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Composite wall panel for industrial housing: buckling test

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Summary
An integral building concept is developed based on industrial produced, load-bearing wall panels. The leading idea is to apply standardized panels combining structural solidity, thermal comfort, integrated piping and simple lightweight assembly. The main structural members are I-shaped studs that in spite of extreme slenderness cannot buckle in-plane of the wall by the support of a skin (kept in-plane by rigid insulation foam, here EPS –expanded polystyrene- is used). Each I-shaped stud consists of 2 hardboard plates (to form the stud’s web) to which 2 fir laths 30x60 mm$^2$ (being both flanges) are attached. These I-shaped studs are positioned 370 mm on center to make a solid and extremely lightweight structure with remarkable buckling resistance. The paper describes laboratory tests of 4 full-scale elements ($b \times h: 2.2 \times 2.8 \text{m}^2$) under axial load. Although the weight of all structural parts itself is about 1 kN (0.17 kN/m$^2$) the average failure load is a spectacular 705.1 kN (with sample standard deviation of 7.4%).

1. Introduction
House construction is hardly developed in recent decennia [1]. And since efficiency of construction on site is on the order of 20% [2] a radical change in house construction will be inevitable in near future. Based on thorough analysis of housing practice [3] an integral building concept is developed with special focus on using durable materials, minimal construction on site and negligible waste.

At the forefront of this integral building concept a new panel is developed as material to compose wall elements. The main features of these panels are the feasibility to mass produce jumbo-size parts (irrespective of final application) and to obtain any predefined lay-out by assembling panels into large elements [4].

Figure 1 shows an example of the panel used as cavity wall with brick as exterior finishing and gypsum fibre board as interior finishing. All kind of other finishing materials can also be applied. The fire-protection of the wall is equal to timber framed houses relying on a cover of gypsum board and mineral wool. The cross-section shows that this composition can also generate space for electrical conduit pipes and (should one require) hoses for heating. The thermal insulation and damp proofing of this cross-section is thoroughly researched [5]. Laboratory tests regarding soundproofing of exterior walls and residential separation walls are recently performed.
1.1 Background

Initial research started in 1997 as PhD-study in which a full industrial wall panel was developed for low-rise residential buildings as an example of industrialization in building [3]. Full industrial production implies that a manufacturer can mass-produce all components of a system without knowing specific circumstances and shapes of final use. Full industrial production will likely give a huge boost to building in improving quality at lower costs. However an essential precondition to introduce an industrial building concept for dwellings is the ability to vary layouts and appearances. A concept that undervalues the most important typifications of building – gearing design to specific expectations and situations – is of no use in real practice. For this reason a key boundary condition is to be appropriate to generate nearly all current layouts and appearances of dwellings [6].

After finishing the PhD-thesis this research is still an ongoing project carried out by students at Eindhoven University of Technology. Different suitable wall panels are tested in acoustic as well as structural laboratories. Feasible details are developed (for finishing, openings, supports, etc) and practical applicability is checked in pilot projects [6].

The structural concept of slender studs supported in-plane of a wall by thin layers of board that will not fold because of glued support by rigid insulation foam (Fig. 2) is tested before in other compositions [7], [8], [9], [10]. In the last structural test I-shaped studs (similar as shown here) were considered showing promising results despite early failure because of incorrect gluing. Therefore the last test is repeated as master thesis of the co-author. But preceding the structural tests a detailed study to improve acoustic sound insulation was performed as well by the co-author. Based on computer simulation and model testing the composition is now tailored to excellent sound insulation. For this reason the thickness of chipboard is increased to 8 mm, shown in Fig. 1 and 2 (while 3 mm proved to be already adequate to obstruct in-plane buckling in previous tests).

2. Laboratory tests

2.1 Making of test specimen

The specimen are assembled mainly based on commercial available insulating sandwich elements, widely applied in the Netherlands in pitched roofs (as structural panel as well as interior finishing).

These elements are a kind of SIPS-structurally insulated panels- and are manufactured using 89 mm thick grey coloured EPS foam sandwiched between two structural skins of app. 8 mm chipboard. The insulating panel used is produced by Isobouw: type Slimfix 3.0/8. These roofing panels are sawn into strips of 333 mm width (2800 mm length). In addition to sandwich strips also hardboard (3.2 mm thick sawn to b\(\times\)d\(\times\)l: 125\(\times\)30\(\times\)2000 mm\(^3\)) and dressed lumber laths (fir, 30\(\times\)60 mm\(^2\), with length 2800 mm) are used. All laths have two 12 mm deep longitudinal saw cuts on one side fitting the width of hardboard.
A part of the I-shaped studs is pre-assembled by applying PU glue into the saw cuts of laths and by putting hardboard sheets in (with strips of EPS in between, shown white in Fig. 3). When assembling panels PU glue is applied on top of all pre-assembled laths next to hardboard followed by positioning sandwich strips (shown up by grey coloured EPS in Fig. 3). A small part of a hardboard strip sticks out of the top that fits to the sawn cuts of the top lath (connected by PU-glue).

