

## EXPERIMENTAL AND NUMERICAL VALIDATION OF FLEXURAL BEHAVIOUR OF MULTI-SCALE PREFABRICATED INDUSTRIALISED BUILDING SYSTEM (IBS) SUB-FRAME

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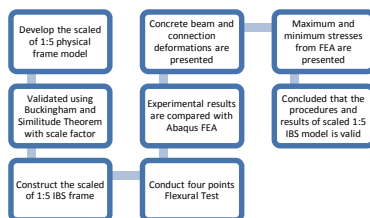
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### Graphical abstract



### Abstract

The paper describes the approach to develop the 1/5 scaled physical model and its applicability is validated against full scale model. Non-dimensional modelling methods using Buckingham Pi Theorem and Similitude Theory are explained and material properties for concrete, reinforcement, steel links, and beam-column connections are provided. The comparison between the results of experimental flexural test and Non-Linear Finite Element Analysis (NLFEA) of 1/5 scaled model and prototype of prefabricated IBS are discussed and presented. This paper is to verify the procedures and results of flexural test for 1/5 scaled model of prefabricated IBS in comparison to the prototype. The IBS components were set-up and tested under two-points monotonic vertical loading in Universiti Teknologi Malaysia Structure Laboratory. Three Linear Variable Displacement Transducers (LVDTs) and two strain gauges were instrumented in the small-scaled model to record deflections and strains. Both small-scaled model and prototype were analysed by Abaqus FEA software. Elastic range for both small scaled model and prototype are determined by scaled factor of 5.0, and proven to be accurate by both experimental test and NLFEA with ultimate capacity of 13 kN load and 10.9 mm vertical deflection. Since the similitude theory only applicable until elastic limit, hence the structural performance in nonlinear state is evaluated in concrete crack patterns and beam-column connection deformations are presented graphically in this paper. Load-displacement with maximum 12.9 mm deflection, 35.64 N/mm<sup>2</sup> ultimate crushing stresses at concrete and beam-column connection with minimum yield strength of 222.6 N/mm<sup>2</sup> are presented. This paper concluded that the procedures and results of flexural test for 1/5 scaled model of prefabricated IBS is valid in comparison to the prototype.

**Keywords:** SMART IBS, scaled models, flexural test, experimental, numerical validation

### Abstrak

Kertas kerja ini menerangkan pendekatan yang dilakukan untuk membangunkan model fizikal yang berskala 1/5 dan seterusnya mengesahkan kesesuaiannya untuk model berskala penuh. Kaedah pemodelan tanpa dimensi dengan menggunakan Teorem Buckingham Pi dan Teori Perumpamaan akan dijelaskan dan sifat-sifat bahan untuk konkrit, tetulang dan pautan, dan sambungan rasuk-tiang disediakan. Keputusan perbandingan antara ujian lenturan eksperimen dan Analisis Unsur Tak Terhingga Tak Linear (NLFEA) untuk model berskala 1/5 dan prototaip pasang siap IBS ini akan dibincangkan dan dibentangkan. Kertas kerja ini adalah untuk mengesahkan prosedur dan keputusan ujian lenturan untuk model pasang siap IBS berskala 1/5 berbanding dengan prototaip. Komponen IBS telah dipasang dan diuji dengan ujian dua titik beban menegak secara monotonik di Makmal Struktur. Tiga Linear Pembolehubah Anjakan Transduser (LVDTs) dan dua tolok terikan telah dipasangkan dalam model berskala kecil untuk merakamkan

pesongan dan terikan. Kedua-dua model berskala kecil dan prototaip telah dianalisis dengan menggunakan perisian Abaqus FEA. Lingkungan elastik untuk model berskala kecil dan prototaip telah ditentukan oleh faktor berskala 5.0, dan telah terbukti dengan tepatnya dengan kedua-dua ujian eksperimen dan NLFEA dengan kapasiti muktamad 13 kN beban dan 10.9 mm pesongan menegak. Oleh kerana teori perumpamaan hanya boleh digunakan sehingga had elastik, maka prestasi struktur dalam keadaan tak linear akan dinilai dengan corak keretakan konkrit dan perubahan bentuk dalam sambungan rasuk-tiang telah dibentangkan menerusi corak dalam kertas ini. Hubungan beban-anjakan rasuk dengan anjakan maksima 12.9 mm, 35.64 N/mm<sup>2</sup> tekanan muktamad pada konkrit dan perubahan bentuk dalam sambungan rasuk-tiang dengan minima tekanan lengkungan 222.6 N/mm<sup>2</sup> telah dibentangkan juga. Kertas ini mempunyai kesimpulan bahawa rasuk konkrit IBS telah gagal terlebih dahulu sebelum kegagalan penyambungannya.

*Kata kunci:* SMART IBS, model berskala, ujian leturan, experiment, pengesahan berangka

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## 1.0 INTRODUCTION

The period between First and Second World War, and war in Middle East countries had witnessed a mass home destruction that leads to high demand of replacement and renewal of housing. The shortages of skilled labour and essential materials for construction were greatly affecting the process of building reclamations.

Industrialised Building System (IBS) was introduced and originally applied in military operation to setup forward base in war. Now, it becomes a solution for house renewal strategies. It provides low cost housing and an improvement of construction processes through an exploration of component size and the prefabrication of standard components. In addition, precast structures have been widely accepted for residential construction in both undeveloped and developing countries to meet the rapid growth of population.

Innovative design of precast concrete components has been widely developed and used around world for past two decades. Flexural test is one of the common tests conducted by all the researchers to investigate the flexural behaviour of precast component especially in beam component.

Yip *et al.* [1] tested the flexural strength and performance of Special Reinforced Lightweight Aggregate Concrete (SRLWAC) beam under vertical static load. The SRLWAC is a beam component in IBS. The results showed the similar structural performance in both experimental and finite element analysis. Yang *et al.* [2] examined the flexural behaviour of the developed hybrid precast concrete beam system and showed that the introduction of prestressing force for longitudinal tension reinforcement has significantly improved the flexural behaviour of the hybrid precast concrete beam. Akiyama *et al.* [3] conducted flexural test of precast high-strength reinforced concrete pile prestressed with unbonded bars arranged at the centre of the cross-section to investigate the increment of pile's flexural capacity. The results of bending tests

demonstrated that the proposed prestressed reinforced concrete pile with carbon-fiber sheets and concrete infilling had a much higher flexural capacity than a conventional precast concrete pile.

