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FLEXURAL STRENGTH OF SPECIAL REINFORCED LIGHTWEIGHT CONCRETE BEAM FOR INDUSTRIALISED BUILDING SYSTEM (IBS)

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Graphical abstract

Abstract

Special reinforced lightweight aggregate concrete (SRLWAC) beam is designed as beam component in Industrialised Building System (IBS). It is used to overcome the difficulties during the component installation due to the heavy lifting task. This paper presents the flexural strength and performance of SRLWAC beam under vertical static load. SRLWAC beam was set-up on two columns corbel and tested under monotonic vertical load. Five Linear Variable Displacement Transducers (LVDTs) were instrumented in the model to record displacement. The ultimate flexural capacity of the beam was obtained at the end of experiment where failure occurred. Performance of the beam was evaluated in load-displacement relationship of beam and mode of failure. SRLWAC beam was then modelled and simulated by nonlinear finite element software- Autodesk Simulation Mechanical. Result from finite element analysis was verified by experimental result. Maximum mid-span displacement, Von-Mises stress, concrete maximum principal stress, and yielding strength of reinforcement were discussed in this paper. The beam was behaved elastically up to 90 kN and deformed plastically until ultimate capacity of 250.1 kN in experimental test. The maximum mid span displacement for experimental and simulation were 15.21 mm and 15.36 mm respectively. The major failure of IBS SRLWAC beam was the splitting of the concrete and yielding of main reinforcements at overlay end. Ductility ratio of IBS SRLWAC beam was 14.2, which was higher than pre-stressed concrete beam.

Keywords: Industrialised Building System (IBS), special reinforced lightweight aggregate concrete (SRLWAC), experimental test, finite element analysis, ultimate flexural capacity

Abstrak

Tetulang khas agregat ringan konkrit rasuk (SRLWAC) telah direka sebagai komponen rasuk dalam sistem binaan berindustri (IBS). Ia adalah digunakan untuk mengatasi kesukaran ketika pemasangan komponen yang disebabkan oleh tugas mengangkat berat. Kertas ini membentangkan kekuatan lenturan dan prestasi rasuk SRLWAC di bawah beban statik secara menegak. Rasuk SRLWAC telah dipasang pada dua tiang yang bertindak sebagai sokongan dan diuji di bawah beban monotonik secara menegak. Lima Linear Pembolehubah Anjakan Transduser (LVDTs) telah dipasangkan di dalam model untuk mencatatkan anjakan rasuk. Kapasiti lenturan muktamad rasuk itu telah diperoleh pada hujung eksperimen di mana kegagalan telah berlaku. Prestasi rasuk telah dinilai melalui hubungan beban-anjakan rasuk dan mod kegagalan. Rasuk SRLWAC kemudiannya dimodelkan dan disimulasikan dengan menggunakan perisian unsur terhingga tak linear - Autodesk Simulasi Mekanikal. Keputusan daripada analisis unsur terhingga telah disahkan oleh keputusan yang diperoleh daripada eksperimen. Anjakan maksimum pada pertengahan rentang, tekanan Von-Mises, tekanan utama maksimum konkrit, dan kekuatan tetulang telah dibincangkan dalam kertas kerja ini. Rasuk ini telah berkelakuan secara anjal sehingga 90 kN dan kemudiannya berubah bentuk secara plastik sehingga mencapai keupayaan muktamad iaitu 250.1 kN dalam ujian eksperimen.

Anjakan maksimum pada pertengahan rentang untuk eksperimen dan simulasi masing-masing adalah 15.21 mm dan 15.36 mm. Kegagalan utama rasuk IBS SRLWAC adalah pemisahan konkrit dan kehilangan kekuatan pada tetulang utama di penghujung rasuk. Nisbah kemuluran rasuk IBS SRLWAC adalah 14.2, iaitu lebih tinggi daripada rasuk pra-tekanan konkrit.

Kata kunci: Sistem binaan berindustri (IBS), tetulang khas agregat ringan konkrit rasuk (SRLWAC), ujian eksperimen, analisis unsur terhingga; kapasiti lenturan muktamad

1.0 INTRODUCTION

Application of Industrialised Building Systems (IBS) is getting popular in civil construction and engineering field. Lachimpadi *et al*. [1] stated that IBS is a construction process which involves prefabrication of components from factories and on-site installation. The usage of IBS in construction field has advantages such as minimize the wastage during construction, develop skilled workers, increase site cleanliness, better quality control and reduces the time of completion of construction [2].

