Thin-Walled Steel Enclosed Lightweight Foamcrete: A Novel Approach to Fabricate Sandwich Composite

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Abstract. This paper presents the results of a series of experiments conducted to explore the applicability of a novel approach to fabricate sandwich composite construction. Sandwich composite is produced by enclosing lightweight foamcrete as core material with thin-walled steel as skin layers. A total of 4 tests were carried out, composed of two duplicates of 2 variants which were distinguished by two steel sheeting thicknesses of 0.4mm and 0.8mm. The performance of the sandwich elements is investigated in terms of ultimate compressive strength, load-vertical strain responses and the failure mode. Experimental results showed significant enhancement in the ultimate compressive strength of the sandwich composite compared to that of the control samples made solely of the lightweight foamcrete. The failure mode of the sandwich element reveals the ductile and composite behaviour thus transforming a pure brittle material into ductile composite material because of the cold-formed thin-walled steel enclosure.

Key words: foamed concrete, composite panel, structural performance, walling system, sandwich composite

INTRODUCTION

Sandwich composite construction has been extensively used in aircraft, naval structures and many structural applications for a long time (Pokharel, N., M. Mahendran, 2003). Owing to the increasing interest in the use of sandwich composite, a good deal of research has continued in these days (Davies, J.M., 1993). Sandwich construction can be defined as composite structural elements, consisting of two thin and stiff faces separated by a comparatively thick layer of low density and stiff core infill material. Tensile and compressive forces are sustained almost entirely by faces. Flat and lightly profiled faces can carry only axial forces as their bending stiffness is insignificant, whereas profiled faces can carry both axial forces and bending moments (Chong, K.P., J.A. Hartsock, 1993). Similarly, the core of sandwich composite keeps the faces apart and stabilizes them against local failures and provides shear connection between faces.

Thin-walled laminated composite is also proved to be an efficient material to produce skins of sandwich system. Improvements in sandwich composite performance can also be potentially achieved by using different material systems for the core instead of conventional polymeric foams. One such material system includes lightweight foamcrete. Foamcrete is a lightweight material which has been extensively used in construction industries particularly for non-structural elements or as partitions. Lightweight foamcrete density is considerably lower than the usual range of concretes made with normal weight aggregates. In essence, the decrease in density of the lightweight foamcrete is obtained by the presence of voids either in the aggregate or in the mortar or in the opening between the coarse aggregate particles. The air-voids are initiated by agitating air with a foaming agent diluted with water; the foam then carefully mixes together with the cement slurry to form lightweight foamcrete. Integrating the air-voids into the base matrix gives a low self-weight, high workability, excellent insulating values, but lower strength in contrast to normal weight concrete.

Over the past 20 years, lightweight foamcrete has principally been employed around the world for bulk filling, trench reinstatements, backfill to retaining walls and bridge abutments, insulation to foundations and roof tiles, sound insulation, stabilising soils (especially in the construction of embankment slopes), grouting for tunnel works, sandwich fill for precast units and pipeline infill. However, in the last few years, there is developing interest in using lightweight foamcrete as a lightweight non-structural and semi-structural material in buildings to take advantage its lightweight and good insulation properties.

For this study, sandwich composite construction has been chosen because of its low thermal conductivity (leading to good insulation and high fire resistance) and usable amount of compressive resistance. It is considered feasible to construct lightweight foamcrete panels to be carried by manual workers on site without the use of machinery. However, since lightweight foamcrete is brittle, a suitable method of using lightweight foamcrete in load-bearing construction would be to use it in composite action with steel, which has high ductility. Should lightweight foamcrete be cast in-situ, the thin steel sheeting can be used as formwork during construction. The need for plywood formwork and the detailing of steel reinforcing bars is largely eliminated which significantly reduces the construction time and cost. Furthermore, because of the low density of
lightweight foamcrete, the pressure on the steel sheeting during construction would be much lower than the case with normal weight concrete, allowing thin steel sheeting to be used.

Fig. 1: Local buckling in thin-walled steel section.

When using thin-walled steel sheeting, the problem of local buckling under compression (Figure 1) should be considered. When using normal weight concrete in composite panel system, inward local buckling of the steel sheeting enclosure is prevented by the concrete inside (Figure 2). Because of low elastic stiffness of lightweight foamcrete, it is necessary to investigate whether lightweight foamcrete could still maintain this function. This paper will present the results of an experimental study of the compressive behaviour of sandwich composite panel made of profiled thin-walled steel sheeting as the facing and lightweight foamcrete as core material.