Tesser and Scotta [4] investigated the shear and flexural strength of the beams with different depth, width and inclination of transverse reinforcement through flexural test. Kulkarni *et al.* [5] proposed a precast hybrid-steel concrete connection detail and showed the connection gives satisfactory flexural performance.

In Malaysia, the demand of housing is gradually increasing especially to provide an affordable residential building to the low and medium income group. Industrialised buildings were chosen by local government to fulfil the demands by using an advancement of technology in construction industry to produce high quality construction products at a low cost of construction operation. The conventional construction method is not able to meet the housing demand due to expensive costs of labour, materials, and transportation, multiple stakeholder and higher activity costs.

Industrialised Building System (IBS) is a sustainable approach and innovative technique that implements repetitive manufacturing in mass quantities of structural components offsite whereby it can control time, cost, quality, utilization of work force and promotes zero waste and sustainable fabrication environment [6]. IBS could be the method of mechanization of construction that solves for a quick, affordable and environmental sustainable housing predicament in Malaysia [7].

The components are manufactured batch by batch in a controlled environment without contaminate natural environment. For batch controlled product, it is necessary to conduct the experimental flexural test for every batch of production for quality assurance, in order to check the design capacity and to satisfy the client's needs and sustainable requirements. Besides, the predictability and consistency of quality of precast components can be maximized so as to ensure they are

up to a required standard such as MS ISO 9001:2000 [8] and accredited by Board of Engineers Malaysia.

Marsono *et al.* [7] had presented one of the standard tests to check the design and strength of full-scaled IBS components via an experimental flexural test and then verify the finite element analysis. Several tests of full scaled IBS experimental and FEA have to be carried out to achieve a reliable IBS components production to the structural engineering quality and meet the European Code of practice requirements. With these confidence results from both experimental and FEA methods, other development may rely on small-scaled model testing due to high costs and expenses on full-scale model physical tests on batches of production.

Hence, in this paper, small-scaled model is engaged in both experimental test and finite element analysis. This helps to reduce the cost and time of experimentation, and overcome the issue of restricted testing facilities available in the laboratory.

Dafin and Prevatt [9] had studied structural load path in wood-framed building using small scaled model. Kim *et al.* [10] carried out pseudodynamic tests to compare the predicted responses of a 1:5 scale reinforced concrete model with those of a prototype by using a constant modulus ratio and a variable modulus ratio. Satish *et al.* [11] developed two test procedures for pseudo dynamic test of scaled concrete structures. The difference in the test results due to variation in testing procedure is also addressed.

The attractiveness of small scale testing is tempered by the need to ensure the model responds like the prototype, which requires geometric, kinematic, and dynamic similarity relationships are met [12]. Using scaling concept, the behaviour of prototype can be investigated as Buckingham Pi Theorem [13] and Similitude Theory [14] is applied in this study. The size of a structural model is reduced without losing important characteristics in the behaviour of the prototype. Thus, geometric similarity is most important in this study as the low mass of the prototype structure is experimentally tested using static loads. In general, small-scale model results are comparable to the full-scale prototype if material similitude requirements are met [15] that relate the response of the scaled model to the full-scale prototype.

In this research, the results of small scaled IBS model are compared in load capacities, crack pattern, mode of failure and connection deformation for both experimental test and finite element analysis.

Verification of small-scale model, using the scaled size, geometry, material properties, connectors and bolts and nuts, will support future research by others in constructing similar models for other type of study such as applicability on-site installation. This study is the first in which a complete scaled and instrumented model of SMART IBS was constructed to study the comparison in between small- and full-scaled prefabricated IBS in response of static load.

## 2.0 METHODOLOGY

Flexural test of full scale SMART IBS frame was conducted by Marsono, *et al.* [7]. SMART IBS is an internationally patented building system assembly [16]. The components are designed and checked to comply with BS 8110 [17] and Eurocode 2 [18].

### 2.1 Structural Specifications for Small Scale Model

From Buckingham Pi Theorem, the appropriate scaling parameters are determined [13], through non-dimensional analysis. For modelling static elastic behaviour, the common  $\pi$  ( $\Pi$ ) term used is given in the following equation:

$$\Pi = \frac{P}{EL^2} \quad (1)$$

Where P is the load, E is the modulus of elasticity (MOE), and L is the geometric length.

For similarity, the  $\pi$  terms are set equal for both scaled model and prototype (Eq. (2)). Rearranging the terms in Eq. (2) becomes Eq. (3).

$$\left(\frac{P}{EL^2}\right)_p = \left(\frac{P}{EL^2}\right)_m \quad (2)$$

$$\frac{P_p}{P_m} = \frac{E_p L_p^2}{E_m L_m^2} = S_E S_L^2 \quad (3)$$

Where  $S_E$  and  $S_L$  are the scale factors of the prototype MOE and geometric length to model scale, respectively.

Table 1 shows the similitude relation for prototype and scaled model in elastic state.

**Table 1** Similitude relations [19]

Parameters	Scale factor
Dimension	S
Linear displacement	S
Point load	$S_E S_L^2$

Small scale of 1/5<sup>th</sup> SMART IBS model was constructed. The scale factor, S for the model is 5. Then, the geometry of the model was scaled by a factor S, that is  $l_m = l_p / S$  where  $l_m$  and  $l_p$  are the geometrical dimensions of the model and prototype respectively. Since the both model and prototype are made of same material, the stress field remains similar. Then, the displacement of the scaled model will be S times less than the corresponding displacement in the prototype in elastic state. The concentrated loads are reduced from prototype loads by factor of  $S_E S_L^2$  that is by factor of  $(1)(5^2) = 25$ .

The similitude relation between prototype and the model was validated with the same boundary conditions, loadings conditions and materials.

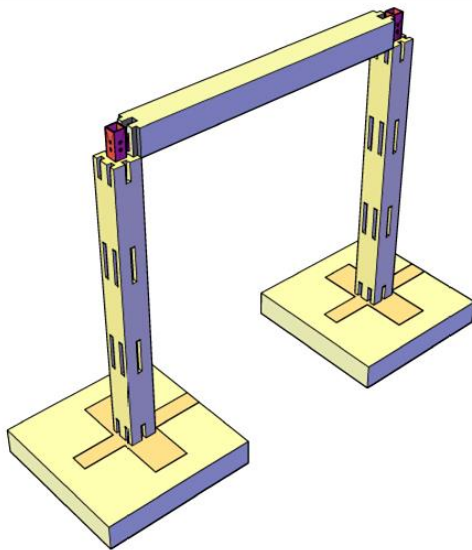
SMART IBS sub-frame with scale 1:5 was constructed. The sub-frame consists of one beam and two columns. The serviceability limit state, ultimate flexural strength and mode of failure of IBS beam was investigated when subjected vertical loads. The performance of beam was assessed and compared to full scale model for validation.