However, the fabrication of IBS structural component requires high precision and skilled works. The problems arise regarding the feasibility of IBS project in the developing country are highlighted by Kamarul *et al*. [3]. Poor coordination is also one of the factors for example, joints of the IBS structure are not standardised and accuracy of the product varies between manufacturers. Besides, IBS structure requires on-site specialised skills for assembly and erection of components. The lack of specially designed assembly equipment and special skilled workers will ultimately increase the difficulties of the construction works [4]. Hence, extensive research and development of new IBS products, manufacturing processes and structural designs are desperately required for promoting and strengthening the confident level of IBS investors [5].

Based on article from CIDB [6], IBS can be divided into five different systems. The five different systems are pre-cast concrete framing, panel and box system, steel formwork system, steel framing system, prefabricated timber framing system and block work system. Among all the five systems, block work system or reinforced masonry is the most potential system to construct a structure with an earthquake resistance capability [7].

Block work system is the combination of normal or lightweight aggregates concrete blocks with interlocking systems together with conventional or prefabricated column-beam and other composite panels or vice-versa [8]. The benefits of using reinforced concrete interlocking block in structural system are able to provide better shear capacity, deformation ability and seismic resistance [9]. The uniqueness of the concrete block with holes enables vertical and horizontal locking steel bars to pass through the block.

According to Zhu *et al*. [9], reinforcement installed in concrete block will result in increasing of ductility and strength of the overall structural system. Additional groove provided on concrete block could enhance the interlocking ability and provide better structural integration between block system. Marwan *et al*. [10] has also proved that seismic performance of the block work structural system was significantly influenced by the ductility of the block itself. Hence, concrete block work system has an ability to resist seismic effect with the correct combination of different size and shape to becoming a structural system.

Besides, many researches had been conducted to improve beam flexural capacity. For example, Gerasimos [11] had tested two types of concrete beams and introduced simple modification method applied in current calculations for better access to the predicted flexural capacity of concrete beam. Other than that, Catarina *et al*. [12] had highlighted most of the in-situ reinforced concrete structural elements especially beam element was lack in appropriate seismic detailing. From this scenario, Catarine *et al*. [12] had presented research on cyclic load test on reinforced concrete beams and access results namely with force-deflection diagram, deformation shape, damage evolution, energy dissipation and rotation at beam supports. Moreover, Xie *et al*. [13] accessed de-bonding prediction of reinforced concrete beam with fully strengthen by pre-stressed fiber reinforced polymer (FRP). FRP or hybrid fibre can be good in strengthen the structural section [14]. However, configuration of FRP into beam section requires an extensive further research in improving the flexural strength of concrete beam.

Lightweight aggregate concrete technology may meet a demand of lightweight structure as well as to promote green environment and recycle waste material [15]. Besides, composite materials such as coconut fibre and glass fibre are used to improve the strength of material and reduce the density of basic material [16]. For instance, Payam *et al*. [8] and Jumaat *et al*. [17] were using lightweight aggregate made from palm oil shell mixed with cement to produce high strength concrete beams. The normal lightweight aggregate has density in the range of 1200-1800 kg/m3 [18]. In addition, lightweight aggregate concrete (LWAC) had compressive strength of 12 to 30 MPa after 28 days. The use of LWAC was able to save 10-20 % of the total cost and reduction of the density for lightweight structural members [19].

As mentioned before, IBS generally can be divided into five different systems. Each system has their advantages and disadvantages. The advantage of IBS SRLWAC beam is to reduce the weight of the product and utilize the sustainable material to replace the conventional aggregate. Transportation and lifting work are always an issue for precast structural element. With the reduction of product weight, the cost of transportation and lifting are able to reduce significantly. Besides, IBS system increases production speed of structural element from production line. Fast production and installation speed enables a structure to be completed ahead of schedule as well.

