Citation for published version:
Gross, C & Walker, PJ 2014, 'Racking performance of timber studwork and hemp-lime walling', Construction and Building Materials, vol. 66, no. 15, pp. 429-435. https://doi.org/10.1016/j.conbuildmat.2014.05.054

DOI:
10.1016/j.conbuildmat.2014.05.054

Publication date:
2014

Document Version
Peer reviewed version

Link to publication

Racking performance of timber studwork and hemp-lime walling

Written: 20/01/2014

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Number of words: 4321
Number of tables: 3
Number of figures: 10

Abstract

Hemp-lime is a natural, sustainable low carbon insulating material. It is formed from three main constituents: hemp shiv; lime based binder; and, water. Its use within the construction industry is a relatively recent development. In the UK hemp-lime is most widely used for solid wall insulation in conjunction with structural timber studwork, either in in-situ casting or more recently innovative prefabricated panels. Current design practice assumes that the hemp-lime does not contribute towards the structural capacity of the wall. Previous work by the authors has confirmed that hemp-lime significantly benefits vertical load bearing capacity of the timber studs. In this paper research that has been undertaken to establish the enhancement the hemp-lime provides to the in-plane racking strength of timber studwork framing is presented. Laboratory testing was undertaken on a series of timber studwork frames both with and without hemp-lime. It was found that the hemp-lime significantly increases both the racking strength and stiffness.

Keywords: Sustainability, Timber structures, Natural Resources, Hemp-lime

1. **Introduction**

In 2008 the UK Government published a strategy for sustainable construction (DBERR (2008)), with its key themes being to design buildings that are sustainable, resource efficient, fit for purpose and adaptive. Minimising the energy used in construction and running of buildings is key to meeting the UK targets of reducing greenhouse gas emissions to 80% of 1990 levels by 2050 (DFT, 2009). These can be achieved through significant reductions in operational carbon emissions by reducing heating and cooling demands (depending on season), with improved insulation levels, increased air tightness, better construction detailing, improved build quality and occupant behaviour amongst leading factors. It is increasingly recognised that low carbon buildings also require use of low carbon materials and components as embodied carbon levels play an increasingly important role in the footprint of a building. The use of natural low carbon building materials is increasing within the UK in response to this need. Hemp-lime composites are one of the many natural, sustainable low energy materials that offer improved building performance for radically lower embodied carbon emissions compared to existing solutions.

Hemp-lime composites have been used in construction for around 20 years. The use of this lightweight composite, comprised of the woody core of the hemp plant (shiv) and lime binder with water to mix, originated in France (Bevan *et al.*, 2008) and its use has become increasingly widespread across continental Europe and in recent years within the United Kingdom (Lawrence, 2009). Hemp-lime was initially used in the restoration of historic timber buildings, as a replacement for wattle and daub that had deteriorated (Bevan *et al.*, 2008). It was found that it provided a long lasting natural infill material that was stable, did not shrink and allowed the buildings to breathe which is vital if their condition is to be maintained (Bevan et al., 2008). Hemp-lime is now used in new construction as a natural, sustainable and carbon neutral (Hemp Technology, 2010) infill wall material around timber-framed construction. It is typically used in domestic scale construction and a demonstration house, The Renewable House, has been constructed at the Building Research Establishment (BRE) to showcase the material. Hemp-lime is currently used within the UK as a solid wall insulating material and does not contribute to the structural performance of the walls. However as it encapsulates the structural studwork frame there is the possibility that it could enhance the performance of the studwork frame despite the relatively low stiffness and strength of the hemp-lime. This has been shown to the case when compressive loads are applied (Gross, 2013).

Due to its relative infancy there has been limited research on the structural performance of hemp-lime. Most studies have focused on the material properties, particularly the compressive strength of hemp-lime at different densities and with different mix proportions (Evrard, 2002, Elfordy et al., 2008, De Bruijn et al., 2009, Hirst et al., 2012). There have been limited studies on the composite behaviour of hemp-lime and structural studwork framing. Several studies have been carried out on the compressive performance of composite walls at both the University of Bath (Helmich, 2008; Gross, 2013) and Queens University in Kingston, Canada (Dutton, 2009).

To date there has been no research published on the in-plane racking performance of hemp-lime walls or panels. In recent years there has been some similar research on ModCell prefabricated straw bale panels undertaken by the authors. These utilise similar materials to composite hemp-lime and studwork frame walls with a timber structural frame and a low stiffness insulating filling material. Several studies (Lawrence et al., 2009; Gross et al., 2009) have shown that through composite action between the timber framing, straw and lime render covering the in-plane racking resistance of the prefabricated straw bale wall panels can be significantly increased and also have the potential to be used in load bearing construction.