2.2 Test set-up

A special set-up is prepared for testing wall panels under axial load using a frame of steel beams (shown in Fig. 4). Above a panel a rigid steel beam (HE 300B) is put to have uniform distributed load in all five studs. This steel beam is pressed downwards by two 500 kN hydraulic jacks. These jacks are linked to ensure equal loading. Underneath a panel there are five load cells to measure the reaction of every stud. In this way a possible load distribution by chipboard is registered. The horizontal deflection of every stud (indicating out-of-plane buckling) is measured at mid span by electronic potential meters. Electronic potential meters are also used to measure vertical deflections at both sides of a panel (shortening).

Since the test panels are made of roofing panels that standard have a white film on one side (meant as interior finishing in pitched roofs) and an orange film on the other side (meant as damp open but waterproof membrane underneath roofing tiles) and since both films are not removed, the look of both sides of an assembled wall is different on all photos in this paper. All panels are positioned such that the white side is facing the front of the test set-up and the orange side faces the back of the test set-up.

A set of small filling plates made of thin steel plate is put on top of each timber lath as well as underneath each lath to ensure that the load is equally introduced into the I-shaped studs without direct loading chipboard (Fig. 5).

All thread rods in Fig. 4 are installed for safety reasons in case of buckling. Once a panel and all measuring equipment are installed also thread rods are placed at the front and back side as a kind of strap around the set-up for extra safety and to reduce deflections in the test set-up. In Fig 4 these rods are partly installed. In Fig 15 the strapped rods can be seen during testing.
In the next part testing of all four panels is described, explicating remarkable aspects and showing failure modes, load distribution during the test, horizontal deflections and ultimate failure loads.

2.2.1 Panel 1

The ultimate load is recorded at 633,7 kN. In Fig. 7 and 8 is seen that there is a certain disruption at point A (at a total load of app. 416 kN). Here a small failure in stud-01 is observed but the load is immediately taken over by adjacent stud-02. The distribution of load stays largely unchanged until a total load of app. 603 kN (point B). Here a rather small failure appears in stud-01, stud-02 and stud-05, but the stud-03 (stud in the middle) together with stud-04 takes most of the load from then.

At point C the maximum load of 633 kN is reached when stud-01 and stud-05 completely fail. Also in Fig.6 is seen that the failure is most serious in these two studs. The total load is only a little reduced, since stud-02, stud-03 and stud-04 are still able to take more load. However stud-04 can not take much extra load, so this stud immediately breaks after point C. Next stud-02 and stud-03 take most of the load until these studs fail in point D. Based on this assumption the chipboard has acted to distribute load. And although these I-shaped studs are very slender regarding in-plane buckling there seemed to be enough support by the chipboard to prevent in-plane buckling.

As is seen in Fig. 8 (with maximum horizontal deflection 9,5 mm, while 15 mm is regarded as ultimate deflection) and the photos showing failure modes in Fig. 6 there is also no out-of-plane buckling observed.

The maximum shortening of the panel is 7,3 mm (left position) and 7,0 mm (right position) at the maximum loading in point C.

The mean maximum load of all five studs is 144,6 kN (with minimum 115,3 kN, maximum 166,5 kN and a standard variation of 13,9 %).
2.2.2 Panel 2

The ultimate load of panel 2 is recorded at 699.8 kN. The first minor failure is observed at app. 396 kN (point A). Here a minor failure in stud-01 occurs, but stud-02 takes over. In point B at app. 429 kN a serious reduction is observed in stud-04 but the total load is not changed since stud-03 takes over.

At app. 524 kN the same happens with stud-02 where the load drops and stud-03 takes over.

In point D at app. 576 kN there is a minor change in stud-01 and extra load in stud-04 and stud-05. From this point also horizontal deflections increases rapidly, although this is modest in absolute displacements.

In point E at app. 644 kN the load in stud-05 falls down while the load in stud-04 takes over.

In point F the maximum load of 699 kN is almost arrived when stud-01 and stud-04 reaches the maximum. Stud-02, stud-03 and stud-05 can take over. However stud-02 can only take a small extra load.

Stud-03 is the last stud to fail in point G. Most studs fail at the underside of the panel close to the supports. However stud-01 fails some distance away from the support at the location of a knot (Fig. 9).

Although deflections in Fig. 11 are quite big (compared to the previous test) the maximum of 13.8 mm is still within acceptable range. The maximum shortening of the panel is 17.3 mm (left position) and 13.5 mm (right position) at maximum loading (point F). This difference is expected because studs on the left are the last that fail. The difference in shortening is small until point D (here 11 mm is measured on both sides).

Buckling (out-of-plane as well as in-plane) was not observed.