Fig. 2: Buckling modes of steel sections and composite sections (Shanmugam, N.E., B. Lakshmi, 2001).

Experimental Programmes:
All specimens were cast in house on the same day under controlled conditions so that the lightweight foamcrete core would have the same design strength.

Material:
The lightweight foamcrete core in this study was made from Ordinary Portland cement (OPC), fine sand, water and stable foam with cement-sand ratio of 2:1 and the water-cement ratio of 0.5. OPC in accordance with BSEN 197-1 was used as a binder. Local sand in compliance with BS EN 12620 with additional sieving to eradicate particles greater than 2.36 mm was employed. To produce foam, Noraite PA-1 foaming agent with weight of around 80 gram/litre. The stable foam was generated by means of foam generator Portafoam TM2 system. This TM2 system runs from an air compressor and consists of a central generating unit, a foaming unit and a lance unit. The profiled steel sheeting was made in-house from plain sheeting of 0.4mm or 0.8mm thickness by fly press. Further details of the lightweight foamcrete mix constituent proportions are outlined in Table 1.

Table 1. Lightweight foamcrete mix constituent proportions of foamcrete mixes.

<table>
<thead>
<tr>
<th>Dry density (kg/m³)</th>
<th>Cement to sand ratio</th>
<th>Water to cement ratio</th>
<th>Cement content (kg/m³)</th>
<th>Sand content (kg/m³)</th>
<th>Surfactant content (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>2.1</td>
<td>0.5</td>
<td>57</td>
<td>28</td>
<td>0.045</td>
</tr>
</tbody>
</table>
Sample Preparation and Testing:

The dimensions of the test samples were 400mm high by 400mm wide by 100mm thick. Figure 3 shows the dimensional view of the sandwich composite samples. A total of 4 sandwich composite samples were tested under axial compression. These 4 samples consisted of two duplicates of 2 types, being two steel thicknesses of 0.4mm and 0.8mm. Lightweight foamcrete with density of 1000 kg/m³ was chosen as it was found to have a useful amount of mechanical properties to construct a lightweight structural element when in composite action with the thin-walled steel. The two profiled steel skins were connected using 6 x 10mm bolts and nuts. In order to observe the strain behaviour, 4 strain gauges were fixed on each steel skin and in all cases; the strain gauges were at mid-height (h/2) of the sample (Figure 3). Two identical tests were also conducted to determine the strength of lightweight foamcrete core alone without any steel plate (control samples). Figure 4 shows the sample of lightweight foamcrete filled profiled thin-walled steel. The test was carried out in a universal compression testing machine with a maximum capacity of 2,500 kN (Figure 5) after 28 days of casting under axial compression. The samples were ground flat at the top and bottom prior to testing so as to ensure equal load distribution.

Fig. 3: Dimensional view of sandwich composite.

Fig. 4: Lightweight foamcrete filled thin-walled steel.
Material Properties of Lightweight Foamcrete and Steel Sheeting:

Three lightweight foamcrete cylinders were cast and tested on the same days as the sandwich composite specimens. The cylinder tests after 28 days gave an average strength of 5.1 N/mm². The test results are given in Table 2 and they are quite consistent. Data from the steel sheeting supplier gave yield strength of 280 N/mm² and a modulus of elasticity of 200,000 N/mm².

Table 2: Compressive strength of lightweight foamcrete cylinder tests.

<table>
<thead>
<tr>
<th>Cylinder dimension</th>
<th>Compressive strength (N/mm²)</th>
<th>Average strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
</tr>
<tr>
<td>100 ø x 200</td>
<td>4.9</td>
<td>5.1</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

A pronounced improvement in the performance of lightweight foamcrete is obtained by enclosing it with thin-walled steel skins to produce a sandwich composite. Table 3 presents the ultimate strength of each sample. The test results for control samples made solely of the lightweight foamcrete reached very similar ultimate strengths while the results for sandwich composite samples (both thicknesses) show a difference of about 10%. The enhancement in ultimate strength as high as 135% of the control was achieved for the sandwich composite with 0.8mm skin layers whereas for the samples with 0.4mm, the improvement was about 58% of the control.

