Scientific Research and Essays Vol. 7(27), pp. 2370-2379, 19 July, 2012
Available online at http://www.academicjournals.org/SRE
DOI: 10.5897/SRE12.115
ISSN 1992-2248 ©2012 Academic Journals

Full Length Research Paper

Reinforced concrete beams with lightweight concrete infill

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Accepted 7 June, 2012

In structural design, an ideal situation in material saving is to reduce the weight of the structure without having to compromise on its strength and serviceability. A new lightweight sandwich reinforced concrete section has been developed with a novel use of lightweight concrete as infill material. The section, namely LSRC section, is suitable for use as beam or slab members. Experimental investigations into the strength of beams with LSRC section shows promising results under both flexural and shear tests. Based on the test results, the flexural capacity of LSRC beams was found to be almost identical to the capacity of the equivalent solid beam. The shear capacity of the LSRC beams was expectedly reduced due to the low compressive strength of the lightweight concrete infill material. ANSYS 12.1 was employed to develop three dimensional nonlinear finite element models of LSRC beams and was verified against the experimental results.

Key words: Lightweight concrete, composite section, sandwich section, ANSYS.

INTRODUCTION

Lighter weight of concrete members is desirable particularly when designers or contractors have to deal with large open floor plans and especially in high rise construction. Several options are available using well developed technologies such as post-tensioned concrete (StrongForce, 2010), prestressed precast planks (Hegger and Roggendrof, 2008), and Bubbledeck technology (Aldejohann and Schnellenbach, 2003). These technologies are usually available as commercial products thereby the main project contractor needs to engage the technology specialist/supplier to deliver their respective products in both design and construction phases. Other researches dealing with sandwich section are: sandwich panel by fiber-glass laminate skins over PVC foam or polyester mat cores (Russo and Zuccarello, 2007), sandwich beam honeycomb core (Abbadi et al., 2009; Meidell, 2009), sandwich beam made up of glass fiber reinforced polymer skins and modified phenolic core material (Manalo et al., 2010a, b; Keller et al., 2007), and also the glass fibre reinforced polymer concrete sandwich slab which was introduced by Schaumann et al. (2009).

Alternative to the specialist products is the use of lightweight material. Lightweight concrete can either be made with lightweight aggregate, foamed technology, or autoclaved aerated technology. The benefits of lightweight concrete are numerous and have been well recognized. Bobrowsky (1980) highlighted the implementation of lightweight concrete in many constructions.

Furthermore, lightweight aggregate is commonly used in structural application for example, in reinforced concrete beams (Bungey and Madandoust, 1994; Ahmad et al., 1995), with high strength fiber (Kayali et al., 2003; Mousa and Uddin, 2009), as an infill in sandwich composite of ferrocement (Memon et al., 2007), and as an infill in reinforced concrete columns (Moulia and Khelafi, 2007). Foamed concrete, or cellular concrete, is either cement or mortar in which foaming agent is added to create air-voids within it. The density of foamed concrete varies in a wide range of 4 to 15.7 kN/m^3 depending on the foam dosage. Literature classification on the properties of foamed concrete (Ramamurthy et al., 2009) and its historical use in construction application (Jones and Mcarthy, 2005) is published recently.

Autoclaved aerated concrete (AAC) was invented in

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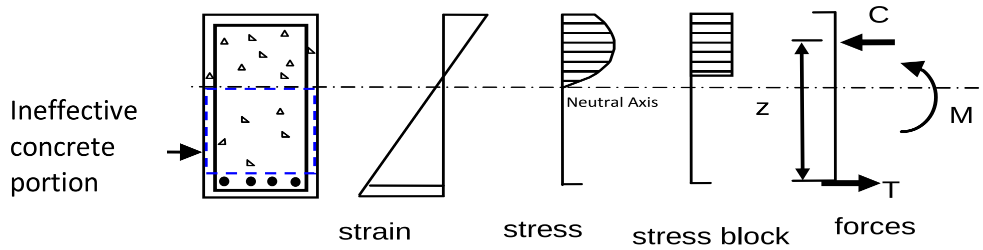


Figure 1. Strain, stress and force diagrams of a reinforced concrete section.

Sweden in the mid 1920s and has been used worldwide. Its density is about one-fourth of normal concrete. AAC provides excellent thermal and sound insulation, and has excellent fire resistant property. AAC products include blocks, wall panels, floor and roof panels, and lintels. Use of AAC as a primary structure is still very limited due to its low compressive strength compared to normal concrete. For domestic construction, AAC can be used as load-bearing walls when integral with reinforcing frame (Moulia and Khelafi, 2007). The Masonry Structures Code of Australia (AS3700, 2001) includes provisions for AAC block design.