There is a need for further research in this area into the performance of composite hemp-lime and studwork frame walls, particularly when in-plane racking loads are applied. This is the focus of the research that is the focus of this paper. The aims of the work presented here are to establish the in-plane racking performance of timber studwork frames with hemp-lime and the effect the hemp-lime has on the performance. To meet these aims the following objectives were developed for this work: undertake laboratory testing of studwork frame wall panels both with and without hemp-lime; analyse the results, develop and implement improvements.

2. Experimental programme

During this study both timber studwork frames with and without hemp-lime were constructed and tested under in-plane racking loads. Frames without hemp-lime were tested to provide a comparison of performance. When using composite hemp-lime and timber framed construction the studs are generally positioned in either the centre of the wall or on the inside edge of the wall. Both of these techniques are currently used in the construction of composite hemp-lime and studwork framing. When the studwork frame is in the centre of the hemp-lime it is fully encapsulated. Additionally full encapsulation may be structurally beneficial. When the studwork frame is on the edge of the hemp-lime permanent shuttering can be used against one face of the wall, which allows for faster construction and easier finishing of the walls internally as the permanent shuttering can simply be skim plastered. However as the studwork frame could separate from the hemp-lime additional horizontal rails have to be fixed to the studs to prevent this. In total five full-size wall panels were tested, four with hemp-lime and one with timber studwork frame only. The details of the wall panels are shown in Table 1. Wall panels R1, R2 and R3 were constructed and tested initially. The results of the testing on these wall panels informed the design of wall panels R4 and R5. In addition to studwork framing and hemp-lime wall R5 included a magnesium silicate sheathing board fixed to the studs to act as permanent shuttering.

The wall panel tests are supported by material tests on the timber and hemp-lime materials. The materials used throughout the experimental programme were maintained from one supplier, with only the positioning of the studwork frames and the connectors used in the leading stud connections varied. The timber studs used were 38mm by 89mm C16 softwood. Due to the limited number of specimens the studs were carefully selected to ensure they were free from major defects, such as knots and shakes, that could disproportionately influence the results. All of the frames were constructed to the same dimensions to suit the test standard methodology for timber stud walling set out in BS EN 594 (1996). The frames were 2.4m high by 2.4m long. The studs were at 600mm centres. Walls R2, R4 and R5 also has 19mm by 38mm timber battens at 600mm vertical centres fixed to the studs as the frames were positioned on the edge of the hemp-lime. The studs were fixed to the header and footer rails in wall panels R1, R2 and R3 with two 3mm diameter by 75mm long nails in each connection. All of the joints in wall panels R4 and R5 were also connected in the same way apart from the leading stud connections, which used two 6.5mm dia. x 150mm long double thread screws in each end. Figure 1 shows the stud and batten layout for the test panels.

The hemp-lime mix used for this study was kept constant throughout, as was the target dry density. The hemp shiv used was Tradical® HF and the binder was

Tradical® HB, both sourced from Lime Technology Ltd. The mix proportions used are as follows: 19.5% hemp shiv, 32% binder and 48.5% water by weight. This is equivalent to using one bale of Tradical HF hemp shiv with 1.5 bags of Tradical HB binder and 50 litres of water. The hemp-lime was cast to achieve a target dry density of 275kg/m^3. The shuttering was removed 24 hours after the hemp-lime casting had been completed. Following this the panels were left to dry and cure in a dry environment, for between 4 and 5 months prior to testing.

3. Test set up

The racking test set up was the same for all of the wall panels. The test set up is shown in Figure 2 and Figure 3. Frame R3 was tested lying flat on the laboratory floor, for reasons of stability during the test; the setup is shown in Figure 4. All of the racking tests followed the set up outlined in BS EN 594 (1996). A horizontal racking load was applied to the header plate via a hydraulic jack. Vertical point loads were applied to the top of each stud through the header plate. All of the loads were measured using load cells. In plane deflections around the perimeter of the panels were recorded using LVDTs measuring both the movement of the hemp-lime and the timber studwork frame. Both the loads and displacements were recorded using a System 6000 data acquisition module.