Table 3: Summary of test results under axial compression.

<table>
<thead>
<tr>
<th>Test designation</th>
<th>Steel thickness (mm)</th>
<th>Ultimate strength (kN)</th>
<th>Average strength (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA1</td>
<td>-</td>
<td>127</td>
<td>125</td>
</tr>
<tr>
<td>CA2</td>
<td></td>
<td>123</td>
<td></td>
</tr>
<tr>
<td>SC1</td>
<td>0.4</td>
<td>189</td>
<td>198</td>
</tr>
<tr>
<td>SC2</td>
<td></td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>SC3</td>
<td>0.8</td>
<td>285</td>
<td>294</td>
</tr>
<tr>
<td>SC4</td>
<td></td>
<td>302</td>
<td></td>
</tr>
</tbody>
</table>

Figures 6 and 7 present the load versus mid-height vertical strain relationships for the four types of specimens. The different strain gauges (S1-S4 and B1-B4) recorded very similar data so only data from one of each set (S1 on the steel surface without any mechanical connectors, B1 on the steel surface between the mechanical fasteners. Figures 6 and 7 indicate that in all cases, the strain gauge S1 recorded more elastic strains than B1, indicating participation of the mechanical fasteners. In all cases, the test sample was able to sustain the maximum applied load for a considerable axial deformation. The descending branch of all the load-strain curves was gradual, indicating good ductility of the test specimen.

Figure 8 compares the load versus mid-height strain (point B1) relationships of the two steel sheeting thicknesses and also with control samples. As expected, the ultimate load and axial stiffness of the sandwich composite increases with increasing steel thickness. The most striking feature of Fig. 2(c) is that the encasement of lightweight foamcrete in thin-walled steel considerably increased the ductility of the panel for both steel thicknesses. The introduction of steel sheeting enables the sandwich composite to sustain a high proportion of its peak load at increasing deformations. In contrast, for the control samples, both specimens failed in a brittle
manner after reaching the peak load and it was not possible to attain the descending branch of the load-strain relationship.

Fig. 6: Load versus mid-height strain relationships for the sandwich composite with 0.4mm steel thickness.

Fig. 7: Load versus mid-height strain relationships for the sandwich composite with 0.8mm steel thickness.

Fig. 8: Comparison of load versus mid-height strain relationships for the sandwich composite with control samples made solely of the lightweight foamerete.
During the axial compression tests, the failure mode of the specimens was closely observed. Figures 9 show a failed sample (a) control sample, (b) sandwich composite with 0.4mm steel sheeting and (c) composite with 0.8mm steel sheeting. The control sample which was made solely of the lightweight foamcrete showed apparent first crack at about 85-90% of their failure load followed by their sudden and complete collapse at failure load. The behaviour of the sandwich samples with 0.4mm and 0.8mm steel sheeting was ductile and the first crack appeared at about 60-65% of their failure load. The lightweight foamcrete core of 1000 kg/m$^3$ density was capable of preventing the sandwich composite from inward buckling. In all cases, failure of the sandwich composite was initiated by local buckling of the steel sheeting, followed by crushing of the foamcrete core. There was no separation of the steel sheeting from the lightweight foamcrete core until near failure, indicating that the mechanical fasteners were able to hold the steel sheeting and the foamcrete core together to enable them to resist the applied load in composite action.

![Fig. 9: Failure mode of samples after tests.](image)

**Conclusions:**

Based on the experimental study conducted and the discussion made, it can be concluded that, the encasement of lightweight foamcrete in thin-walled steel is a novel and potential approach to produce lightweight sandwich composite. The sandwich elements produced are high performance in compressive strength compared to samples made solely of the lightweight foamcrete. Failure of the sandwich composite was initiated by outward local buckling of the steel sheeting which was followed by concrete crushing of the lightweight foamcrete core. The lightweight foamcrete core of 1000 kg/m$^3$ density was sufficient to prevent the steel sheeting from inward buckling. All the samples showed good ductility, giving gradual reduction in load carrying capacity at increasing deformation. In contrast, without using steel sheeting, the core lightweight foamcrete samples experienced brittle failure after reaching the peak load. These composites have the potential to be applied in earthquake borne areas, aircraft and naval structures.
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REFERENCES