Based on the literature study, AAC has not been incorporated with normal concrete for use as part of reinforced concrete beams and slabs. This paper proposes a newly developed LSRC section, which can be used as beams or slabs (Vimonsatit et al., 2010a, b). In a reinforced concrete section design, the flexural capacity of the section is calculated from the coupling between compression in concrete and tension in reinforcing steel. Design codes (for example, ACI318-02, AS3600-2009, Eurocode-2) permit the use of uniform stress block to simplify the effective concrete in compression above the neutral axis. As a result the part of concrete below the neutral axis has no contribution to the flexural capacity of the section. This is the basis of the developed LSRC section in which prefabricated AAC blocks are used to replace the ineffective concrete portion of the reinforced concrete section under bending. In effect, AAC blocks act as an internal, permanent form inside the slab section, which can be replaced by any lightweight materials that can form and support the concrete while pouring. It is necessary to note that the shear capacity and stiffness of the section will be affected and require a further investigation. An experimental program has been conducted to investigate the flexural and shear capacities of LSRC beams when compared with the solid beam of identical height. Three dimensional nonlinear finite element model of LSRC beams have been developed to simulate the behavior of the beams.

In the following sections the details of the experimental investigation on the flexural and shear tests of LSRC beams will be described. The results of the flexural and shear capacities and the load-deformation behavior will be presented. Finally, the use of ANSYS 12.1 for the FEM modeling of LSRC beams will be demonstrated and the resulting numerical simulation will be compared with the tested results.

Research significance

The paper presents a novel use of lightweight concrete as infill of a reinforced concrete section. This new developed section can be used as beam or slab, which has advantage due to its lighter weight. The weight reduction leads to several benefits in terms of cost and construction time. Based on the presented experimental and numerical works, the new proposed lightweight section shows great potentials for industrial use. The weights saving benefits also contribute towards sustainability and buildability design objectives of concrete structure.

EXPERIMENTAL INVESTIGATION

LSRC section

In reinforced concrete, the structural properties of the component materials are put to efficient use. The concrete carries compression and the steel reinforcement carries tension. The relationship between stress and strain in a normal concrete cross-section is almost linear at small values of stress. However, at stresses higher than about 40% of the compressive concrete strength, the stress-strain relation becomes increasingly affected by the formation and development of microcracks at the interfaces between the mortar and coarse aggregate (Warner et al., 1998).

In determining the flexural capacity under the bending theory, a typical strain, stress and force diagram of a reinforced concrete section is as seen in Figure 1. Concrete has low tensile strength, therefore when a concrete member is subjected to flexure, the concrete area under the neutral axis of the cross-section is considered ineffective when it is in tension at ultimate limit states. In creating an LSRC section, prefabricated lightweight (in this case AAC) blocks are used to replace the concrete within this ineffective region. The developed LSRC section can be used for beams or slabs. Typical LSRC beam and slab sections are as shown in Figures 2a and b, respectively.

Construction of LSRC members

As per any reinforced concrete members, the construction of LSRC

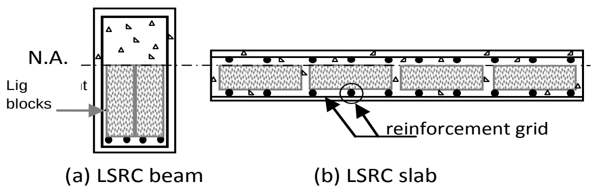


Figure 2. Reinforced concrete section with lightweight blocks infill.

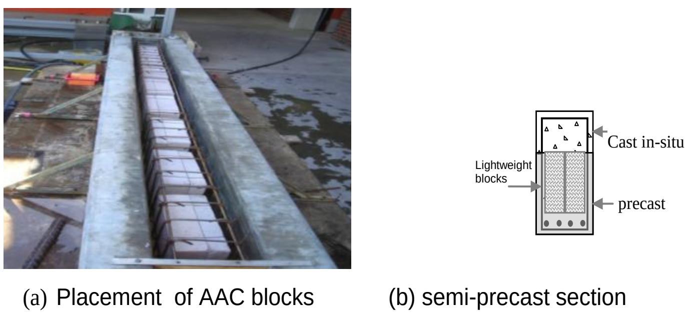


Figure 3. Construction of LSRC member.

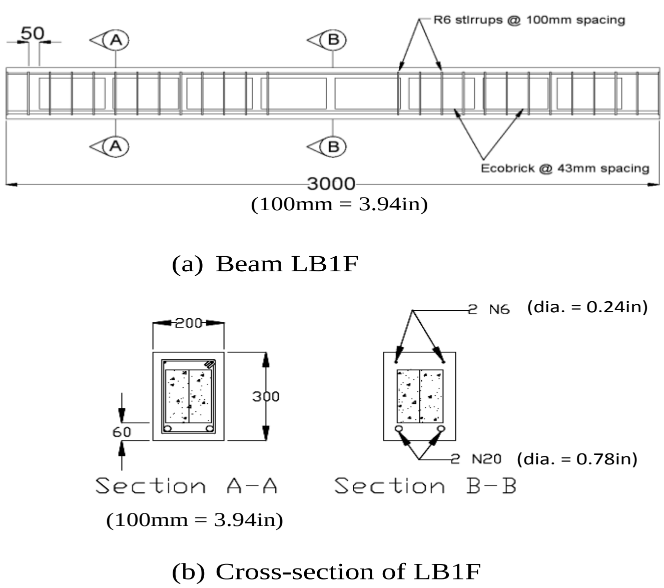


Figure 4. LSRC beam and section.

members can be either fully precast, semi-precast, or cast *in-situ*. Lightweight blocks can be technically placed between the lower and upper reinforcements of the section. In a beam member, the encasing shear stirrups can be installed before or after the placement of the blocks. When preparing for the experiment, the casting bed and steel mould were prepared and secured; lower and upper reinforcing steels and shear stirrups were prefabricated. Lightweight blocks were inserted within the encasing stirrups through the side of the beam. This method of construction is typical for either precast or cast in-situ members. Figure 3a shows a ready-to-cast LSRC beam in a steel mould at the Concrete Lab of Civil Engineering Department, Curtin University, where the experiment was conducted.

