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dr.ir. Faas MOONEN
Associate professor
Structural Design,
Faculty of Building and
Architecture
Eindhoven University of
Technology
The Netherlands
s.p.g.moonen@bwk.tue.nl

Faas Moonen, born 1958, studied architecture and structural design at Eindhoven University of Technology (TU/e). In 1983 he became a structural designer for Philips-Architecture and Engineering Department (AIB) with projects worldwide. He returned at TU/e in 1992 to teach structural design, where he defended the thesis “developing an industrialised foundation” in 2001.

Summary

The paper describes research regarding wall panels of a new house building method grounded on integration of interacting requirements of contemporary feasibilities. The main concept is a structure of sideways supported slender studs combining perfect load bearing as well as insulating properties by using solely inexpensive materials. The result so far is a panel existing of 95-97% immobile air that can bear about 1000 times its deadweight. Laboratory tests indicate that extreme lightweight panels fit for walls of two-storey dwellings, even if concrete floors are put in.

The wall panels are especially developed for industrialised production but have facilities to create an irregular, pre-defined layout of a dwelling with a minimum of labour at the building-site. Some pilot projects are performed to study the practical appropriateness of this concept. Of course many other aspects are integrated within the research framework, for instance regarding automation in design and production, acoustical and thermal performances, integration of service pipes, aesthetics at inside/outside... Achievements regarding internal and external moisture exposure are presented in a separate paper [6]. This paper presents a general view of the state of development so far.

Keywords: industrialised house building, developing wall panels, flexible building method

1. Introduction

The building method avails of industrialised building (figure 1). This concept draws a distinction between standardised manufacturing (for high quality at reduced costs) preceding prefabricated tailoring (for flexible applications to meet fanciful demands of architects) to get to simple on site construction (for being less depending of uncontrollable site conditions and weather situations).

The concept of industrialised building is worked out within the research framework of developing a building method. This concept (“discerning the sequence: standardisation preceding prefabrication and leading to simple assembly”) does not concern execution, but is worthwhile to consider in a design phase. In execution there is no apparent reason to discern this sequence, however in developing it is worthwhile to put effort in increasingly transposing activities to the next level for gaining quality, reducing costs, etc. without losing flexibility and adaptability. A tool is developed to determine activities of industrialised building that can be assigned to a higher level. In other developments it is found that it is well possible to make a pre-defined irregular
plan with only industrially produced elements.

2. Industrialised house building

2.1 Minimising wastage

Several possibilities are studied to assemble standard elements (figure 2). A platform construction seems to advantage, but projected on industrial elements there is some 30% wastage direct at production. The relative high percentage of residues of Structural Insulated Panels (SIP’s) confirms this. When using smaller elements (outline in the middle) wastage is quite reduced, but in return problems of stability are replied. Therefore the outline on the right of figure 2 is adopted. Additional studies show little wastage with elements available in different widths (400-800-1200-2000 mm). The overall idea is to use very long standard elements available from stock. After receiving project-requirements elements are cut into lengths and assembled to tailor-made panels including windows et cetera. Transport possibilities determine the proportions. Figure 5 shows a possible practise.

2.2 Structural concept

The structural concept is a very slender stud that cannot bent out sideways because of obstructing sheets [2]. This stud is exceptional strong under axial load (and horizontal wind load) because the slender stud is sideways supported by inflexible thin sheets. A thin sheet can offer strong resistance to (lateral torsional-)buckling of the stud when the supporting forces and the sheet itself remain in one plane. In figure 3 this is realised by connecting hardboard sheets to rigid insulation and with a simple but proper connection to studs. The structural concept is first studied [2], with standard sandwich roof elements for reasons of practical availability. These elements have similar composition regarding sideways supported studs.
Figure 4 shows the initial test set-up of horizontal loaded elements under compression with buckling length 2.8 m. Studs of 22x99 or 22x146 mm² and sheets of 3 or 8 mm are available. All studs show clear out-of-plane buckling. The ultimate load of two studs 22x146 mm² with 3 mm chipboard is about 100 kN. As a reference about 55 kN would be required in a load-bearing wall of a two-storey house with concrete floors.

