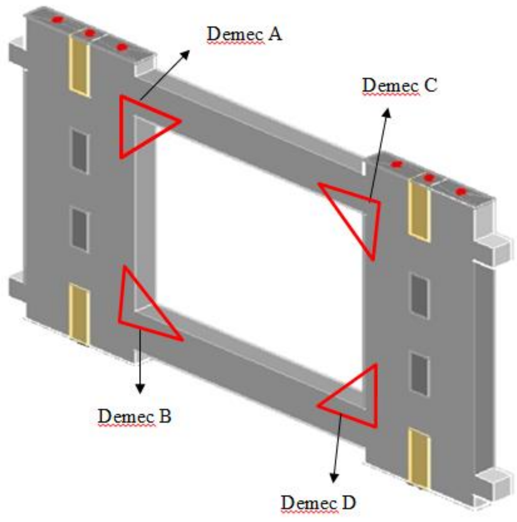

Figure 7(b) Position of Demec Systems for Conventional Sub-systems Model

For IBS block work sub-systems, the movement between blocks at Demec C is larger, followed by Demec B and finally Demec A. The same situation happened for both sub-systems of original geometry and interlocking geometry.

The movement of blocks at Demec C is the largest because Demec C is located at the bottom part of column connected to ground beam. When the lateral load is subjected to the structure, the bottom part of model sustain most of the load acting on the model and also the compressive force that is formed by the self-weight of whole model. When the action of load is applied and released repeatedly to the model, the bolt connection between the bottom column and ground beam starts to fail. At last, the corbel of bottom column of original geometry and the ground beam of interlocking geometry is crushed which cause the movement at Demec C to become larger. The damage of the ground beam of interlocking geometry is more serious than the damage of the column's corbel of original geometry. Therefore, the movement of blocks at bottom parts for interlocking geometry is larger than the movement of blocks for original geometry.

Demec B is located at the middle of left column which shows the movement of blocks between column and infill while Demec A is installed at the upper part of column and connected with upper beamas shown in Figure 7(a). The movement of blocks at Demec B is larger than Demec A. This is because the column and infill at Demec B is not connected by any special connection and it is only bonded by the surface friction between blocks. The column and beam at Demec A is connected with bolt connection which will limit the movement between blocks. Moreover, the upper part of structure is considered as free ended hence the upper structure is more flexible to resist the load applied on it. Hence, the movement of blocks at Demec A is the smallest.

For conventional sub-system, it seems that the movement of Demec A and Demec D is corresponding between each other and Demec B is corresponding with Demec C. This situation can be seen obviously through Figure 8. When the lateral load is applied from the left direction of the model, Demec A and Demec D are under tension state while Demec B and Demec C are under compression state. In contrast, when the lateral load is subjected from the right direction, Demec A and Demec D are under compression state while Demec B and Demec C are under tension state as shown in Figure 8. When the process of loading and unloading keeps repeating from both directions, shear cracks started to form at the connection part between column and beam. Therefore, the Demec movement increases every cycle because the shear cracks become larger and larger until the concrete at the connection part crushes and break into two as shown in Figures 9(a) and 9(b).

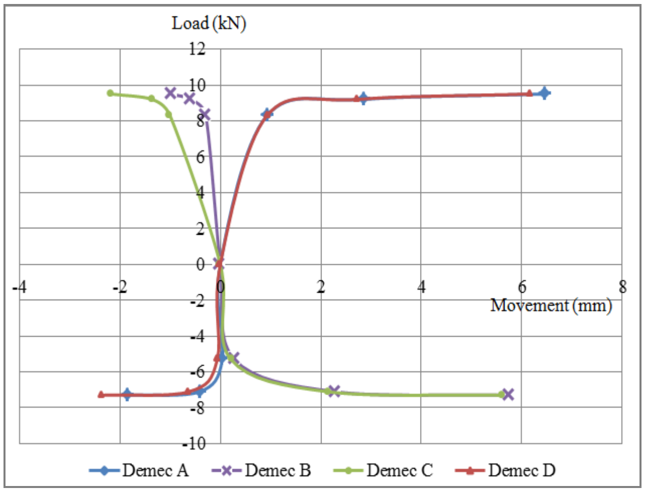

Figure 8 Load and Demec Movement of Conventional Sub-system

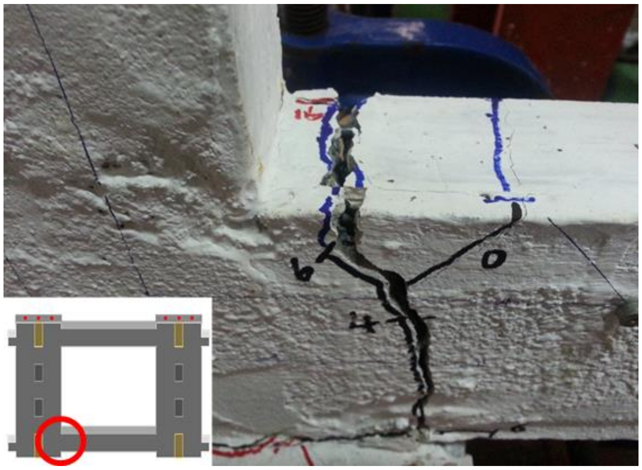

Figure 9(a) Beam Elements Separated from the Structure at Bottom Left Part and Reinforcement Exposed