When dealing with a large concrete member such as a long span beam or a large floor construction, it is of advantage for constructors to consider semi-precast construction method. The semi-precast construction helps resolve, to a certain extent, the complication due to the heavy weight of the structure. LSRC members are also suitable for semi-precast construction. The lower part of concrete section can be cast with the lower reinforcing steels in which the shear stirrups and lightweight blocks are already put in place. The semi-precast LSRC members can be depicted in Figure 3b. Alternatively, the precast can be done with the portion below the underside of the blocks, which means that the concrete can be cast prior to the placement of the blocks. If this is the case, side formworks will be required when prepare the upper part of the section for concreting. It is necessary to ensure that the section is monolithic by making sure during casting that the concrete can flow in properly through to the sides of the beam and in the gaps between the lightweight blocks.

Materials

The concrete used was grade 40, having the compressive strength of 43.3 MPa (6280 psi) at 28 days. Superplasticiser was added to the concrete mix to increase the workability of the concrete to ensure the concrete filled all the gaps for beam specimens with AAC blocks in it. The maximum size of aggregate was 10 mm (0.39 in). The strength value of AAC blocks used was 3.5 MPa (507 psi). All beams were provided with top and bottom longitudinal bars, N20 bars (dia. 0.78 in) were used as the bottom steel in all beams with tensile strength at yield was 560 MPa (81221 psi) while the yield strength of R-bars which was used as the top bar and the stirrup was 300 MPa (43511 psi).

Beam specimens

The tested beam had a rectangular cross section, with a constant width and depth of 200 mm (7.87 in) by 300 mm (11.81 in). The beam length was 3000 mm (9.84 ft), with 2800 mm (9.19 ft) clear span when set up for testing. Five beams were manufactured for two series of four-point test – the flexural test and the shear test. The distance between the two point loads was 800 and 1680 mm for the flexural and shears tests, respectively.

The flexural test was to compare the flexural capacity between the solid and LSRC beams. Three beams were prepared, one solid (SB1F) and two with AAC blocks (LB1F and LB2F). LB1F beam had the maximum number of blocks that could be placed in it, while LB2F has half the amount of that contained in LB1F. In the shear test, two beams were prepared, one solid (SB1S) and one with AAC blocks (LB1S). The standard dimensions of the AAC blocks used were 180 mm (7.09 in) long, 300 mm (11.81 in) wide, and 75 mm (2.95 in) thick. The blocks needed to be placed within the tension region of the beam cross-section when subject to bending, that is, below the calculated depth of the neutral axis. It is therefore necessary to cut the blocks to fit within this depth; the block depth was cut to 160 mm (6.30 in). Similarly, the maximum block width that could be accommodated within the dimension of the tested beams was 115 mm (4.53 in), therefore, two blocks were tied together but one side of the blocks was cut by 35 mm (1.38 in). Steel bar, 10 mm (0.39 in) in diameter, was used to tie the blocks together.

As a result, when the tied blocks were placed, there were gaps between the blocks and the stirrups, and the blocks and the longitudinal bars. These gaps were useful in enhancing the grip of the reinforcing bars in the concrete section. Figure 4 shows a typical LSRC beam with AAC blocks infill.

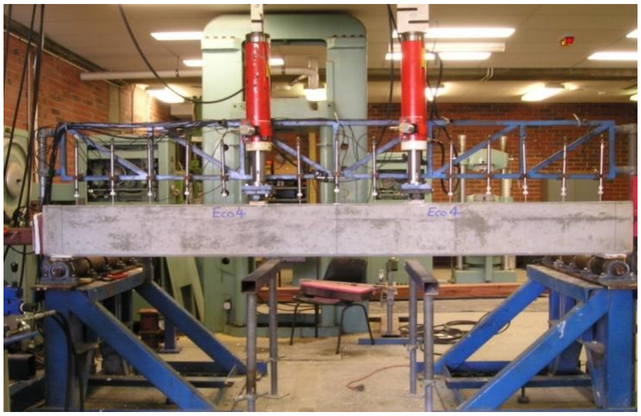


Figure 5. Typical test set up.