The model's length of both beam and column is 660 mm. The sub-frame was assembled with centre-to-centre distance of 700 mm between columns, which represent the distance of 3500 mm between full scale columns.

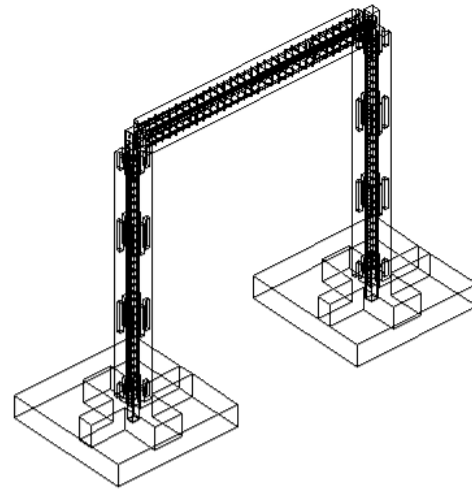
Both beam and column has 60 mm x 60 mm cross section. Bolts and nuts are used to connect steel rectangular hollow section (RHS) of 25 x 25 x 120 mm of column to the U-shaped steel plate of 160 x 40 x 20 mm in the beam-ends. The steel plate was cut and welded to fabricate the U-shaped steel plate.

The diameter of all reinforcements and links are 6 mm and 1.5 mm respectively. The concrete cover of 6 mm is provided to the main reinforcements. Figure 1 shows the specifications and details of the IBS frame.

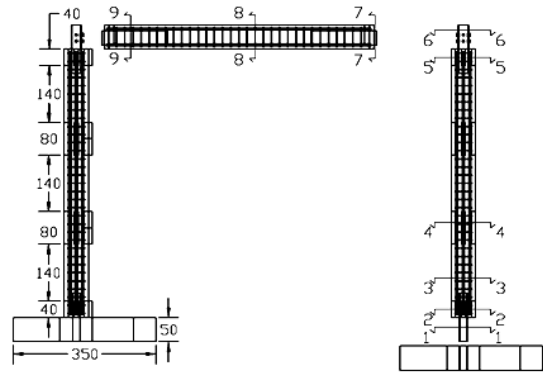
The U-shaped steel plates in beam were tied together with 5 mm diameter longitudinal main reinforcements at top and bottom part of beam. The half-height of steel RHS of column was casted together into the concrete to provide rigid bonding between the concrete and connectors.



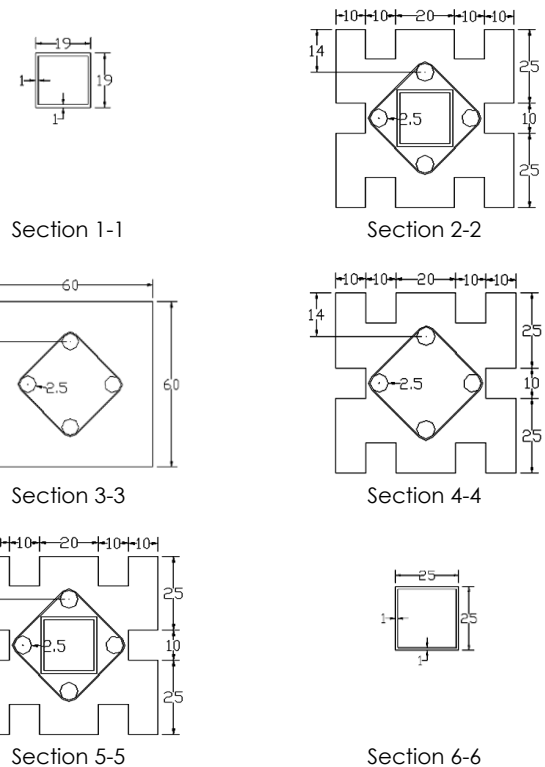
(a) 3D perspective view

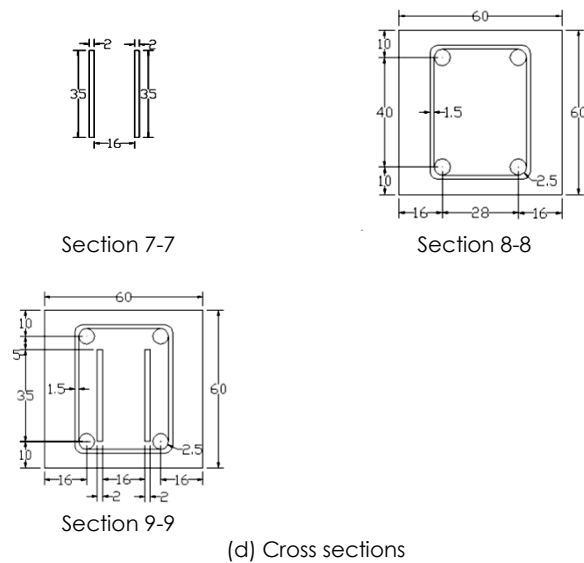


(b) 3D wireframe view



(c) 2D front view





**Figure 1** Specifications and details of IBS frame

## 2.2 Material Properties of Small Scale Model

The prescribed material properties are normal strength concrete of class C30/37 according to Eurocode 2 [18]

(characteristic cylindrical compressive strength  $f_{ck,cyl} = 30$  MPa) with a maximum aggregate size of 5 mm.

The concrete cylinders of diameter of 100 mm and height of 200 mm were cast along with every batch of components concrete casting. The samples were tested for compressive strength and tensile strength at 28 days, and on the day of structural testing. The concrete split tensile strength is computed with compliance of ASTM C496 [20]. Concrete compression strength is obtained to predict the limit of concrete crush and tensile strength is to predict the limit of concrete cracks during laboratory testing as well as Young's modulus value for predicting the linear and non-linear profile state of the concrete. The mean concrete compressive strength at an age of 28 days,  $f_{cm}$  (28) is 38 MPa. Modulus of elasticity (MOE) of the scaled component should be equal to the full scale component in order to comply with the similitude law which is 32 GPa.

All the steels were tested in UTM Mechanical Engineering laboratory using Universal Testing Machine to obtain its mechanical properties as shown in Table 2. The main mechanical properties such as yield stress, yield strain, ultimate stress, ultimate strain and modulus of elasticity are presented.