2.3 Developing a cross-section and different kind of architectural details

Because the structural concept proves to be useful, a study regarding architectural details is carried out. Figure 5 gives a possible practise with materials and their functions. A tailor-made panel is composed out of standard elements. Therefore studs of adjacent elements must be fixed. Two connectors are developed, one connector is used in workshop to put together panels out of different standard elements and another connector is developed to adjoin ready-made panels on site. Because also panels with intermediate widths are required for making irregular plans, also a third connector is developed to connect the stud of a standard element to a filling strip. The filling strip is a rather massive element that can be sawn to a required width and length. Filling strips are placed in between elements to produce panels with any pre-defined width. Since the smallest standard element is 400 mm in width, the width of the filling elements is always less than 400 mm.

Next architectural details are studied showing that it is possible to make solid details with elements that consists of 95% immobile air and with a 22 mm plank as strongest part. At least on paper…. but is it also possible to realise these details for castles out of air in a practical situation?
2.4 Trial projects: studying details in “airy” wall panels by practical experience

Developing lightweight panels makes no sense if panels at the end cannot be used. Therefore two trial-projects are realised in an early stage by using sandwich roof elements (figure 4) since elements sketched in figure 5 are not available yet. Standard roof elements have similar composition regarding detailing as shown in figure 6 [1]. Existing panels are also useful to study how a pre-defined layout can be composed out of standard elements. Various details are tested by practical experience for instance in a workplace on 4 photos at the bottom with partly flat roof and also with a pitched roof. The laboratory building on two photos top left mainly focus on construction of full size multi-storey panels.

![Fig. 6 Two projects with different details](image)

2.5 Wall panels without vapour barrier

Within the framework also internal and external moisture exposure is studied. One of the objectives is to develop a construction that does not depend on a vapour barrier such as used in timber frame construction. A common used vapour barrier is undesirable since it is impracticable to create a leakage free layer and at the same time locate service pipes for electric wiring. And even if an airtight layer is assured a vapour barrier can be harmful in summer-situations when air-conditioners create a cold indoor climate. The barrier is in a summer-situation located at the cold site, and might contribute to condensation instead of preventing condensation and so potential causing decay in structural members.

The traditional vapour barrier (a polyethylene-foil applied at the inside face of studs) is in this specific composition substituted by additional insulation at the inner side of the outer cavity. Here 50 mm expanded polystyrene is added. Simulations regarding building physics in two sections of the cross-section (figure 9) validate this. Vapour diffusion without condensation is described in a separate paper [6] of the congress.
2.6 Aspects regarding production

After trial-projects affirmed multi-purpose uses of lightweight wall panels, additional structural research is regarded to the composition in figure 3. Photos of making test pieces are shown in figure 7. Panels are produced in the laboratory workshop to study feasibility regarding construction as well as regarding structural behaviour under axial load. Panels are 2,8 m in height to compare the results with other tests (figure 4). This height also gives conservative data when compared to practical use. The panel consists of five studs 28x148 mm$^2$ with each 4 longitudinal saw-cuts. Hardboard sheets are glued to EPS before putting in longitudinal grooves. The total width of a panel is 2,028 m.

2.7 Testing full-scale panels

The panels of figure 7 are tested in a vertical set-up (figure 8). On top a rigid steel beam is placed to have a uniform divided load from two linked hydraulic jacks onto the panel. Load cells underneath each stud measure possible load transfer from one stud to another via hardboard sheeting. The slenderness ratio of the studs is $\lambda = 65$ for out-of plane buckling. When ignoring support from hardboard sheets studs would have a slenderness ratio of $\lambda = 440$. In the test four panels are tested and all clearly buckled out of plane validating the hypothesis of figure 3. There is quite some load distribution from one stud to another, what might explain a rather low standard deviation of 12% (an effect that is also noticed in preliminary tests).

With a deadweight of the panel of just 45 kg, and a considerable buckling length, the average failure load under axial compression is 486,7 kN. This load can be compared to the dead weight of a concrete block of 2,7 x 2,7 x 2,7 m$^3$. Since an extreme loaded wall segment in a two-storey dwelling requires maximum 110 kN, this wall panel can be used as a starting point for an industrialised house building method.