The mean maximum load of all studs is 150.9 kN (with minimum 135.6 kN, maximum 173.1 kN and a standard variation of 8.8%).
The ultimate load of panel 3 is recorded at 744.9 kN. The test is stopped here because the maximum measurement range of the load cells underneath the panels was reached (at 175 kN). Since panel 3 was the first panel in the test series the load bearing capacity was initially underestimated by choosing 175 kN load cells. Based on the values of this test all load cells in the other tests are replaced by load cells of at least 350 kN.

Based on measurements in the other tests (with only one stud –in panel 4– loaded over 175 kN until 180 kN) it is concluded that the load of panel 3 is real close to its ultimate load.

Also already failure is observed in stud-05 and stud-01. The failure of one of the laths in stud-01 is shown in Fig. 12 and is positioned at the bottom as well as at the top of this panel. The observed failure of stud-05 is much smaller.

Looking at the graph in Fig. 14 showing deflections at mid span shows that the horizontal deflection stays small (maximum 2.2 mm). Also the load distribution graph (Fig. 13) gives a regular progress until the test was stopped.

The first minor change is at point A at app. 680 kN. Here a very small regression in load is observed in stud-05 (where stud-02 takes over).

When approaching the maximum of 744 kN at point C first a small failure in stud-01 is observed, followed by a failure in stud-05.

The maximum shortening of the panel is 12.8 mm (left position) and 14.5 mm (right position) at the maximum loading in point C.

Buckling (out-of-plane as well as in-plane) was not observed.

The mean maximum load of all studs is 149.5 kN (with minimum 127.4 kN, maximum 176.4 kN and a standard variation of 14.5 %).
The ultimate load of panel 4 is recorded at 742.1 kN.

No failure is observed until point A is reached at app. 651 kN. Here the load of stud-04 falls back, while stud-03 (in the middle) takes over.

At point B stud-04 reaches its maximum while stud-05 is also close to its maximum. Here almost all extra load is taken by stud-03.

Point B is also well visible in the graph of horizontal deflection at mid span (Fig. 17) by the change in the curves. Here one might conclude that buckling out-of-plane starts. However the absolute value at failure is with 14.2 mm still moderate. This is also concluded from the failure mode shown in fig. 15. The stud that fails first (stud-04) is shattered at the introduction of the load. Stud-02 and stud-03 fail about 40 cm below the introduction of the load. Here also the chipboard is torn.

From these observations it is concluded that buckling (out-of-plane as well as in-plane) did not occur although the panel almost did reach this point.

The maximum shortening of the panel is 15.2 mm (left position) and 16.4 mm (right position) at the maximum loading in point C.

The mean maximum load of all studs is 150.7 kN (with minimum 124.6 kN, maximum 181.3 kN and a standard variation of 13.7 %).
2.3 General remarks

The average load of these 4 test panels is 705.1 kN with a sample standard deviation of 51.9 kN (7.4%). The small standard deviation compared to other experiments with timber under axial load is also observed in previous tests [7] [8]. The small standard deviation can be explained by the possibility of the panels to redistribute load by means of shear forces in the chipboard, as can be concluded from fig. 7, 10, 13 and 16. In these load distribution graphs is seen that although the introduction of the load is uniform the distribution over the I-shaped studs is far from equal.

All panels showed local failure (Fig. 18) rather close to a support or load introduction. Only one panel showed failure in chipboard as well as in the I-shaped studs. The maximum horizontal displacement at mid-span is 14.2 mm (about 1/200th of the panel height). Thus based on failure modes, observations and measurements it is concluded that buckling (in-plane as well as out-of-plane) did not occur.

3. Conclusions and further research

The lightweight building concept for low-rise residential buildings is developed as ongoing research issues for students of the Faculty Architecture, Building and Planning. This paper describes structural tests of the base component being a full-scale load-bearing wall panel under axial load. With a deadweight of the panels of just 17 kg/m² and a realistic buckling length of 2.8 meter, the average failure load under axial compression is found 705.1 kN. This impressive experimental result gives good prospects when compared to a required load of 130–175 kN per panel in a three storey house with concrete floors [4]. When used in timber framed housing the required load is even less than 100 kN per panel. Figure 1 shows an example of a cross-section of an outer wall illustrating that the insulation screed in the middle of this wall is almost closed and yet does not reduce the ability to resist heavy loading.

Since it is expected that house building in the end will shift towards using large-sized industrially produced panels, the results so far (and also regarding economics, durability, building physics and acoustics [6]) are promising to continue developing this concept. Based on these results we expect to develop a concept where a complete wall can be composed out of full industrial produced panels that are cut to length and assembled in ready-to-mount elements including windows, doors, etcetera that can be used to realise any pre-defined plan. Still lots of tests have to be performed (especially regarding shear resistance of the wall). This will generate many new educational challenges for students. Also pilot projects are planned to demonstrating building practice that this concept is significant advantageous in real practice as well considerable durable compared to common applications in building.

4. References