**Table 2** Mechanical properties of steel

Type	Diameter/ Thickness (mm)		$f_y$ (MPa)	$\epsilon_y$ (%)	$f_u$ (MPa)	$\epsilon_u$ (%)	E (GPa)
	Nominal	Measured					
Steel (link)	1.5	1.52	922.74	0.60	964.57	1.44	227.343
Steel bar	5	5.38	650.70	0.32	761.99	1.46	199.578
Steel plate (column)	1	0.86	222.60	0.31	253.80	9.20	150.700
Steel plate (beam)	2	2.64	446.09	0.32	555.57	17.30	206.441

Note:  $f_y$  and  $\epsilon_y$  is yield strength and strain respectively while  $f_u$  and  $\epsilon_u$  is ultimate strength and strain respectively

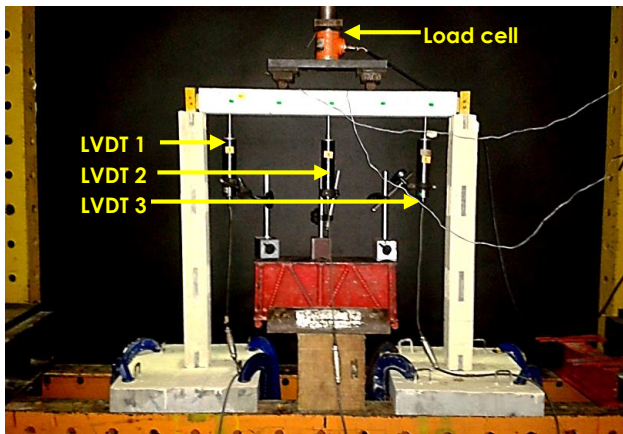
## 2.3 Experimental Test

Testing was carried out in structure laboratory. The frame was tested under vertical two-point loads on beam. Figure 2 shows the set-up of frame for flexural test.

In flexural test, three Linear Variable Displacement Transducers (LVDTs) were installed at bottom of beam to measure the vertical deflection. LVDT 1 and LVDT 3 were placed at the bottom of beam near ends to measure the deflection occurred under the U-shaped steel plate while LVDT 2 was placed under mid-span of beam to measure the deflection at maximum moment zone. Load cell and LVDTs were connected to a data logger for data recording at every millimetre of the applied monotonic vertical load. The deformations of the main longitudinal steel reinforcement were measured by electrical resistance strain gauges which were embedded under the surface of steel reinforcement inside the concrete.

The loading procedure with reference with BS EN 12390-5: 2009 [21] was conducted. The frame was loaded symmetrically at the centre line of 1/3 and 2/3 of beam's length. The maximum allowable deflection of beam at serviceability limit state of beam was 1.4 mm (centre to centre support span/500) in compliance with Eurocode 2 [18]. Hence, the frame was slowly loaded with an incremental of 0.5 kN to the target deflection of 1.4 mm. First hairline crack was observed at 2 kN with displacement of 1.0 mm which indicates the frame has reached serviceability limit state. Then, the beam was loaded continuously with incremental of 0.5kN/minutes until failure occurs. Since U-shaped steel plates were casted near the support, the beam is not fail at the support.





**Figure 2** Diagram of frame flexural test set-up

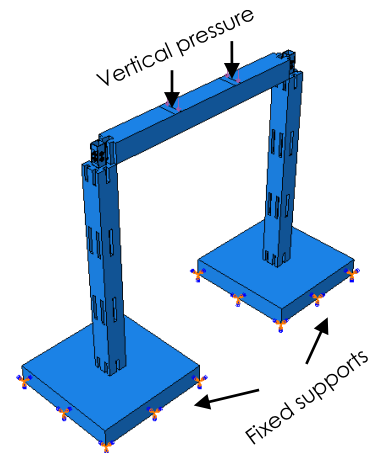
## 2.4 Non-linear Finite Element Analysis

In this research, nonlinear finite element analysis (NLFEA) was conducted to obtain more comprehensive and visibly hidden behaviour, failure pattern of structure and compared to the experimental results. Abaqus FEA software was chosen as it can accurately calculate the structural performance in linear and nonlinear state analysis.

Similar structural specifications, material properties and boundary conditions of the models were assigned in Abaqus FEA to simulate towards the real experimental models as shown in Figure 3. The frame was fixed to the ground, and geometrical nonlinearities were defined according to the tested material properties.

Maximum and minimum principal stresses of concrete were used to detect the location of concrete cracking and crushing respectively. In addition, the deformation of steel plate and RHS were evaluated using von Mises stresses whereas maximum principal stress of steel were used to evaluate the deformation of main reinforcement.

The similarities of load-deflection relationships, crack patterns and mode of failures simulated by Abaqus FEA were discussed and compared to experimental results.



**Figure 3** Modelling of 1/5 scaled model in Abaqus FEA

## 3.0 RESULTS AND DISCUSSION

### 3.1 Comparison of Load-Displacement of Small-Scaled SMART IBS Frame in Experimental Test and FEA

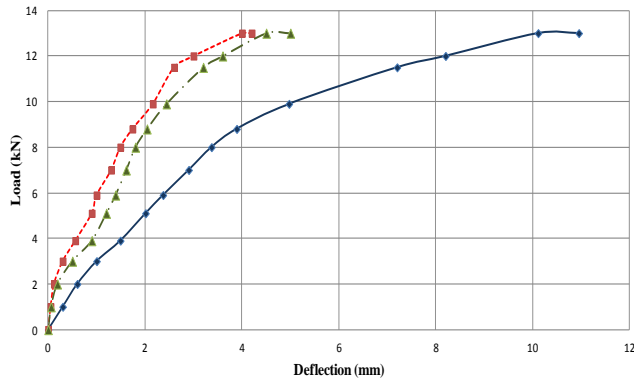
The behaviour of innovative IBS frame (prototype) was presented in Marsono, *et al.* [7]. The beam behaves elastically up to load of 50 kN and 5 mm of vertical displacement with appearance of first vertical crack at mid-span. Then, the plastic behaviour starts to control the structural system. The experimental ultimate capacity of new innovative IBS beam was 133 kN with 24.13 mm deflection at mid-span of beam. The concrete beam was failed before connection failed.

The experimental result in this paper was presented in the load-displacement diagram from the onset of loading to its ultimate limit state. Figure 4 shows the experimental load-deflection at three points by LVDT 1, LVDT 2 and LVDT 3. The beam behaves elastically up to 2 kN with deflection of 1 mm before start entering the non-linear behaviour with appearance of first vertical crack at mid-span. As the applied loads were increasing, multiple newly formed and propagated cracks occurred in the mid-span of beam which means that the bottom of beam was essentially in flexural tension state.