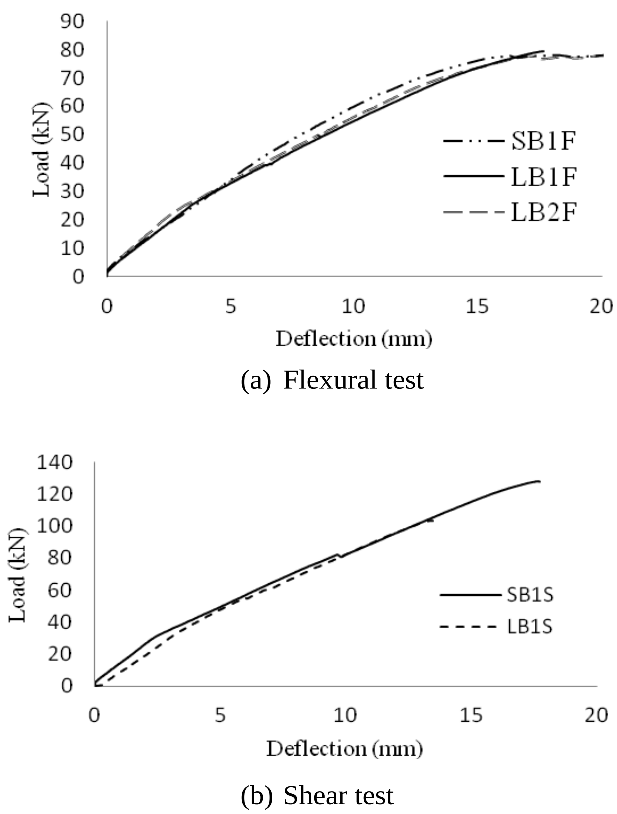


Figure 6. Load versus mid-span deflection.

Test set-up

Three beams were designed to fail in flexure, and two beams to fail in shear. The beams were simply supported and were subjected to two point loads. The distance between the two point loads was 800 mm (2.62 ft) and 1680 mm (5.51 ft) in the flexure and shear tests respectively. The typical test set up is as shown in Figure 5. The beams were loaded to failure using a 20 tonne (4.4 kips) capacity hydraulic jack to apply each of the two point loads. The jacks were attached to a reaction frame. Two supporting frames with 200 mm (7.87 in) long × 150 mm (5.91 in) diameter steel rollers were used as the end support.

To ensure a uniform dispersion of force during loading and to eliminate any torsion effects on the beam due to slight irregularities in the dimension of the beams, plaster of paris (POP) and 100 mm (3.94 in) wide × 250 mm (9.84 in) long × 20 mm (0.79 in) thick distribution plates were placed on the rollers and also under the jacks.

Instrumentation

The vertical deflections of the test beams were measured using Linear Variable Differential Transformers (LVDTs) which were placed at 200 mm spacing within 2.8 m span. LVDTs were also attached on each loading jack to capture the vertical deflection at the loading point. The LVDTs were attached to a truss frame as seen in Figure 5. With this arrangement, the curvature of the beam can be identified in relation to the loading increment. During the initial set up of the LVDTs, the instruments were calibrated before the test commenced. An automated data acquisition system with a Nicolet data logger system was used to record the load-deformation from the jacks and the LVDTs.

EXPERIMENTAL RESULTS

The failure loads of the solid and LSRC beams under the flexure test were found to be of insignificantly different. It was found that beam LB1F, which had the maximum number of AAC blocks, failed at an average load of 78.9 kN (17731 lbs), LB2F and SB1F beams failed at 78.6 kN (17664 lbs) and 78.5 kN (17641 lbs), respectively. These load values were taken from the average of the loads applied from the two hydraulic jacks.

When a beam is more critical in shear, rather than in flexure, an LSRC beam is expected to exhibit lower shear resistance than the equivalent solid beam. This is because the inserted AAC blocks in an LSRC beam have lower compressive strength than the normal concrete. As a result, an LSRC beam has less effective concrete area to resist the shear when compared to the solid beam of identical height. Based on the two beam tests, the failure loads of SB1S and LB1S were 128 kN (28766 lbs) and 102 kN (22923 lbs), respectively. A significant 20% reduction in the shear capacity of LSRC beam compared to the equivalent solid beam.

The load-deformation behaviour of all the tested beams was found to be similar and followed the same trend. The loads versus deflections at the mid-span of all the beams under flexure and shear are plotted in Figure 6.

Under the flexural test, the main flexure cracks were developed within the two loading points and widen up as load increased. At failure, the concrete in the compression region crushed. It was seen that the exposed reinforcing steel in this region buckled. The typical crack formations at failure under the flexural test of solid and LSRC beams are as shown in Figures 7a and b, respectively.

For beams tested in shear, the behaviors of the two tested beams were similar. Small flexure cracks occurred first at the midspan region of the beam. Subsequently, the flexure cracks extended as flexure-shear cracks were

(a)Solid Beam (b) Beam with Lightweight Blocks Infill

Figure 7. Crack formation at failure under the flexural test.

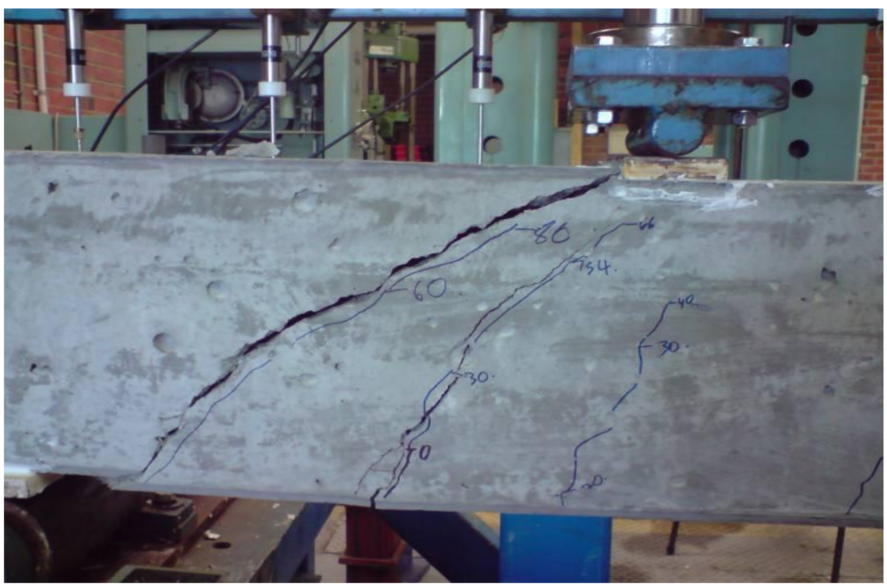


Figure 8. Crack formation at failure under shear test.