All of the test panels were securely fixed to the laboratory floor to prevent sliding and uplift of their bases as set out in BS EN 594 (1996). The loading regime for all of the in-plane racking tests was based on the process set out in BS EN 594 (1996) and was as follows:

Stabilising cycle:

- Apply 5kN vertical loads to studs (F_v - constant vertical load applied to top of studs)
- Apply horizontal load of $0.1F_{max, est}$ (Estimated racking failure load) and hold for two minutes
- Unload horizontal load and hold for five minutes

Stiffness cycle:

- Apply horizontal load of $0.4F_{max, est}$ and hold for five minutes
- Unload horizontal load and hold for five minutes

Strength cycle:

- Apply horizontal load of $0.4F_{max, est}$ and hold for five minutes
- Continue increasing horizontal load until failure occurs.

Failure was considered to have occurred when there was either a significant structural failure of the panel or the horizontal deflection at the top corner reached 100mm (height/24).

The test procedure is designed to test the resistance to racking of panels that are able to deform in plane both vertically and horizontally. The stabilising cycle allows settlements to occur within the wall panel. This would normally happen during construction as the upper storeys or roof is constructed and vertical load was slowly applied to the wall. The stiffness cycle allows the initial stiffness that is likely to dominate serviceability deflections to be established. Finally the strength cycle allows the ultimate strength of the wall panel to be found.

4. Material Properties

The hemp-lime material properties were established by testing cylindrical specimens cast from the same mix and at the same time as the wall panels. Following casting the cylinders were left in their waxed lined cardboard moulds for seven days. Once the moulds had been removed the cylinders were then stored with the wall panels until the time of testing. This ensured that the material used in the cylinders had been subjected to the same drying conditions as the hemp-lime in the walls panels. The cylinders were tested at the same time as the wall panels. Compressive strength, density and moisture content were recorded.

Compressive testing of the cylinders was carried out using a Dartec 100kN testing machine. The specimens were loaded under displacement control, at a rate of 3mm per minute. Prior to testing the diameter, length and weight of each specimen was recorded. Compressive stress was taken as load divided by original cross-sectional area; compressive strength as maximum (peak) compressive stress. Compressive strain was taken as change in height of the entire cylinder (platen movement) divided by original height. This is seen as a valid method for measuring strain as work undertaken at the University of Bath by Hirst et al (2012). The average compressive strength of the hemp-lime cast with walls R1 and R2 was 0.45N/mm^2 and for the hemp-lime cast with walls R4 and R5 was 0.35N/mm^2. Figure 5 shows the stress strain plots for the cylinders tested.

The average moisture content of the cylinders from walls R1 and R2 was 9.4% and the average dry density was 315kg/m^3. The average moisture content of the cylinders from walls R4 and R5 was 8.5% and the average dry density was 323kg/m^3. Both of these densities are higher than the target 275kg/m^3 as these cylinders were not weighed as they were fabricated, as this was not possible at the manufacturing facility. Specimens of hemp-lime were also taken from within the wall panels at the time of testing and the average moisture content in the centre of the walls was 20.7%. The average dry density of the hemp-lime in the walls was measured at 295kg/m^3.

The material properties of the timber used in the studwork frames were taken from BS EN 1995 (2004). Only the moisture content of the timber at the time of testing was measured in the laboratory. The average moisture content of the studs in the centre of the hemp-lime (Wall R1) was 21.5% and for the wall with the studs on the edge of the hemp-lime (Walls R2, R4, R5) was 18.2%.

Prior to construction of wall panels R4 and R5 the stud to header and footer rail connections were tested. Five different mechanical connectors were tested. The connectors used were 3.75mm x 75mm long nails (N), No.8 x 75mm long screws (No.8), No.12 x 100mm long screws (No.12), 6.5mm dia. x 150mm long Double Thread screws (DT) and 6mm dia. x 140mm long Washer Head screws (WH). Small sections of joint were constructed with two connectors per joint. The joints were tested in the Dartec 100kN testing frame. The base of the joint was fixed to the bottom jaw of the testing frame and the vertical section of the joint (representing the stud) was loaded in tension via the top jaw as shown in Figure 6. Five specimens for each connector type were tested.

The average stiffness and average maximum load for each connector type are shown in Table 2. The stiffness was taken between 15% and 30% of the maximum load. From the result shown in Table 2 it is clear that the nailed connections are both the least stiff and they have the lowest maximum load. They also have a high variation. This is a result of the failure mode which was shank withdrawal which caused peaks and troughs in the failure load as the nail slipped before the timber gripped again. The double thread screwed connections are the stiffest and the washer head screwed connections have the highest load capacity. For walls R4 and R5 the double thread screws were chosen for the leading studs as the stiffness is likely to influence the performance of the studwork frames under in plane racking loads rather than the strength.