The performance of small scale model was validated and proven true as predicted by similitude theory. The displacement of scaled model is 1 mm, which is 5 times less than the corresponding displacement of 5 mm in the prototype in elastic state. In addition, the loads are reduced from prototype loads by factor of 25. This is validated as the load of 2 kN is obtained by model compared to the load of 50 kN by prototype in elastic state.

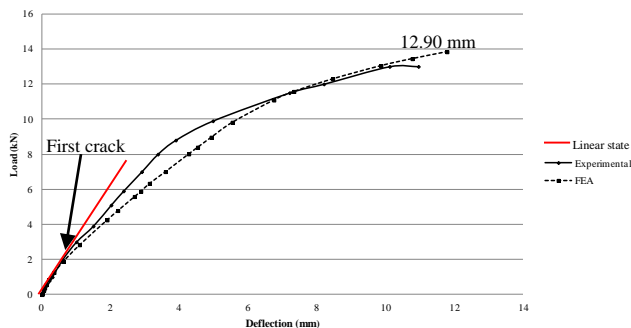
Once the concrete has cracked and deformed, the force that was sustained previously by concrete had distributed to the tensile reinforcement through the uncracked region of concrete. In this state, the stiffness of beam was reducing and plastic behaviour

starts to control the structural system. The ultimate load capacity of beam was 13 kN with deflection of 10.95 mm as it could not take any further applied loads but with the increasing in deflection.



**Figure 4** Experimental load versus vertical displacement diagram at all deflection point

The comparison between nonlinear finite element analysis (NLFEA) and experimental results in load-displacement relationship of the small scale model is shown in Figure 5. The elastic behaviour of the model resulted from NLFEA and experimental tests were closely similar especially at the first stage of loading until the occurrence of the first crack under elastic state loading of 2 kN with deflection of 1 mm. However, there were some deviations of load-displacement relationship in plastic state after the occurrence of the first crack. Abaqus FEA was not able to capture the crack propagation at plastic state when the cracks were started to propagate and thus reduce the internal resistance of the models.

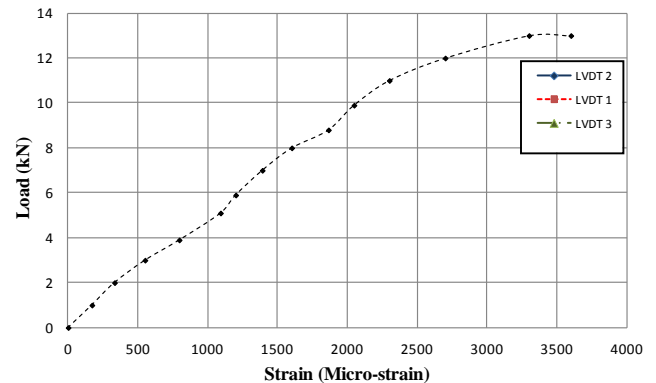


**Figure 5** Comparison of load-displacement relationship in flexural experimental test and NLFEA at mid span (LVDT 2) of beam

**3.2 Load-Strain Relationship of Steel Bar of Small-Scaled SMART IBS Beam in Experimental Test**

Strain gauge was installed at the bottom of steel reinforcement at the mid-span inside the concrete to measure the strain of steel reinforcement during

experiment. The load-strain relationship of steel bar is shown in Figure 6. It is clearly shown the relationship was linear before the first crack appears at 2 kN. The slope of load-strain curve starts to decrease slowly when flexural cracks start to appear. The strain of bottom steel reinforcement was extended to 3600 micro-strain and yielded together with the failure of system at 13 kN. This characterises the flexural failure of beam with the appearance of vertical cracks and yield of its horizontal steels.



**Figure 6** Load-strain relationship of steel bar

**3.3 Comparison of Crack Patterns and Mode of Failure of Small-Scaled SMART IBS Beam in Experimental Test and FEA**

Figure 7(a) shows the first flexural crack that appears from the bottom of mid-span of beam. The formation of the first crack indicates that the SMART IBS beam has exceeded its serviceability limit state. The serviceability limit state for the beam was 1.4 mm as to comply with Eurocode 2 [18] (centre to centre support span/250). After the first flexural crack appeared, the beam has lost its elasticity and the beam was not able to return to its original state. Nonlinear state of beam starts after this state and multiple of flexural cracks had propagated with upwards face direction at beam mid-span. This means that the bottom of beam was in flexural tension state.

Once the beam concrete has cracked and deformed, the force that sustained previously by concrete had been distributed to the tensile reinforcement through the uncracked region of concrete. As the load increases further, the stiffness of the beam has reduced when the reinforcing bars and concrete start to reach its yield strength. The beam met its ultimate capacity when it could not take any further applied loads but with the increasing of deflection. The cracks patterns of beam at the ultimate capacity are shown in Figure 7(b), Figure 8(a) and Figure 8(b).

Figure 9 shows the profile deflection of beam at ultimate capacity. It is shown that the beam was in ductile condition. The beam was divided into 5 parts. The deflection at point of LVDT 1 and 3 (Part 2 and 4)

were lesser than the deflection at LVDT 2 (Part 3). This was because of the maximum bending moment and cracking were concentrated at maximum bending moment zone which was the mid-span of beam (Part 3).