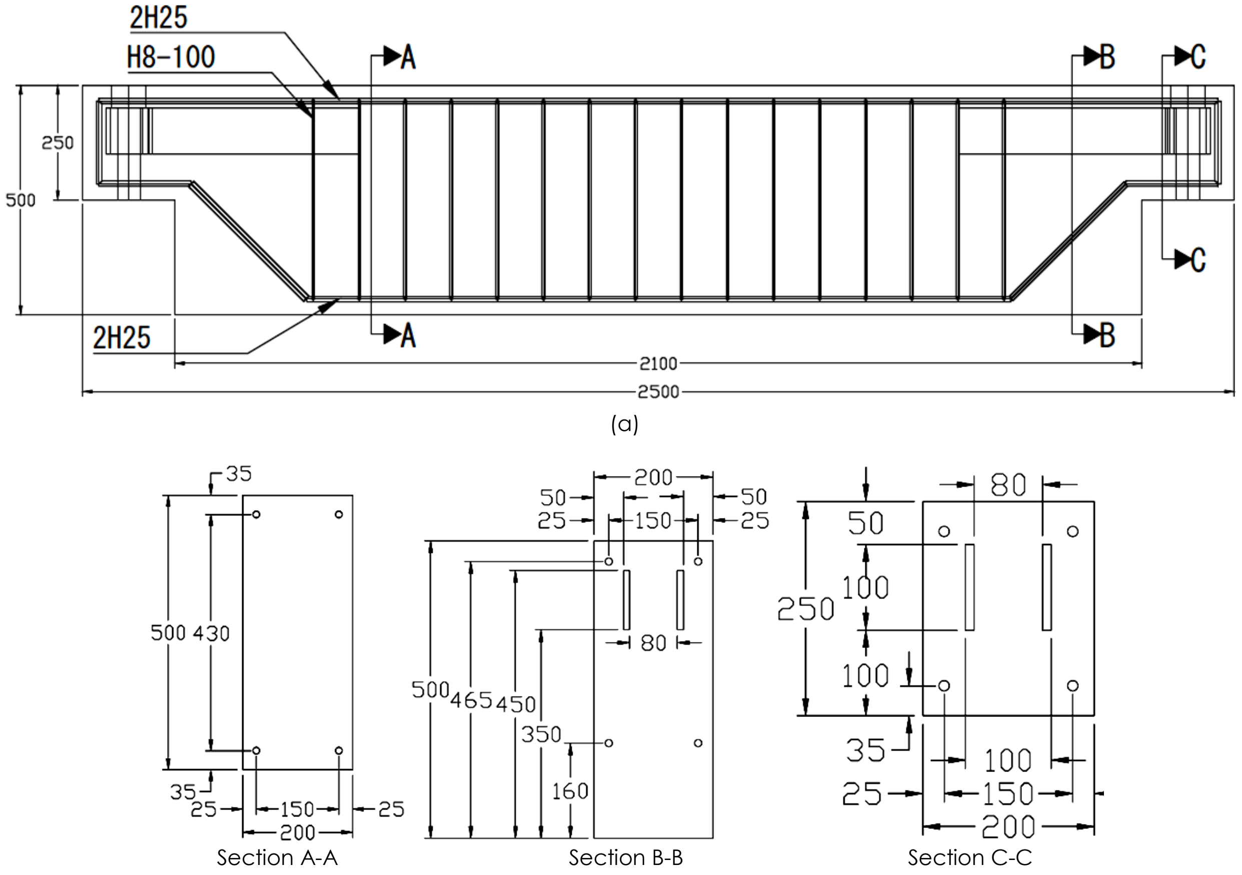
This study intends to reveal the ultimate capacity, ductility, and failure behaviour of SRLWAC beam under static vertical load as well as verify the result from nonlinear finite element software - Autodesk Simulation Mechanics (ASM).

2.0 EXPERIMENTAL DETAILS

2.1 IBS SRLWAC Beam Specification

IBS SRLWAC beam was designed according to European code 2- Design for reinforced concrete structure [20]. SRLWAC beam has total length of 2500mm. The clear span of beam is 2100 mm. There is 200 mm length from both sides of the beam to act as support for shear block connection. The beam has 500 mm depth and 200 mm width. The diameter of main reinforcement and links are 25 mm and 8 mm respectively. Minimum concrete cover of 25 mm was provided to the main reinforcement. Figure 1 shows the view and details of IBS SRLWAC beam.

Two steel plates are embedded inside the beam. These steel plates are responsible to anchor the bolt hole from tearing apart by tensile force. Without the steel plates as anchor, the concrete around the bolt hole is weak against tensile force. The length, width, depth and thickness of the steel plate anchor are 550 mm, 150 mm, 100 mm and 10 mm respectively. During the beam fabrication work, the steel plate was fixed at surrounding of bolt holes and another end of the steel plate was welded on shear reinforcement to restrict the movement of steel plate.



(a)

Section A-A

Section B-B

Section C-C

(b)

Figure 1 View and details of IBS SRLWAC beam: (a) 2D front view; (b) cross-sections

2.2 Materials Properties

The grade 500 high strength steel reinforcement bar with minimum yield stress, fy of 500 MPa was used. In this research, a normal concrete was designed according to Building Research Establishment- Design of normal concrete mixes to produce a normal concrete with density of 2365 kg/m3 as shown in Table 1. However, lightweight aggregate that comply with standard stated in European Code 2 [20] lightweight concrete structure 11.3.1 clause 1 was used in the design. The density of lightweight aggregate was 1020 kg/m3. With usage of lightweight aggregate, a normal concrete mix with grade 40 was designed.

Based on the mix design shown in Table 1, the obtained concrete modulus of elasticity at 28 days was 15.6 GPa. The concrete was designed as grade 40 with tested concrete characteristic strength at 28 days concrete of 40 MPa.