developed between the support and the loading point. At the load approaching the failure load, critical web shears crack were developed diagonally within the shear span. The cracks continued to widen as the load increased, and failure occurred soon after depicting a typical sudden type of shear failure. The typical progressions of the cracks and the failure modes of the beam tested in shear are shown in Figure 8. After the test, it was of concern to determine whether the inclination of the critical shear crack was influenced by the position of the AAC blocks within the crack region. After the beam failed, the beam was cut using concrete saw to examine the actual position of the blocks. It was found that the cracks propagated right through the blocks as if the section was monolithic. This behavior indicates good bonding between the concrete and the blocks.

Correlation of test results with design prediction

The test results on the failure loads of the beams are compared with the predicted values obtained from design equations based on Australian standard for concrete design (AS3600-2009). In the calculation, rectangular stress block concept was adopted in which a uniform stress of magnitude 0.85f'_c was used to replace the nonlinear stress distribution above the neutral axis. A single parameter γ was used to define both the magnitude and the location of the compressive force in concrete. Based on AS 3600 (2009), the value γ for normal concrete with f'_c up to 50 MPa (7252 psi), is $\gamma = 1.05 - 0.007(f'_c)$, $(0.65 \leq \gamma \leq 0.85)$.

The predicted flexural capacity was calculated from the solid beam section, which was equal to 82.7kNm (18585 lbs). Based on the test results of the maximum load at failure, the moment of the tested beams was 78.5 (17641), 78.6 (17664) and 78.9 (17731) kNm (psi) for solid, LB2F and LB1F, respectively. These results show good correlation with the ultimate design moment value, having only 5% difference. Based on these results, the concrete replacement by AAC blocks, as tested on LB1F and LB2F, seems to virtually have no effect on the flexural strength of the section, which is as expected.

The predicted shear capacity obtained from the design calculation based on AS3600 (2009) also shows good correlation with the LSRC beams. The design value of the shear capacity appears to be conservative for the solid beam. The test/predicted shear capacity ratios for the solid and LSRC beams were 1.27 and 1.01, respectively. Therefore, it seems that design adjustment needs to be made should the designer wish to maintain the same level of conservativeness in predicting the shear capacity of an LSRC beam, as that of an equivalent solid beam.

Numerical investigation

ANSYS 12.1 (2010) was employed to simulate the flexural and shear behaviour of the beam by finite element method. The concrete was modelled with solid65, which has eight nodes with three degrees of freedom at each node, that is, translation in the nodal x, y, and z directions. The element is capable of plastic deformation, cracking in three orthogonal directions, and crushing.

A link8 element was used to model the steel reinforcement. This element is also capable of plastic deformation. Two nodes are required for this element which has three degree of freedom, as in the case of the concrete element. Discrete method was applied in the modelling of the reinforcement and stirrups used in the tested specimen. The two elements were connecting at the adjacent nodes of the concrete solid element, such that the two materials shared the same nodes. By taking advantage of the symmetry of the beam layout, only half of the beam in longitudinal direction has been modelled in the finite element analysis.

Concrete

ANSYS requires an input data for material properties concrete in terms of Elastic modulus (E_c), ultimate uniaxial compressive strength (f_c'), ultimate uniaxial tensile strength (modulus of rupture, f_r), Poisson's ratio (ν), and shear transfer coefficient (β_t). The modulus of elasticity of concrete used was 26500 MPa (3843.5 ksi) which was determined in accordance with AS 1012.17 (1997). The initial Poisson's ratio for concrete was assumed to be 0.2 for all the beams.

The shear transfer coefficient, β_t, represents the conditions of the crack face. The value of β_t, ranges from 0 to 1, with 0 representing a smooth crack (complete loss of shear transfer) and 1 representing a rough crack (that is, no loss of shear transfer) as described in ANSYS. The value of β_t specified in this study is 0.2, which is recommended as the lower limit to avoid having convergence problems (Dahmani et al., 2010).