2.8 Improved cross-section

When making test-panels (figure 7) it was found that structural behaviour strongly depends on accuracy of longitudinal grooves. If for instance grooves in figure 3 are too narrow, hardboard will be squeezed together, resulting in possible peeling off of hardboard and rigid insulation in between studs. And if longitudinal grooves are too wide, hardboard will be ripped apart from the rigid insulation near the stud. In both situations the resistance of the hardboard in preventing buckling of studs is strongly decreased. Therefore a new composition is developed, shown in figure 10.
The principle of this composition (figure 10) matches figure 3. Only the rectangular stud with longitudinal saw-cuts is replaced by an I-shaped stud. The double web of the I-shaped stud is made of hardboard, put into longitudinal saw-cut in the flanges. With this composition the percentage of immobile air is further decreased and gives a more equal thermal resistance. Again a panel was made in laboratory (figure 11) showing that construction is simplified. Four panels were made with the same overall dimension as panels in figure 8. Each panel consists of ten fir laths of 30x48 mm² (2.8 meter long) about 70% of what is used for panels with rectangular studs. The average failure load under axial compression is 378.5 kN some 75% of what is found for panels with rectangular studs.

2.9 Supports for heavy loading
As well as testing full-size panels with I-shaped studs (figure 11), also structural tests regarding heavy loaded connections are performed. Figure 12 shows the test piece, where a vertical load is applied in the middle of the extended steel strip. Although there is little solid material in the I-shaped stud of figure 10 the ultimate shear force still reaches 30 kN, followed by long plastic behaviour that in the end forced the test to stop.

There is still a lot of additional research required to make this support into a practical bearing, but these preliminary results show great promise.

2.10 Acoustical performances
Also a preliminary test is performed in an acoustical laboratory. A panel of 1.23 x 1.48 m² is put in a standard test set-up. The panel consists of three I-shaped beams and is finished with internal lining (gypsum fibreboard) at one side (front site in figure 13). Behind the gypsum fibreboard and in between the fir laths mineral wool is applied. The sound insulation is measured without applying an outside finishing. The result of the measurements of acoustical insulation corresponds in general to the insulation of a double glazed windowpane of fair quality.

Based on the acoustical test some improvements are suggested by acoustical specialists. Thus the composition of the wall will once more alter to optimise performances. The impact of advances regarding acoustics are not known at this stage, neither or this strongly affects previous tests regarding structure, building physics or construction.

3. Discussion en preliminary conclusions
The paper describes progress in developing a new house building method:

the building method aims to integrate interacting requirements of contemporary feasibilities, incorporated in application-independent wall panels, that can be easily adapted to meet fanciful demands of architects, in order to realise pre-defined, irregular lay-outs, and finally is simple assembled on site.

One should consider that all aspects mentioned in this paper are apparently described as monodisciplinary items. But one should realise that all aspects interact, requiring a multi-disciplinary
approach. Therefore it is not possible to sketch a full picture within the scope of the proceedings. Another aspect of interacting requirements is that findings change constantly by continuation of research. Thus explanations for aspects are often (partly) based on an expired point of departure. In this research program previous basic assumption needs frequent validation.

- The building method follows principles of industrialised building, developed within the research framework. The concept draws a distinction between standardised manufacturing preceding prefabricated tailoring to get to simple on site construction. Simple construction and transposing activities to indoor work makes the process less depending on site and weather conditions. Also indoor work is more efficient compared to outdoor work. Prefabricated tailoring is needed to facilitate construction of unique objects, a typical feature of building. Then again it is worthwhile to transpose as much activities as possible from prefab tailoring to standard manufacturing by developing clever elements. Automated manufacturing is advisable since it facilitates high quality at substantially reduced costs.

- Industrial produced wall panels are put upright from foundation to the edge of the roof to make it possible to apply almost all of it, and so reducing wastage. The structural core is an I-shaped stud made of two fir laths with a double web of hardboard strips put into longitudinal grooves. The composition is found suitable in automated construction, can invoke substantial strength, can be used in suitable architectural details, has perfect thermal resistance (containing 97% of immobile air) and weights including interior lining only 23.4 kg/m². Introducing heavy loads, for instance of a floor, requires special supports. Preliminary test (30 kN ultimate load) show great promise.

- Regarding acoustical performance improving is still required. This will have consequence on the presented composition of the wall panels. The prospect is that adding materials within the concept of the presented composition can substantially improve acoustical performances.

Notwithstanding the presented results a great many questions are still waiting for an answer.

3.1 References