Table 1 Mixture of concrete

Water / Cement ratio	Cement (kg/m^3)	Water (kg/m^3)	Fine Aggregate (kg/m^3)	Lightweight Aggregate (kg/m^3)	Density (kg/m^3)	Slump (mm)
0.42	495	210	640	1020	2365	30-60

3.0 METHODOLOGY OF STUDY

Before experimental test, theoretical ultimate strength calculation for the beam with pinned-roller support was carried out to predict the ultimate flexural strength of the beam. It was based on Hibbeler [23] with beam deflection formulae as shown in Equation 1.

$$v_{max} = \frac{-PL^3}{48EI} \tag{1}$$

The calculated beam maximum deflection of 5 mm was based on the standard in European code 2 [20] with deflection limit state 7.4.1 clause (5) span/500. According to the serviceability limit state in European code 2 [20], the beam deflection must not exceed the maximum of 5 mm deflection. This is because as excessive deflection may damage the other part of the structure. Then, the predicted ultimate load of the beam was 249.6 kN with deflection of 5 mm as shown in Table 2.

Table 2 Parameters used for ultimate load prediction

Deflection, v (mm)	Modulus of elasticity, E (GPa)	Geometric properties of area element, I (mm^4)	Length, L (mm)	Point load, P (kN)	Predicted ultimate load, P/2 (kN)
5	15.6	2.08×10^9	2500	499.2	249.6

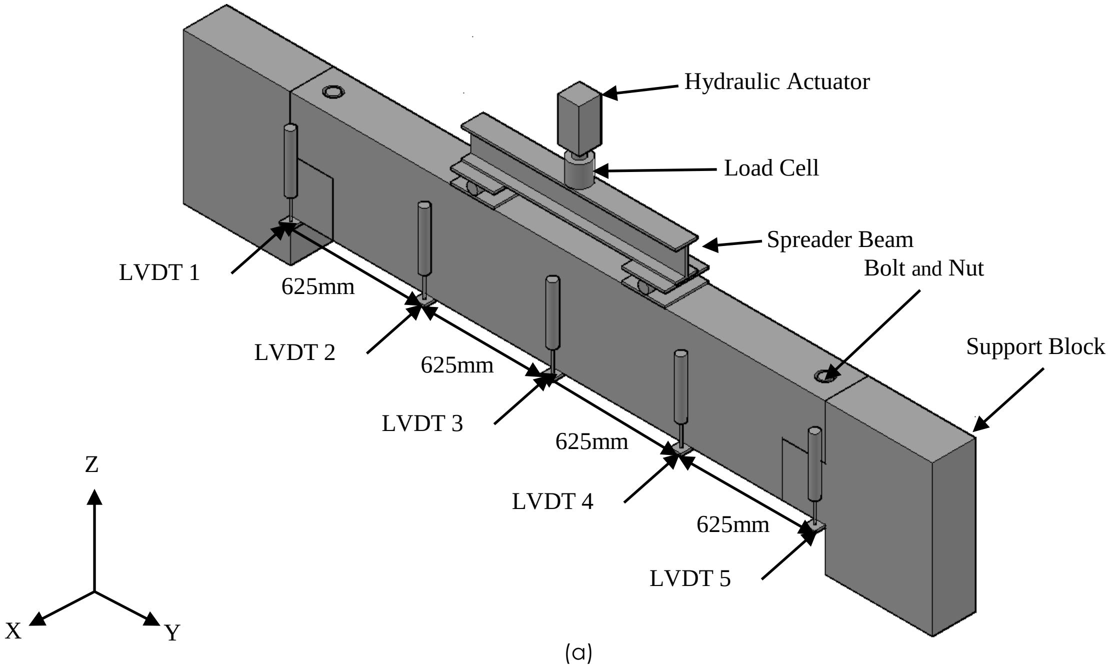
In experimental test, an IBS SRLWAC beam was assembled and tested by two-point vertical loads inside the structural testing rig. Five Linear Variable Displacement Transducer (LVDTs) were equally placed with distance of 625 mm to each other to measure the displacement of the beam as shown in Figure 2. Load cells and LVDTs were connected to a data logger to record and save the small steps of monotonic load. The loading procedure with reference to BS EN 12390-5: 2009 [21] was conducted. The standard verification method was also supported by Marsono *et al*. [22]. Three levels of load were applied in experimental testing. At first, the beam was tested up to 10 % of predicted maximum loads which was 30 kN to stabilize the tested frame. Then, the load was increased up to 30 % of total predicted maximum load which was 80 kN in second level for serviceability limit check. In the final load level, the specimen was tested to the ultimate capacity. All the hairlines and cracks were marked on the beam surface during the testing.