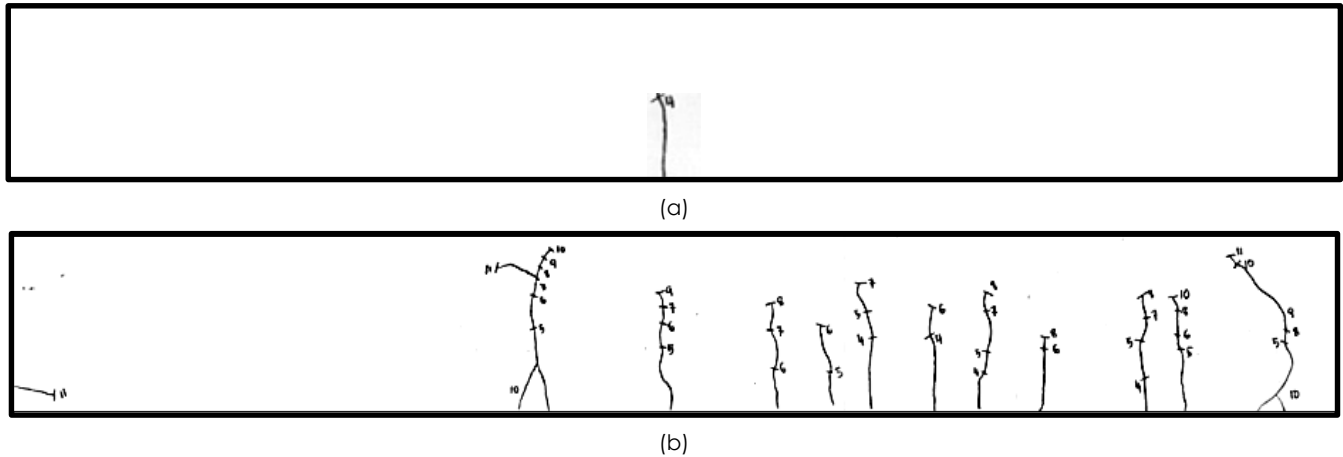
Numerous of flexural cracks at upwards face at beam mid-span can be observed. The absence of diagonal shear crack at both ends of beam indicates shear strength of the beam was sufficient provided by the U-shaped steel plate of beam. At the end of the experiment, both columns were still in good condition with no defect and crack as shown in Figure 8.

The deformation pattern of system at final load by NLFEA for flexural test is shown in Figure 10(a) and it was similar to the experimental test as shown in Figure 8. The maximum deformation was occurred at the maximum moment zone at the mid-span of beam shown in Figure 10(a).

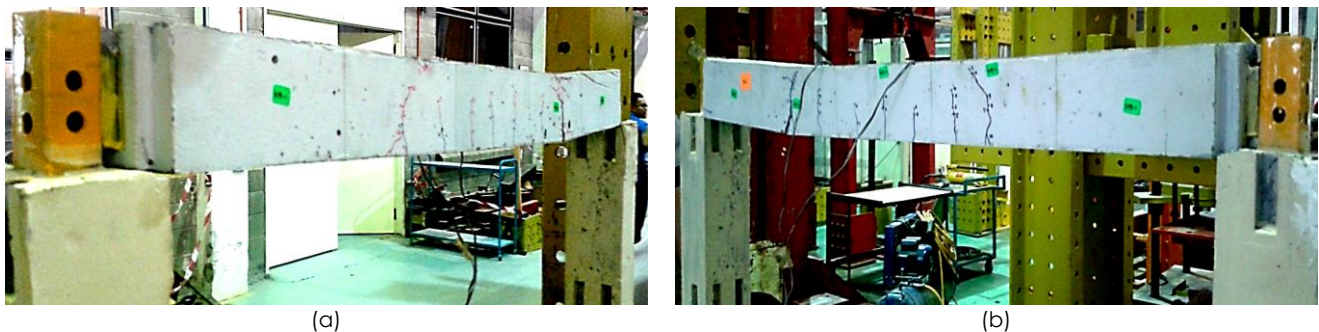
During the experimental test, the concrete beam was crack at the bottom of the mid-span of beam. For all models in NLFEA, maximum principal stress with

value more than  $+3.615 \text{ N/mm}^2$  of concrete element indicates the area of concrete cracking whereas minimum principal stress with value less than  $35.64 \text{ N/mm}^2$  indicates the location of concrete crushing. The contour plots with different colour show the different principal stresses occurred in concrete.

The plot of maximum and minimum principle stresses for concrete only of the beam are shown in Figure 11(a) and Figure 11(b) respectively. Figure 11(a) and Figure 13 clearly show that the concrete beam was cracking at the maximum moment zone at the bottom of beam. On the other hand, the concrete has local failures under loads at the top side of beam in Figure 11(b) and Figure 14. Figure 13 shows the concrete beam at both end sides was cracking whereas Figure 12 shows the column concrete around RHS crushes due to the applied force acting vertically and hence RHS is bending inward and creates stresses at the surrounding of concrete.