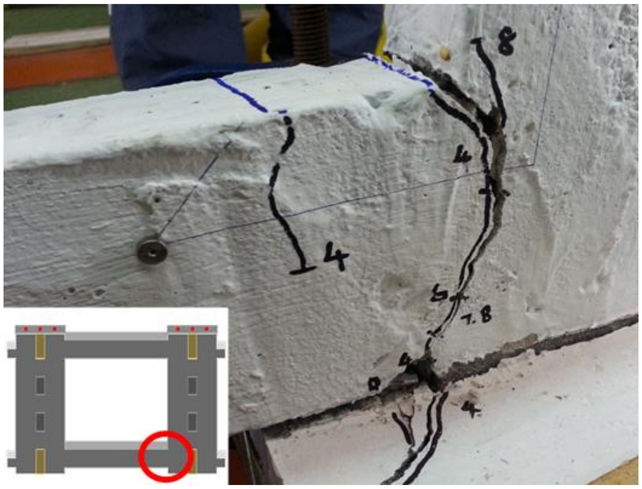

Figure 9(b) Beam Elements Separated from the Structure at Bottom Right Part and Reinforcement Exposed

3.5 Strain in Clamping Bolt

Figure 10 shows the strain curves of both IBS block work sub-systems and conventional sub-system. From the strain curve of original geometry sub-system, it clearly shows that its strain curve is very close to the elastic stiffness line. This means that the bolt is receiving the loads homogenously and does not received any sudden load. For original geometry model, the bolt retained its elastic stiffness behavior from first cycle until third cycle. This shows that the bolt is receiving the loads homogenously. Hence there are only minor damages occurred on the model from first to third cycle. The most serious damage is the concrete crushing at the column's corbel at the final cycle of load.

From the strain curves, it shows that the range of loading that can be sustained by the bolt of interlocking geometry sub-system is larger and its elongation of bolt is smaller than the elongation of bolt for original geometry sub-system and conventional sub-system. This means that the loading and stress from the interlocking structure do not rely much on the bolt strength so that the bolt does not reach its yield stress under the testing. For interlocking geometry model, the bolt maintained its elastic stiffness behavior at the first cyclic only and the homogenous load is lost in the system at 1.4 kN. After that, the strain curve of the bolt goes to non-linear for the rest of testing due to the bolt has lost its homogenous behavior in receiving loads at the second cycle of test. Hence the loads are sustained by the whole model until there are major damages occurred on the model. Major shear cracks were appeared on beam component and the damage of component cannot be repaired.

For conventional sub-system, the bolt started to lose its elastic stiffness at the first cycle of loading. As shown in Figure 10, the strain curve has reached its elastic limit and the strain value started to become constant. The bolt started to yield at the end of the second cycle of loading. As the third cyclic push over test starts, the bolt is in its plasticity state. The strain curve shows that the bolt is in ductile deformation but does not experienced necking and failed. However, the bolt is not stressed and elongated in perpendicular direction with its cross section. Therefore, the bolt is predicted to break into two parts without necking if the loading is increased.

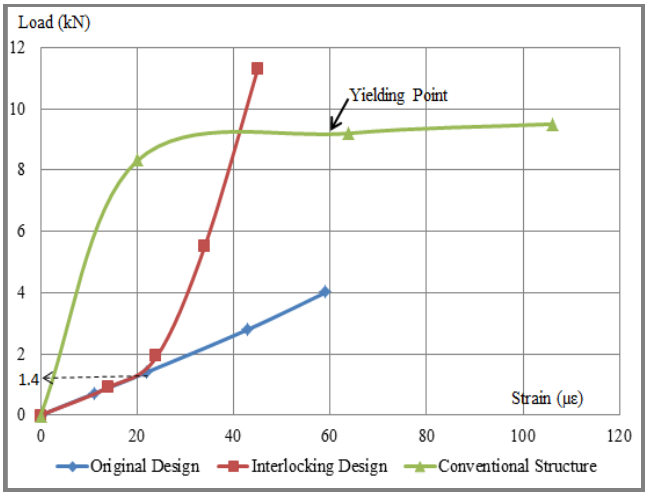

Figure 10 Strain Curve of Clamping Bolts

4.0 CONCLUSION

Table 2 shows the comparison of structural behavior between models under push over cyclic test for original geometry, interlocking geometry of IBS block works sub-systems and conventional sub-system.

Table 2 Comparison of Structural Behavior between Models

Structural Behavior	IBS Block Work Sub-Systems		Conventional Sub-System
	Original Geometry	**Interlocking Geometry**	
Stiffness	89.74 kN/m	230.77 kN/m	19.23 kN/m
Ductility	Higher (1.6°)	Higher (1.8°)	Lower (2.6°)
Flexibility	High	High	Low
Column Deformation	Smaller	Smallest	Largest
Bonding between Blocks	Lower	Higher	Highest
Sliding between Blocks	Slightly	No Sliding Action	No Sliding Action

From the structural behavior of models shown in Table 2, it shows that the interlocking geometry block work sub-system has the highest stiffness at the third cycle while the conventional sub-system has the lowest stiffness at its third cycle of test because the sub-system lost its stiffness after the shear cracks appeared and expanded. Furthermore, both IBS block work sub-systems have the better ductility compared to conventional sub-system as the ductility decreased with the increasing of degree inclination.

At last, it can be concluded that the IBS interlocking geometry block work sub-system has the most suitable structural behavior in terms of stiffness, ductility and flexibility. The IBS original geometry sub-system is ductile and flexible but lack structural stiffness while the conventional sub-system is not flexible.

As a conclusion, the IBS block work sub-system with interlocking configuration has performed better than original geometry model. Both of the IBS Block Work Sub-Systems should be improved at the beam-column connection to prevent connection failure which led to structural failure. By comparing the data with the control model of Conventional Sub-System, the IBS Block Work Sub-Systems have achieved the targeted structural strength which proved that it is safe and suitable for many structural usages such as residential houses. In terms of stiffness and ductility, both the IBS Block Work Sub-Systems performed better than Conventional Sub-System.

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