For finite element simulation, Autodesk Simulation Mechanical (ASM) 2015 software was used to simulate the behaviour of the IBS SRLWAC beam up to non-linear state. Firstly, the modelling work was performed in Autodesk AutoCAD software. Full 3D concrete beam together with reinforcements were modelled in Autodesk AutoCAD software and save as dwg format. Secondly, the ASM 2015 software was launched and opened the dwg file with non linear material analysis option. Once the 3D model shows up in the finite element software, every component such as concrete, main reinforcement, shear links and steel plates were checked accordingly to prevent missing components.

All the checked components were assigned as brick elements. The brick element was defined as plastic von Mises curve with kinematic hardening for model plastic behaviour simulation. Similar experimental material properties were used as input in finite element simulation. The purpose of using tested experimental material properties in finite element simulation is to obtain the simulated non-linear state results as close as possible.

The default contact for all components was perfectly bonded. Bonded contact allows the applied loads transmitted to other adjacent nodes during the analysis. In finite element analysis, two point loads were assigned on to the surface of the steel pad as shown in Figure 3. Same amount of applied loads with 30 kN, 83.7 kN and 250.1 kN from experimental test were inserted into the finite element for simulation. The applied load was placed exactly the same position as the experimental testing which were located at ⅓ and ⅔ of the beam. Both ends of the beam were assigned as fixed support with restrain from translation and rotation in x, y and z direction as shown in Figure 3.

Meshing of the beam model was begun after all the boundary condition was defined. The default meshing size was set at 100%. The mesh size can be enlarge up to maximum 190% or micronized down to 10%. Of course finer mesh size provides accurate results from finite element simulation. However, finer mesh size may require longer time to complete a simulation. Mesh size of 100% was applied toward beam concrete and steel plates in this simulation. Only mesh size of 24% was applied toward main reinforcement and shear links for better bonding and contacts. The non-linear finite element simulation was begun, after the model was successfully meshed.



(a)

(b)

Figure 2 (a) Perspective view of test set-up; (b) Experimental test set-up

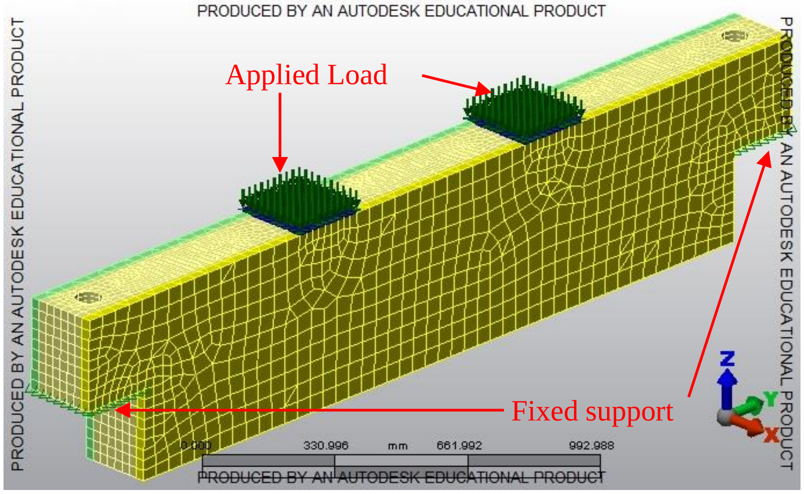


Figure 3 Finite element modelling in ASM 2015

4.0 RESULT AND DISSCUSSION

4.1 Load-displacement of IBS SRLWAC beam

Figure 4 shows the experimental load-displacement of SRLWAC beam at LVDT 1, 2, 3, 4 and 5. The beam was loaded slowly to the first 10 kN. This was to stabilize the tested specimen on testing frame. As the beam was slowly loaded, the displacement of beam was increasing steadily up to the first 10 kN. However, the incremental of displacement began to slow down beyond 10 kN as the beam starts to take loadings and experience elastic deformations.

LVDT 1 and 5 were used to record the displacement at both ends of the beam. Both LVDTs were record same displacement along the test. However, the displacement of LVDT 5 was increased abnormally when the crushing of concrete corbel support was observed as shown in Figure 4 at loading capacity of 230 kN. Due to this event, the displacement shown in Figure 4 for LVDT 4 was further increased to 14.9 mm at load of 250.1 kN.

The displacement of beam at LVDT 2 and 4 were having significant difference from each other beyond 200 kN as shown in Figure 4. This was due to the unsymmetrical concrete cracking pattern along both ends of the beam as shown in Figure 7. From Figure 4, the recorded displacement at LVDT 2 and LVDT 4 were 11.1 mm and 14.9 mm respectively. Large beam displacement occurred at LVDT 4 was triggered by the crushing of the corbel support when applied load has reached to 230 kN as shown in Figure 8. Hence, LVDT 4 had recorded larger beam displacement compared to LVDT 2. Otherwise, the displacement at LVDT 2 and 4 should be approximately similar.