5. Results and analysis

Figure 7 shows the results from the racking tests with horizontal displacement at the top of the wall against the applied racking load. All of the walls displayed a similar pattern with an initial high stiffness that then reduced. The reduction in stiffness corresponded to an element beginning to fail within the wall panels. In wall panels R1 and R2 it was as the leading stud connections began to fail (Figure 8). In wall panel R4 this was when the hemp-lime began to develop cracking (Figure 9) and in wall panel R5 it was when the screws started to pull through the sheathing board (Figure 10).

It can be seen that Wall R5 performed the best with the highest stiffness throughout the test as well as the highest racking load achieved. Wall R5 should be the strongest and stiffest due to the improved leading stud connection and Multi-pro sheathing board. Walls R1 and R4 both have similar stiffness during the second phase of testing when the stiffness had reduced. These walls were of similar construction with the only differences being that Wall R1 had the frame in the centre whereas Wall R4 had the frame on the edge and R4 had improved leading stud connections. Wall R4 should have performed better than Wall R1 due to the improved connection, however the lack of performance increase is likely to be due to the some damage sustained by the panel when it was accidentally dropped during transport. There were large cracks present in the hemp-lime and as a result the stiffness reduced at a lower load than the other three walls.

In wall R2 the hemp-lime had not fully cured and therefore was weaker than the other three walls. Despite this, and the initial damage to Wall R4, all of the walls with hemp-lime were significantly stronger and stiffer than Frame R3.

In all of the tests the racking load did not suddenly drop after the peak load was reached and all of the walls with hemp-lime displayed some ductility. The hemp-lime helps to provide this ductility along with the multi-pro sheathing board on Wall R5. Hemp-lime is a ductile material under compressive loads when tested alone as seen in the materials properties tests. As it takes load from the studs during racking loading the hemp-lime also behaves in this way providing post peak load ductility to the wall panels. The sheathing board fulfils a similar function as the screws continue to pull through the board and deform as the overall wall deflections increase. At extreme deflections where the screws are caused to pull through the edges of the boards this ductility may decrease.

Table 3 shows the racking stiffness and racking strength of all the walls calculated following the methods set out in BS EN 594 (1996). The racking strength is the highest load achieved by the panel during the test. Therefore these racking strength values were achieved at very high displacements of over 70mm for Wall R1, over 40mm for Wall R2, over 50mm for Wall R4 and over 30mm for Wall R5.

The design racking resistance for both walls has been calculated using the methods set out in BS 5268-6.1 (1996) Section 5. The design racking resistance, R_b, of Wall R1 is 1.43kN/m, of Wall R2 is 0.89kN/m, of Wall R4 is 1.14kN/m and of Wall R5 is 1.94kN/m. These values include factors of safety as set out in BS 5268-6.1 (1996). BS 5268 (1996) separates racking panel sheathing materials into four categories, with Category 1 being the strongest and Category 4 the weakest. Category 1 sheathing includes plywood and oriented strand board (OSB), Category 2 is for bitumen impregnated insulation board , Category 3 is for 30mm thick plasterboard and Category 4 is for 12.5mm thick plasterboard. Comparing these values with those given in Table 2 of BS 5268 (1996) for the design racking resistance of common sheathing materials Walls R1 and R4 have a greater racking resistance than Category 2 materials (0.9kN/m), Wall R2 has a greater racking resistance than Category 3 materials (0.6kN/m) and Wall R5 has a greater racking resistance than Category 1 materials (1.68kN/m).

When hemp-lime and studwork composite walling is used for construction the outer surface needs protecting from the weather. This can either be provided by rain screen cladding or render. When render is used a further enhancement to the racking performance may occur. Renders are commonly used within straw bale construction to increase the strength of load bearing straw bale walls and the same could be considered when using hemp-lime. There may be a small increase in racking performance when a render is used, but the studs transfer the racking loads to the centre of the hemp-lime mass or to the other face. Deflection in the hemp-lime across the depth of the wall is unlikely to allow transfer of the entire racking load into the render skin and therefore the enhancement in performance may be limited. Additionally when a render is used the serviceability deflection of the wall will have to be carefully considered to avoid cracking of the render.