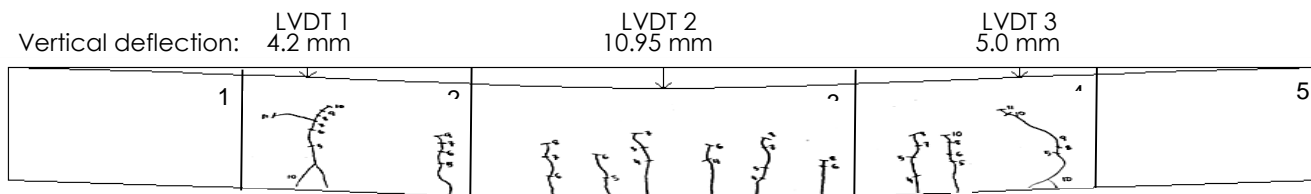


**Figure 7** Experimental crack pattern of beam front view (a) at 2 kN and (b) at 13 kN

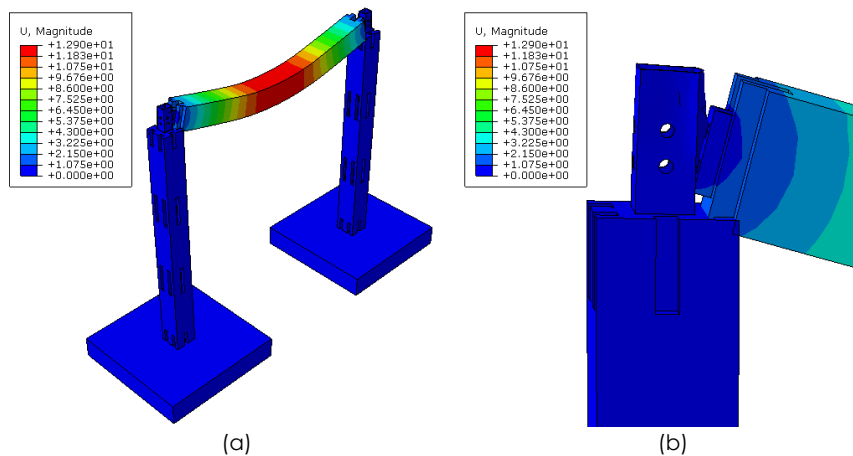


**Figure 8** Experimental deformation pattern of beam at load 13 kN (a) front view and (b) rear view

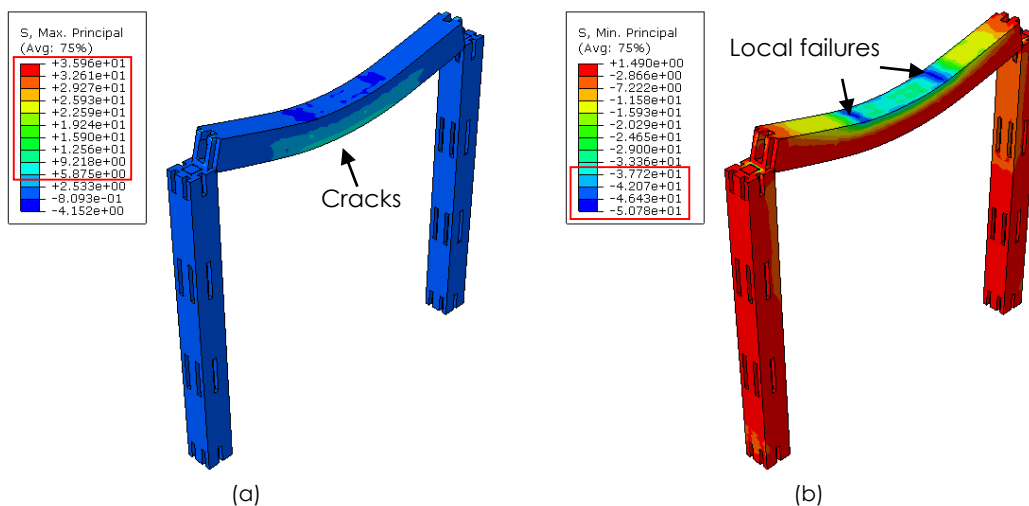




**Figure 9** Site view profile of deflection of beam at ultimate state (13 kN)



**Figure 10** Deformation pattern for beam flexural analysis (a) overall deformation and (b) deformation at beam-column connection



**Figure 11** Principle stresses of concrete only for flexural analysis (a) maximum and (b) minimum

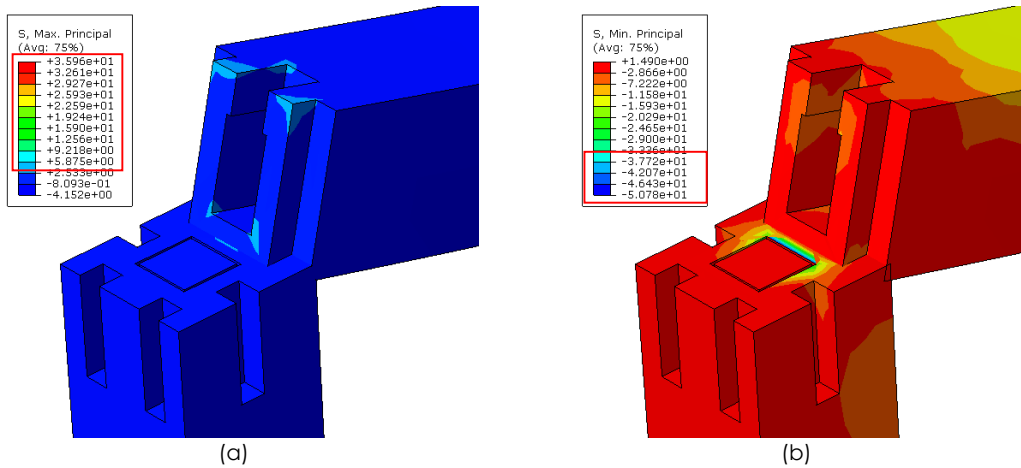


Figure 12 Principle stresses of concrete only at connection (a) maximum and (b) minimum

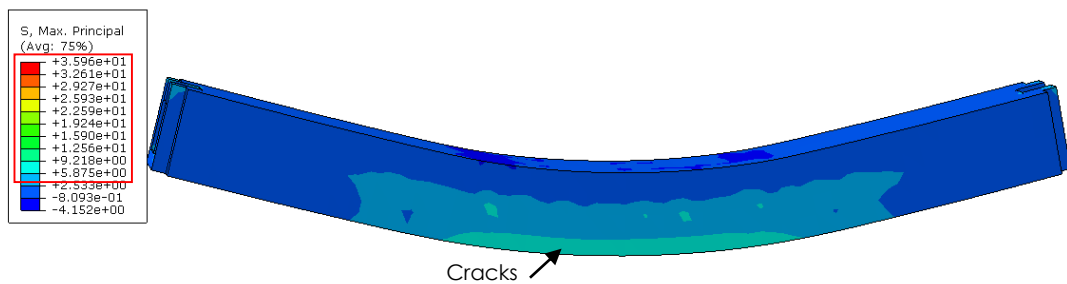


Figure 13 Maximum principle stresses of concrete beam

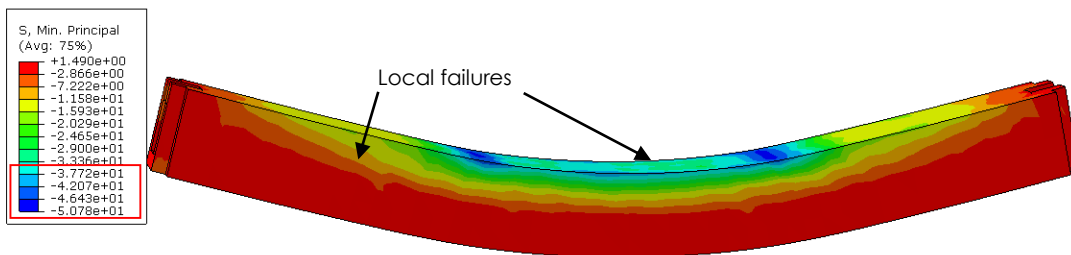


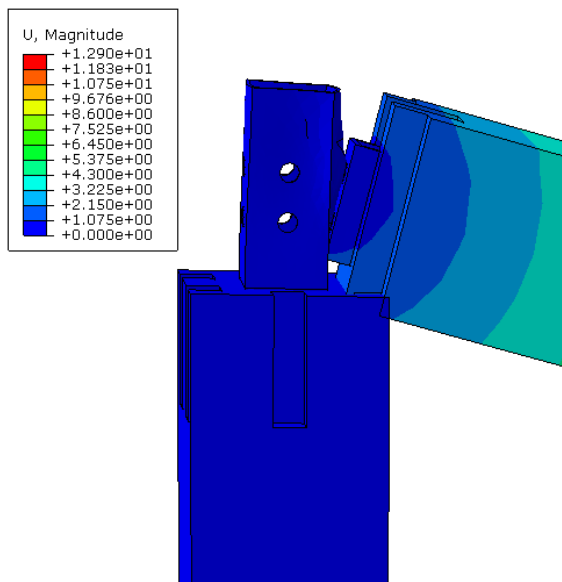
Figure 14 Minimum principle stresses of concrete beam

The experimental deformation at beam-column connection at the end of the test is shown in Figure 15. The sustained load by concrete beam previously was transferred to the main reinforcement once the concrete has cracked. Consequently, the main reinforcements were in tension and the tensile stresses were transferred to the U-shaped steel plates of beam. High tensile stresses of U-shaped steel plates were transferred to the column RHS jointed by bolts and nuts. The RHS starts to yield and bend inward towards the U-shaped steel plate of beam. Further additional loadings may cause the failure of connection. The deformation pattern of connection was similar to the prototype by Marsono *et al.* [7]. The ductile behaviour of connection is important to increase the ductility level of beam.