Figure 5 shows the experimental load versus mid-span displacement of SRLWAC beam. The beam behaves elastically up to 90 kN before proceed to non-linear behaviour with appearance of first vertical hairline crack at mid-span. Then, the stiffness of beam was reducing as plastic behaviour starts to control the structural system. Beyond 90 kN, the beam starts to behave plastically and shows significant difference in displacement recorded by all five LVDTs as shown in Figure 4. The displacement of beam was increased gradually up to ultimate capacity of 250.1 kN with maximum displacement of 15.2 mm.

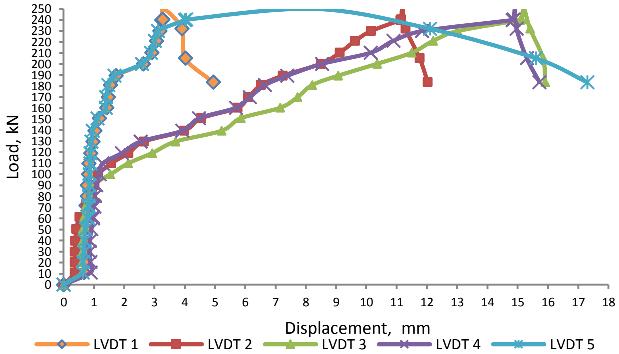


Figure 4 Experimental loads - displacement relationship

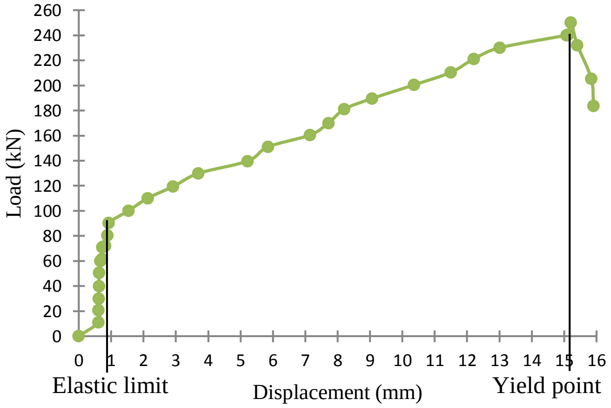


Figure 5 Load versus mid-span displacement of SRLWAC beam

Table 3 shows the summary of results for both experiment and finite element analysis of SRLWAC beam. The recorded maximum displacement was happened at the mid-span of beam from both experimental and finite element analysis. The mid-span deflection indicates that the beam was experiencing flexural ductility behaviour.

Table 3 SRLWAC Beam Deflection and Capacities

Loaded Beam (kN)	LVDT 1 (mm)	LVDT 2 (mm)	LVDT 3 (mm)	LVDT 4 (mm)	LVDT 5 (mm)	Max. Deflection (mm)
Experimental Results						
30	0.59	0.61	0.75	0.57	0.56	0.75
83.7	0.77	0.70	0.89	0.82	0.80	0.89
250.1	3.31	11.19	15.21	14.91	8.30	15.21
Finite Element Simulated Results						
30	0.07	0.15	0.22	0.15	0.07	0.22
83.7	0.21	0.41	0.61	0.42	0.20	0.61
250.1	4.53	9.52	15.36	9.63	4.47	15.36

The graph of load versus deflection for both experimental and simulated results was shown in Figure 6. From Figure 6, the simulated displacement was increased linearly as load increased up to 140 kN with first 1 mm displacement. This indicates the simulated beam was having elastic deformation within first 1 mm displacement as the top chord concrete beam starts to take compressive load and bottom chord starts to take tensile load. After 140 kN, the simulated concrete beam behaves plastically and the cracks were propagated. Hence, the tensile force sustained previously by the concrete beam was transferred to the main reinforcements and cause the yielding at mid-span and both ends connections.

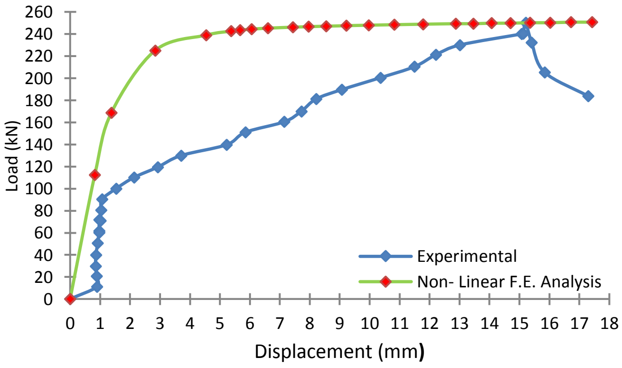


Figure 6 Experimental and simulated results for SRLWAC beam

4.2 Crack pattern and mode of failure

Two types of crack patterns were obtained in this IBS SRLWAC beam as shown in Figure 7. The cracks were shear failure crack and flexural crack. Besides, mode of failure such as crushing and splitting were obtained in IBS SRLWAC beam as well. The first shear crack appeared on the beam was located at overlay right end with 50 kN applied load as shown in Figure 9(b).