The numerical expressions by Desayi and Krisnan (1964), Equations 1 and 2, were used along with Equation 3 (Gere and Timoshenko, 1997) to construct the multi-linear isotropic stress-strain curve for concrete in this study.

$$f_c = \frac{E_c \varepsilon}{1 + (\frac{\varepsilon}{\varepsilon_0})^2} \quad (1)$$

$$\varepsilon_0 = \frac{2 f_c'}{E_c} \quad (2)$$

$$E_c = \frac{f_c}{\varepsilon} \quad (3)$$

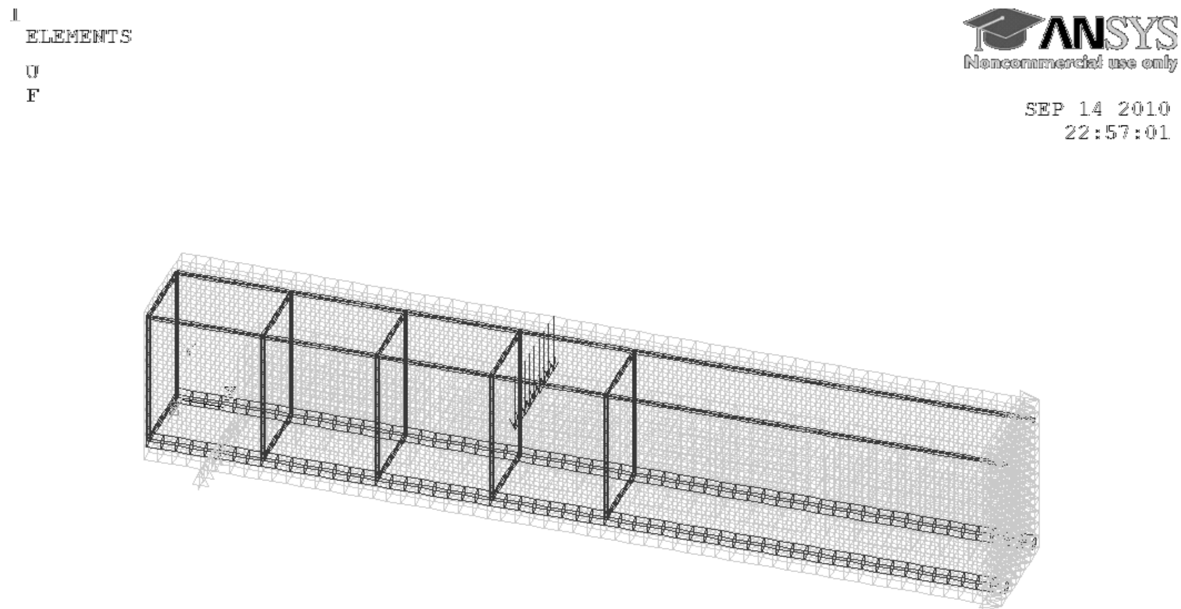
where fc is the concrete stress at any strain ε, and ε_0 is the strain at the ultimate compressive strength f_c'. The compressive stress at 0.3 of the compressive strength was used as the first point of the multi-linear stress-strain curve. The crushing capability of the concrete was turned off to avoid any premature failure (Barbosa and Riberio, 1998).

Steel reinforcement

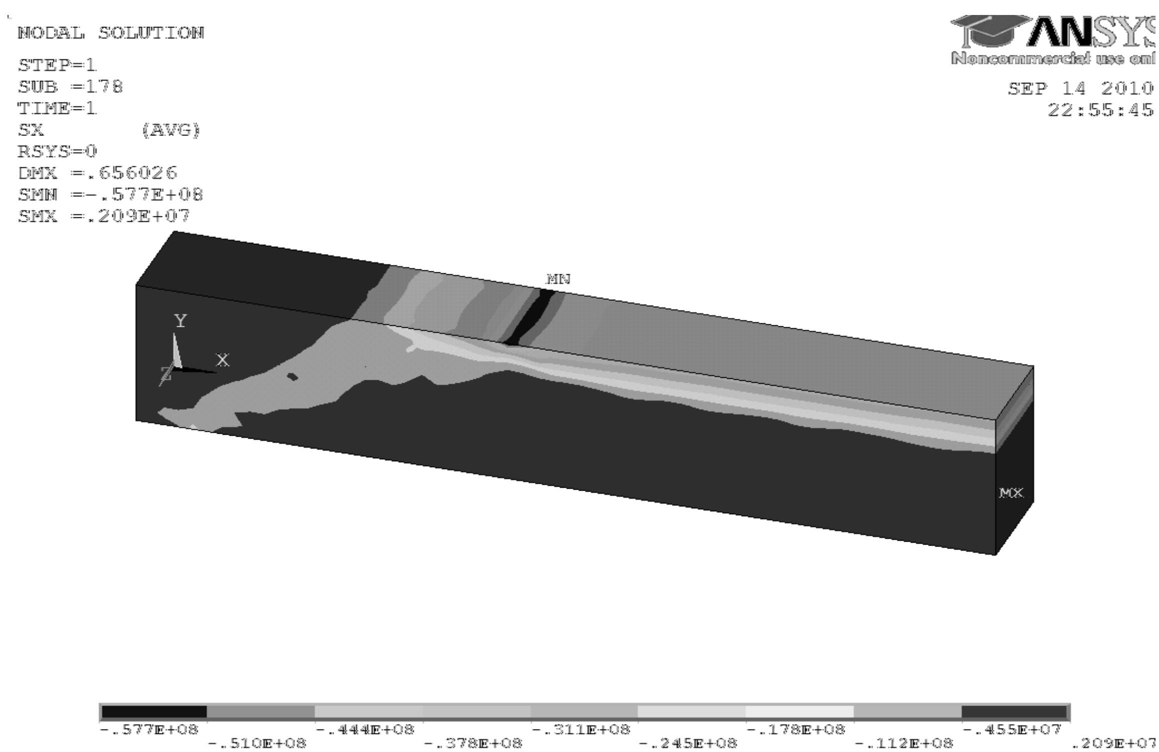
The steel for the finite element models was assumed to be an elastic-perfectly plastic material and identical in tension and compression. Poisson ratio of 0.3 was used for the steel. Elastic modulus, E_s = 200,000 MPa (29008 ksi).