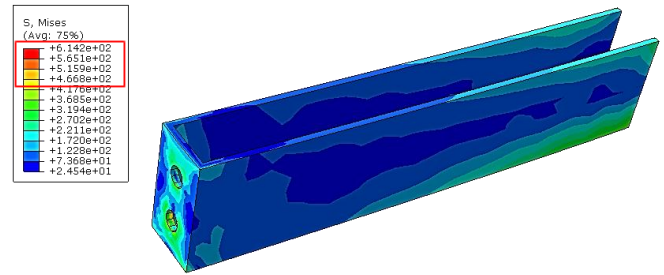
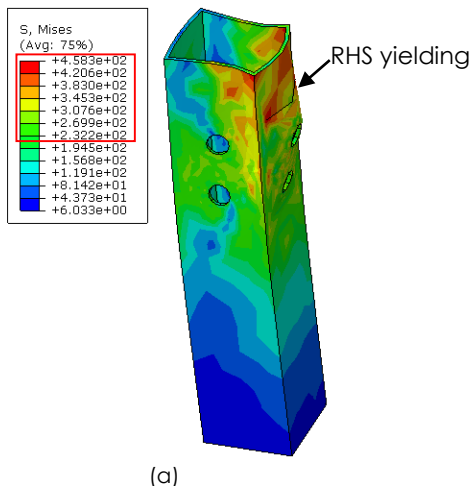


Figure 15 Experimental deformation at beam-column connection

Connection deformations in NLFEA as shown in Figure 16 were verified by experimental test. Figure 17 shows stress distribution of RHS and U-shaped steel plate at ultimate limit state, 13 kN. Von Mises stress was used to locate the failure stress of ductile materials such as horizontal main reinforcement, RHS and beam steel plate. The yield stress of RHS and U-shaped steel plate of beam was 222.6 N/mm<sup>2</sup> and 446.09 N/mm<sup>2</sup> respectively. Hence, the stress with value more than 222.6 N/mm<sup>2</sup> indicates the RHS has yielded whereas stress of with value more than 446.09 N/mm<sup>2</sup> indicates the U-shaped steel plate has yielded as illustrated in Figure 17(a) and Figure 17(b) respectively. The theory is main reinforcements were in tension and the tensile stressed were transferred to the end plates. Hence, the high tensile stress in end U-shaped steel plates cause the plates start to yield as shown in Figure 17(a) and Figure 17(b). RHS of column starts to yield and hence causes the RHS bend inward to the steel plate of beam. Further additional loadings may cause the failure of connection.

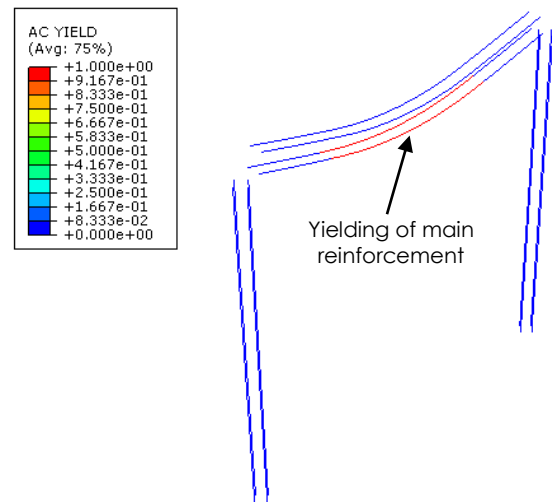


**Figure 16** Deformation at beam-column connection by NLFEA

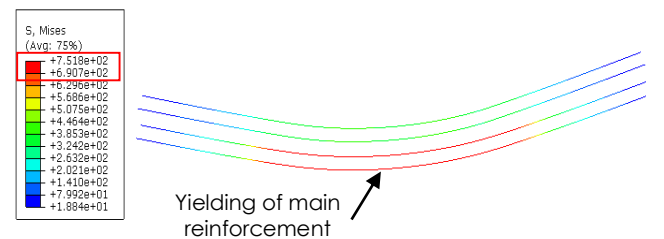


**Figure 17** Stress distribution of IBS components at 13 kN (a) RHS of column and (b) U-shaped steel plate of beam

Figure 18 shows the AC yield of main reinforcement. The red colour at the mid span with value of 1 indicates the main reinforcement was currently yielding. The load that sustained previously by concrete beam had transferred to the main reinforcement once the concrete cracked. Von Mises stress of main reinforcement with value more than 650.70 N/mm<sup>2</sup> indicates the yielding of steel as shown in Figure 19 with ultimate stress of main reinforcement was 751.8 N/mm<sup>2</sup>.



**Figure 18** AC yield of main reinforcements



**Figure 19** Stress distribution of main reinforcement in beam

Both small-scaled model and prototype were tested experimentally and analyzed using FEA software. From all the comparisons shown as above, the similarities of load-deflection relationships, crack patterns and mode of failures for both prototype and small-scaled model were proved.

#### 4.0 CONCLUSION

In this study, the procedures and results of flexural test for 1/5 scaled-model of IBS was validated. The overall small-scaled IBS system behaviour was validated against a full-scale prototype by accurately produce similar deformation pattern at full-scale up to elastic limit of model. This was the first time a small-scale of prefabricated SMART IBS model adhering to similitude requirements was constructed to investigate and validate the flexural test procedures and results. The paper presented method to select appropriate model scale materials complement to similitude requirements. High ductile characteristic of SMART IBS model was proven experimentally. Both full- and small-scaled model share the similar failure mode. The concrete beam was crack at mid-span and steel connector was yield at ultimate limit state. In conclusion, the experimental test has proven that the concrete beam was failed before connection failed.

#### Acknowledgement

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