6. Conclusions and further work

When subjected to in-plane racking loads hemp-lime at a target dry density of 275kg/m^3 increases the racking resistance of timber studwork frames. The weakness in the structural system is the leading stud connections. When these are strengthened both the racking stiffness and strength are increased. When hemp-lime is being relied upon to provide in-plane racking resistance in a standard 2.4m long by 2.4m high wall panel with 38mm by 89mm C16 studs, the design racking resistance is equivalent to a Category 2 wall construction as detailed in BS 5268 (1996). The racking stiffness is improved significantly by the use of permanent shuttering that acts as a sheathing board such as Multi-pro XS boarding. With sheathing the design racking resistance is higher than Category 1 wall constructions as detailed in BS 5268 (1996).

During this study the racking performance has been investigated with and without sheathing boards, however the performance of a completed wall has not been studied. If the external finish was render then this could enhance the racking performance as it may increase the stiffness of the wall and the render will reduce the deformation in the hemp-lime. Other finishes such as rain screen cladding could be investigated, but they are unlikely to have an effect on the structural performance.

Acknowledgements

The authors' would like to thank EPSRC and Lime Technology Ltd for financial support of this research work. In addition the authors’ thank the following individuals for their help and support throughout this work as without them it would not have been possible: Mike Lawrence, Will Bazeley, Brian Purnell, Jamie Febry, Neil Price, Sophie Hayward and Graham Mott (all at the University of Bath), Mark Patten, Dave Mayle and Max Burbidge, Piers Ashley Carter (all at Lime Technology) and Richard Hartley (Advanced Timber Structures).

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Tables

Table 1 Wall panel details

Wall No.	Frame position	Hemp-lime	Sheathing
R1	Centre	300mm thick	None
R2	Edge	300mm thick	None
R3	NA	Frame only	None
R4	Edge	300mm thick	None
R5	Edge	300mm thick	Multi-pro XS sheathing

Table 2 Connector test results

	Stiffness		Load applied	
Connector type	Average (N/mm)	Coefficient of variation (%)	Maximum (kN)	Coefficient of variation (%)
Nail	433	77.6	0.55	11.8
No. 8 screw	485	26.8	3.06	3.2
No. 12 screw	1137	20.2	5.49	10.0
Double thread screw	2710	15.6	9.89	5.0
Washer head screw	2155	15.7	13.16	12.9

Table 3 Racking stiffness and strength

	Racking stiffness (kN/mm deflection)	Racking strength (kN/m length of wall)
Wall R1	0.26	6.08
Wall R2	0.75	9.69
Wall R4	1.27	10.62
Wall R5	0.79	6.74