Comparison of numerical and experimental results

The typical finite element model of the beam and the results at failure are illustrated in Figure 9. The load deflection characteristics from the finite element analysis (SB1F, LB1F and LB2F) are plotted to compare with the flexural test results in Figure 10. All results show similar



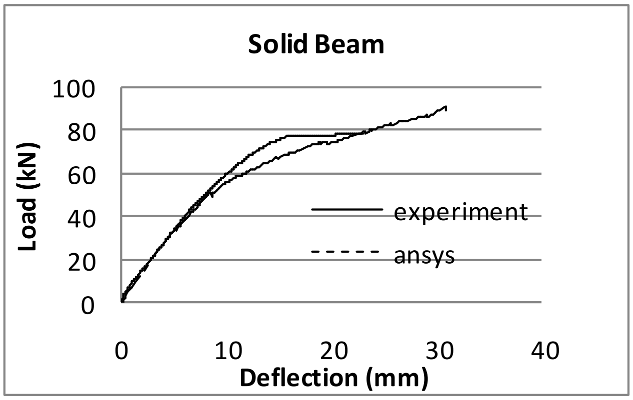
(a) Beam and reinforcement



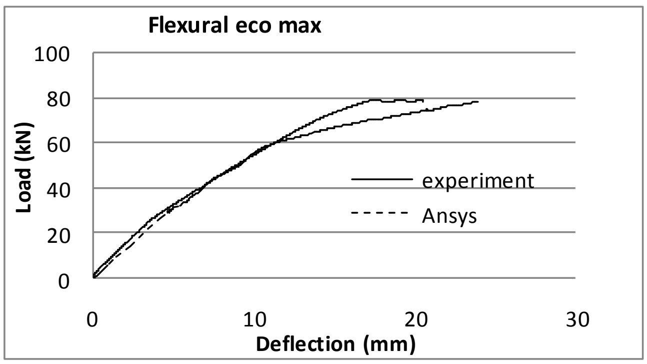
(b) Stress contour at shear failure

Figure 9. FEM model of LSRC beam and results.

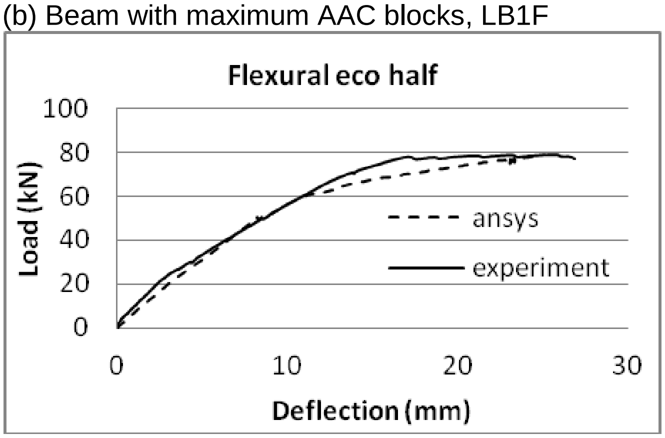
trend of the linear and nonlinear behavior of the beam. In the linear range, the load-deflection relation from the finite element analysis agrees well with the experimental results when the applied load is below 40kN (8989 lbs). After the first cracking, the finite element model shows strength of AAC infill material. The comparison of greater



(a) Solid beam, SB1F

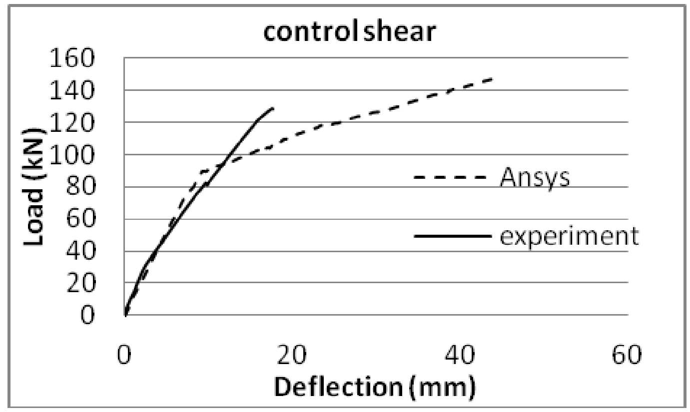


(b) Beam with maximum AAC blocks, LB1F

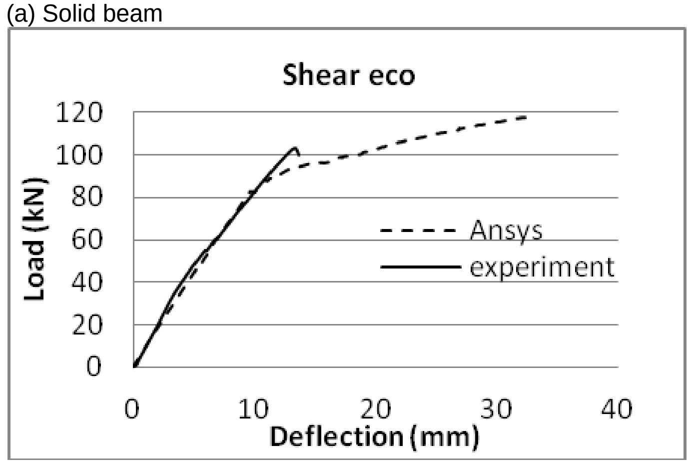


(c) Beam with half number of AAC blocks, LB2F

Figure 10. Load deflection relation of beams failed in flexure.