The following shear crack was founded at overlay left end as well with 80 kN applied load as shown in Figure 9(a). The other shear cracks were appeared and propagated simultaneously with the increment of applied load.

The flexural crack starts to appear at mid span of the beam at 120 kN applied load as shown in Figure 9(a). Applied loads beyond 120 kN shear crack and flexural crack propagation were become obvious or noticeable.

The crushing of the concrete corbel support was noticed when applied load reached 170 kN as shown in Figure 8.The ultimate capacity of this beam was 250.1 kN with 15.21 mm. The cause of the failure of IBS SRLWAC beam was the splitting of the concrete at overlay right end as shown in Figure 9(b).

Further applied loads were results in decreasing in beam load resistance capacity due to necking of steel main reinforcements. The beam was totally failed at load 183.7 kN with 17.30 mm mid span displacement.

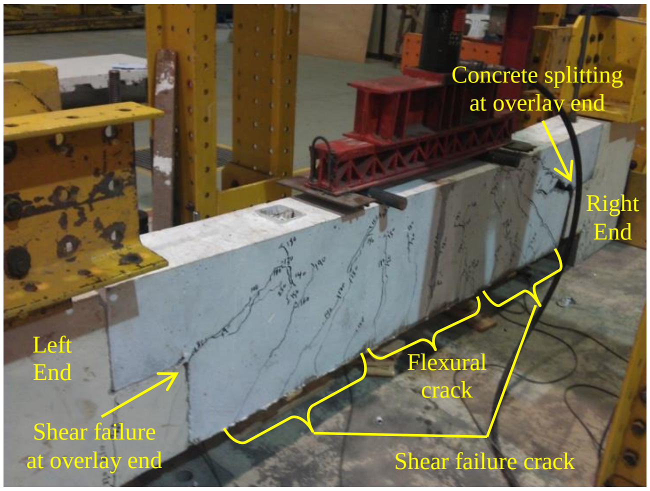
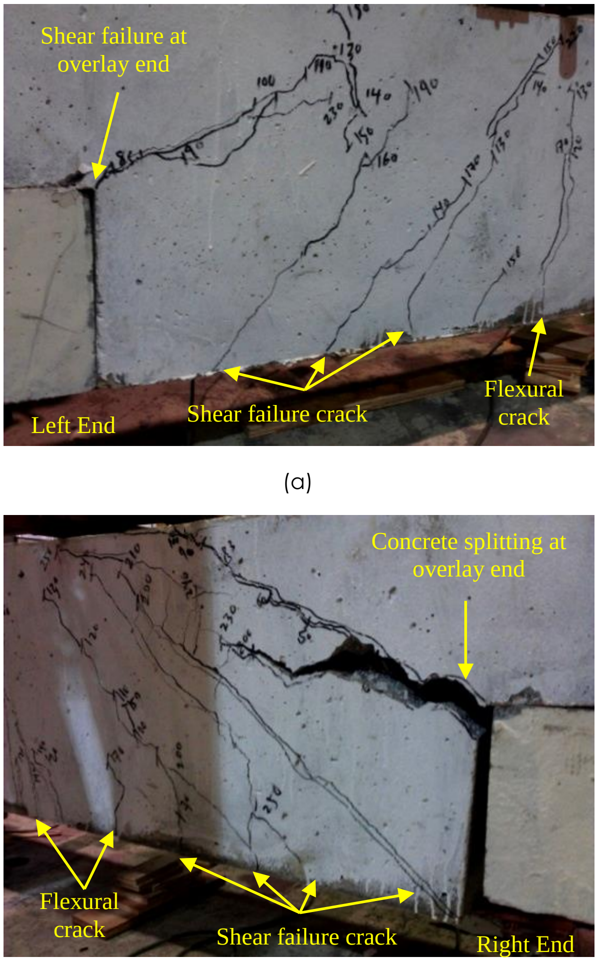


Figure 7 Crushing of corbel support

Figure 8 Crushing of corbel support



(a)

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(b)

Figure 9 Beam end connection splitting (a) left (b) right

Figure 10 shows the deformation pattern of SRLWAC beam at applied load of 250 kN with maximum displacement at the mid-span of 15.36 mm in finite element analysis. Maximum Von-Mises stress of 306.78 N/mm² shows the yielding of main reinforcement as illustrated in Figure 11. Besides, the yielding of main reinforcement was also found at beam-column connection part at both sides as shown in Figure 11. This indicates the prediction of finite element analysis was true and valid.