Figures

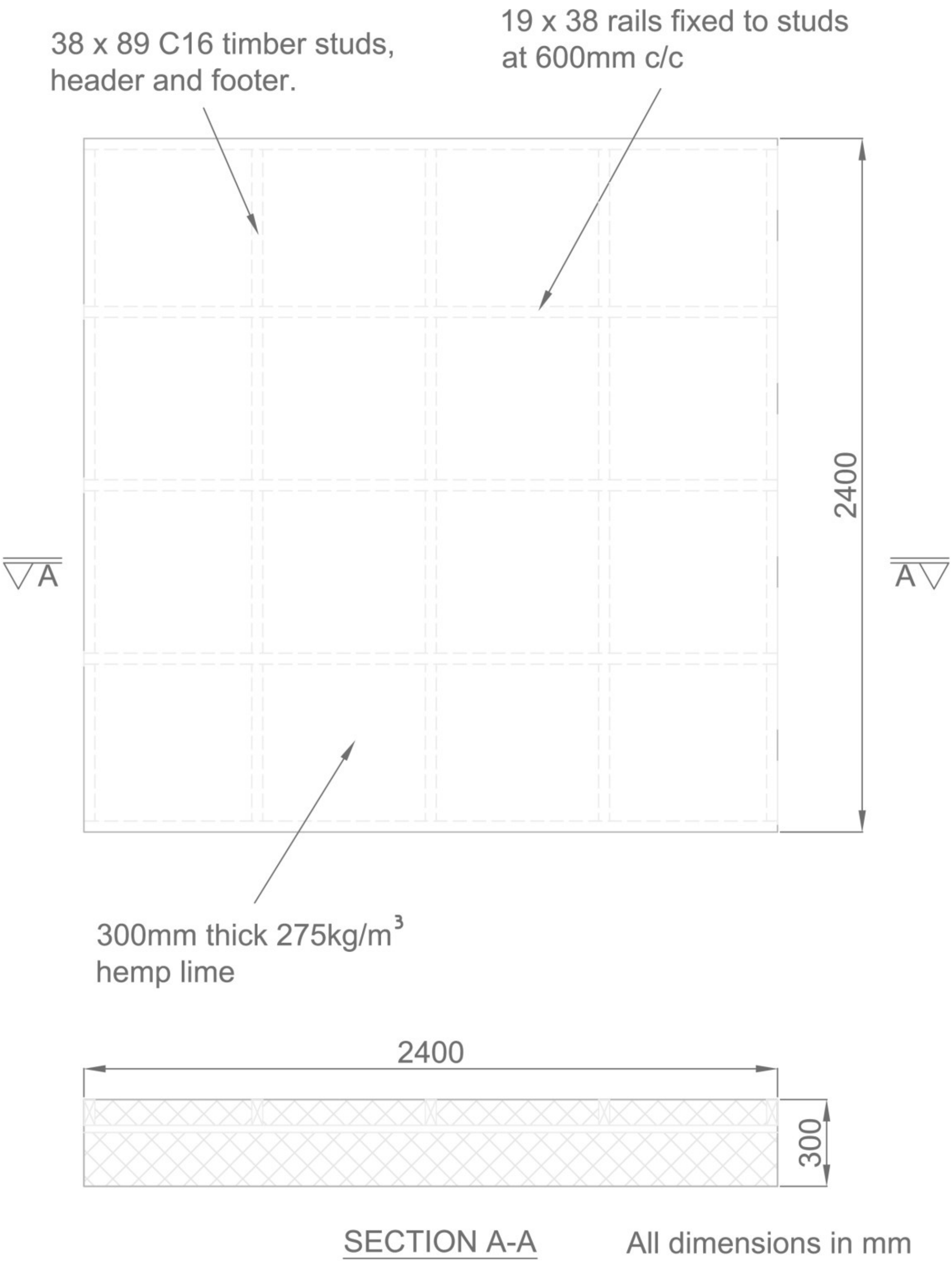
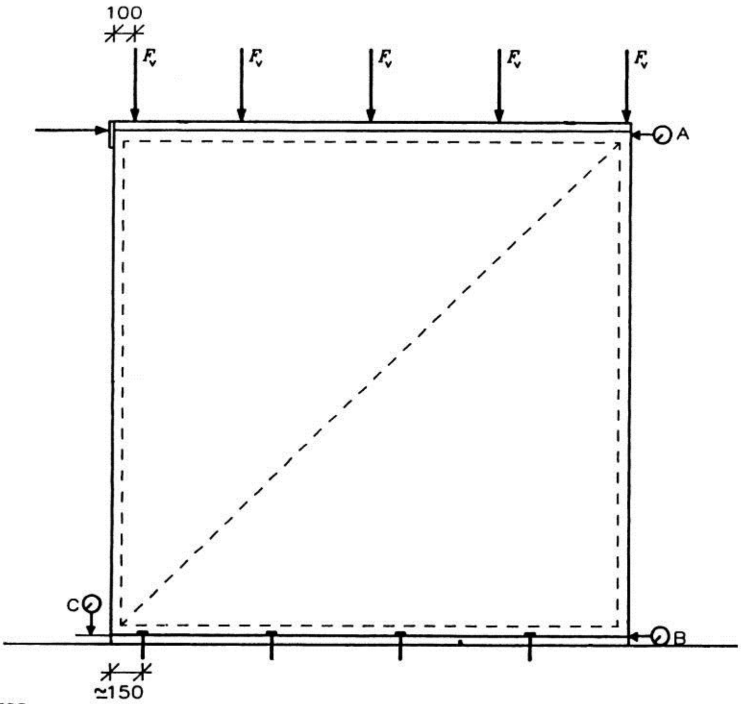