(a) Solid beam



(b) Beam with maximum AAC blocks

Figure 11. Load deflection relation of beams failed in shear.

stiffness than the tested beam. The final load for the model is also greater than the ultimate load of the actual beam by 16%. Based on these results, the concrete replacement by AAC blocks, as tested on LB1F and LB2F, has virtually no effect on the flexural strength of the section, which is as expected under the shear (SB1S and LB1S), the results also show the similar trend between the experiment and the numerical results, as shown in Figure 11. The shear strength reduction was as expected due to the reduction in the compressive analytical and experimental results is reported in Table 1.

There are several factors that may cause the greater stiffness in the finite element models. Microcracks produced by drying shrinkage and handling are present in the concrete to some degree. These would reduce the stiffness of the actual beams; however, the finite element models do not include micro cracks during the analysis.

Perfect bond between the concrete and reinforcing steel elements was assumed in the finite element analysis but the assumption would not be true for the actual beams. As bond slip occurs, the composite action between the concrete and steel reinforcing is lost. Thus, as also pointed out by (Kachlakev et al., 2001), the overall stiffness of the actual beams could be lower than what the finite element models would predict, due to the factors that have not been incorporated into the models.

Conclusions

A newly developed LSRC section for use as concrete beams has been proposed. LSRC beams under flexure and shear have been experimentally and numerically investigated. Based on the test and the numerical results, the following conclusions can be drawn:

Table 1. Load at failure from the experiment and numerical results.

Specimen	Ultimate load		Ratio
	Test, kN (kips)	FEM, kN (kips)	
SB1F	78.5 (17.6)	93.1 (20.9)	1.18
LB1F	78.9 (17.7)	94.0 (21.1)	1.19
LB2F	78.0 (17.5)	93.9 (21.1)	1.20
SB1S	128.2 (28.8)	153.0 (34.4)	1.19
LB1S	103.5 (23.3)	107.6 (24.2)	1.04

Under the flexure test, there was insignificant difference of less than three percent in the flexural capacity between the solid beam and the beams filled with AAC blocks. The predicted load at failure matched very well with the failure loads obtained from all the tests. These results show that the proposed LSRC sections seem to perform well under flexure.

The results show that the flexural capacity of the two LSRC beams is actually greater than the solid beam. This is due to the self weight reduction of the tested beam, which was about 10 to 20% of the equivalent solid beam. At failure load, the bending moments caused by the applied load and the self weight of the solid beam and of the LSRC beams, taken into account the weight reduction by AAC blocks infill, were almost equal in all the tested beams under flexure.

Based on the shear tests, the LSRC beam had lower shear capacity than the equivalent solid beam. The reduction of the shear capacity is 22%, which is quite significant in design. This result deserves more attention in order to determine the influence of the shear capacity in an LSRC beam.

Due to the conservativeness of the shear design provision in AS3600 (2009), it can still safely predict the shear capacity of the tested LSRC beam. However, it is recommended that similar level of conservativeness should be maintained because the shear failure is sudden in nature. As a result, it seems that design equations for LSRC members in shear need to be adjusted. Further works on the investigation of shear behavior and capacity of LSRC slabs, which have been conducted by the authors, show similar results.

Finite element model based on computer program ANSYS (12.1) has been developed to predict the behavior and strength of lightweight sandwich reinforced concrete beams. The model is verified against the experimental results. Based on the presented investigation, the developed model compares well in the low loading range. In the high loading range the model is less conservative. The model and the analysis method can be further improved by incorporating the factors affecting the stiffness and the nonlinear behavior of the beam such as micro cracking and bonding between the concrete and the steel. A simple adjustment can be made to the value of the modulus of elasticity in the analysis based on an empirical-based technique. Further investigations are required to investigate the consistency of the results and the factors affecting the results.

Based on the developed FEM model, the behavior and strength of LSRC beams under different load patterns and support constraints can be further predicted. This investigation is necessary as the first step for interested practitioners to gain more insight of LSRC performances and its use as an alternative lightweight concrete option.

A significant issue of LSRC beams lies with the behavior at service loading. The stiffness, the beam deflection, and the cracking behavior of LSRC beams need to be further investigated and compared with solid beams. This part of the research is not within the scope of this paper.

ACKNOWLEDGEMENTS

The authors appreciated the comments provided by Professor B.V. Rangan on this topic. Lightweight concrete blocks used in the experiment sponsored by Ecobrick, Australia were gratefully acknowledged. The reported experimental work was part of a final year project by M. A. Mazlan under the Department of Civil Engineering, Curtin University.

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