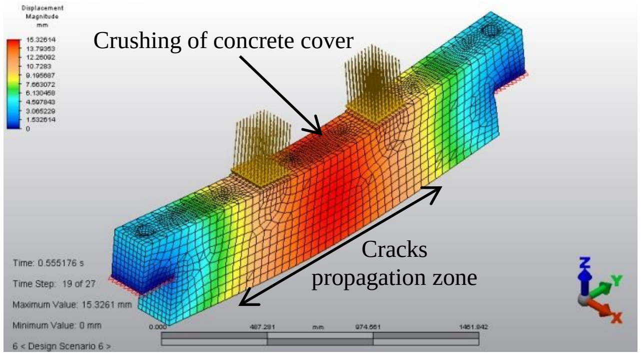

Figure 10 Non-Linear finite element analysis of SRLWAC beam

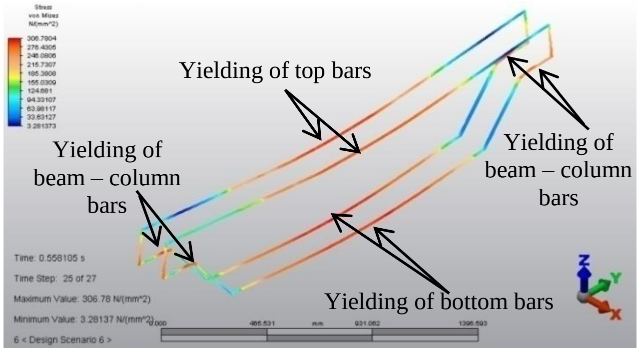

Figure 11 Internal reinforcement deformation pattern of SRLWAC beam

The simulated propagation of cracks was started from light blue to red colour contour as shown in Figure 12. The light blue colour contour with range 3.81 N/mm² to 39.33 N/mm² indicates area with fine crack lines, green to yellow colour indicates clear hair line crack and light orange to red colour indicates the wide cracks were formed around the edge of the beam connection. In this simulation the maximum principal stress of 145.88 N/mm² shows the concrete around the inner edge of the support has red contour and suffers from extreme tensile stress. This was due to irregularities of the cross session. The crack pattern and severe crack formation shown in Figure 12 was having similarly as shown in Figure 7.

In summary, the calculated and simulated maximum mid-span displacement from Table 3 was having the difference of 1% and approximately similar. However, the difference between simulated curve pattern and experimental curve was due to the concrete material was modelled as homogeneous material in finite element software but in fact the concrete was not a perfectly homogeneous material. Besides, the effect bond-slip between steel bars and concrete was neglected from the finite element simulation as well.

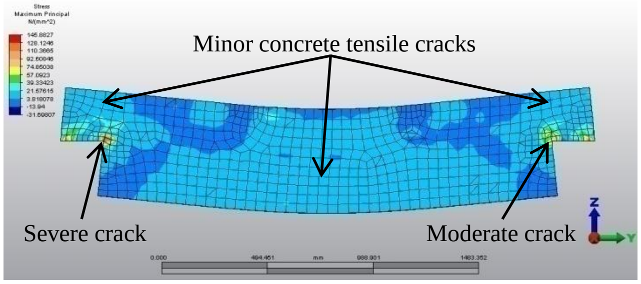

Figure 12 Symmetrical behaviour of simulated maximum principal stress in beam end connection

4.3 Ductility of IBS SRLWAC Beam

The flexural ductility of the beam was calculated by curvature ductility factor, μ in Equation 2 [24] with ϕ_U and ϕ_Y were defined as ultimate curvature and yield curvature respectively. In addition, Lestuzzi [19] had presented similar displacement ductility ratio as shown in Equation 3 for structural element with U_p and U_y were defined as peak displacement and yield displacement respectively. From Figure 5, the calculated U_p was 15.2 mm and U_y was 1.07 mm.

$$\mu = \frac{\phi_u}{\phi_y} \tag{2}$$

$$\mu = \frac{U_p}{U_y} \tag{3}$$

The calculated ductility ratio of 14.2 was higher and better than pre-stressed concrete beam's ductility ratio of 3.0 specified in PCI design handbook [25]. This indicates the characteristic of this SRLWAC beam has higher ductility. However, ductility curve for reinforced beam was always influenced by factors such as tensile reinforcement ratio, compressive strength of concrete and yield strength of reinforcement [26].

4.0 CONCLUSION

Based on the results and discussions, the IBS SRLWAC beam was behaved elastically until load of 90 kN and then deformed plastically until ultimate capacity of 250.1 kN. The recorded beam maximum mid-span deflection of 15.21 mm from experimental test was almost similar compared the finite element simulation of 15.36 mm. The cause of the failure of IBS SRLWAC beam was the splitting of the concrete at overlay right end. The calculated ductility ratio for lightweight aggregate concrete beam was 14.2, which was higher than pre-stressed concrete beam.

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