Figure 1 Typical stud arrangement



Sizes in millimetres

Figure 2 BS EN 594 (1996) racking test set up


Figure 3 Wall R2 in test rig

Figure 4 Wall R3 in test rig

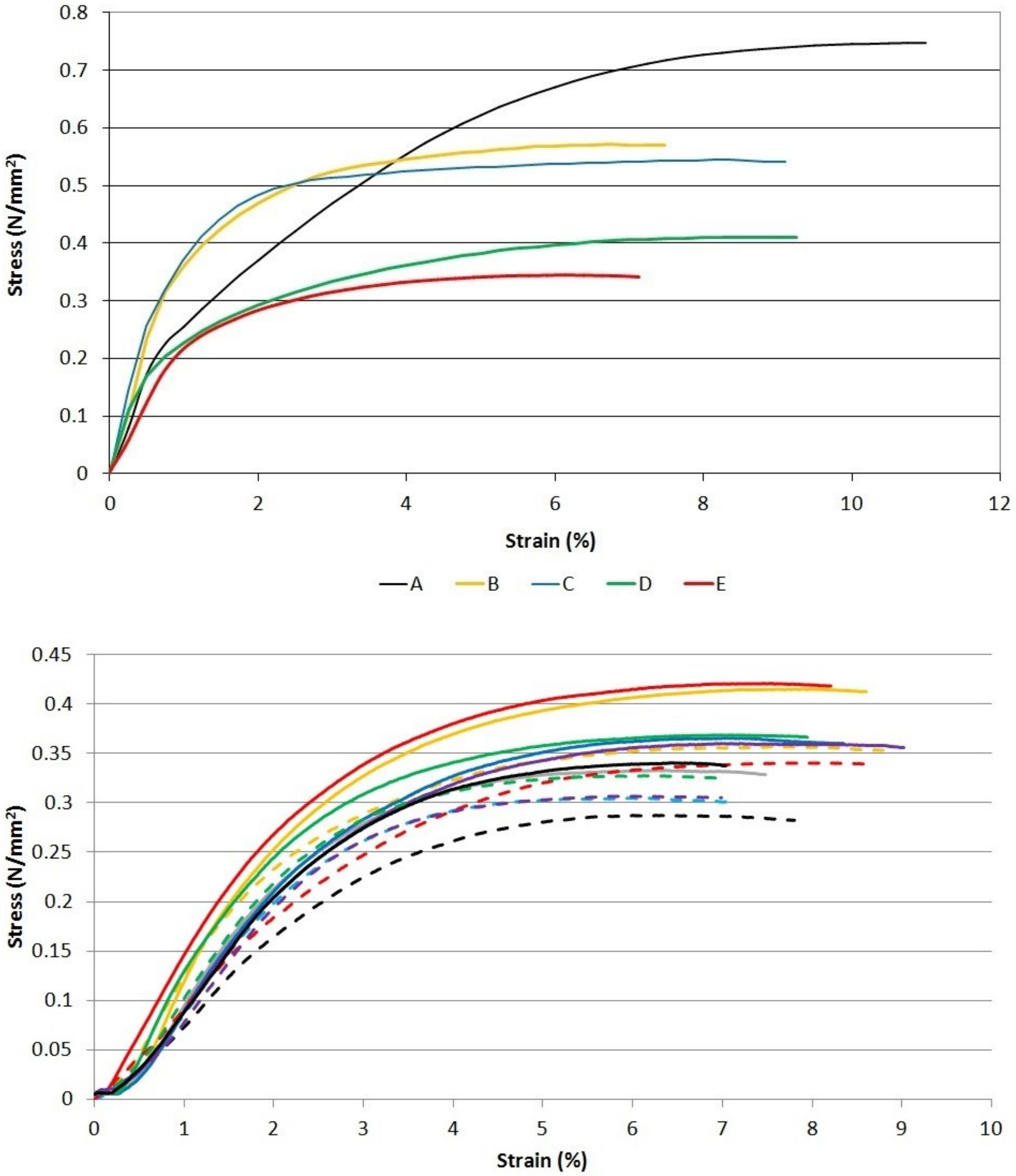


Figure 5 Hemp-lime cylinder stress strain plots (Walls R1 and R2 top, Walls R4 and R5 bottom)

Figure 6 Leading stud joint testing

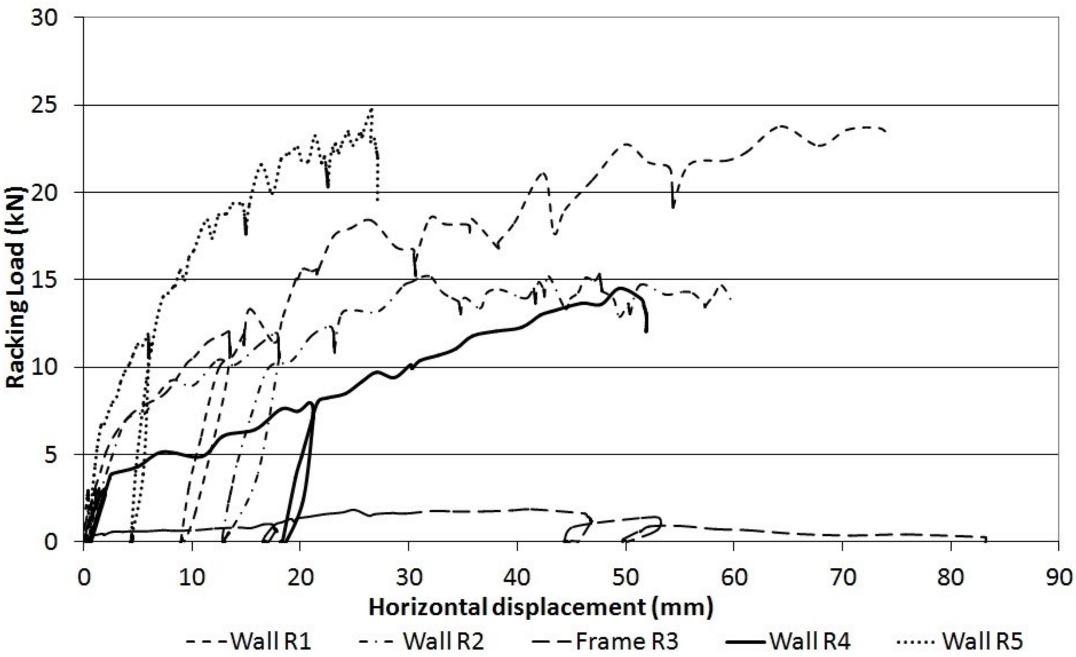


Figure 7 Racking test results

Figure 8 Leading stud connection failure

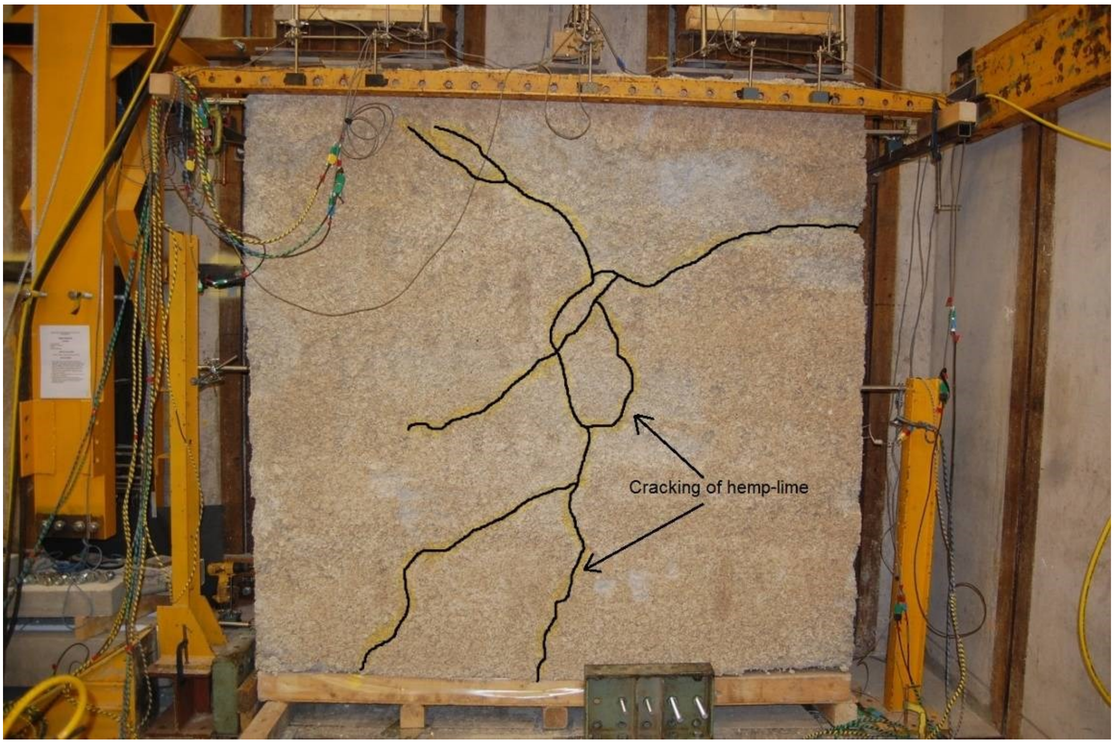


Figure 9 Hemp-lime cracking


Figure 10 Screws pulling through sheathing board