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Summary Considerable attention has been paid to airtightness in timber-framed dwellings over the last 15 years. As a result it is now possible routinely to construct timber framed houses with air leakages below 3 ac h^{-1} at 50 Pa. Less attention has been paid to airtightness in masonry dwellings, particularly in the UK. This paper presents results of laboratory work whcih confirms the very high airtightness of wet-plastered masonry, and identifies a significant weakness in the construction of conventional load-bearing masonry dwellings. Field experience with airtightness in masonry dwellings is described, including the construction of a new detached house with a leakage of less than 3 ac h^{-1} at 50 Pa.

Airtightness in masonry dwellings: Laboratory and field experience†

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1 Introduction

The traditional form of construction in the UK for the last two hundred years has been in load-bearing masonry walls with timber-framed roofs and intermediate floors. Over the last 15 years the position has often been advanced that the alternative of using timber-framed walls is inherently more energy efficient, offering the possibility of greater thicknesses of insulation and higher levels of airtightness. Evidence for the truth of these propositions has been found in pioneering work in northern Europe and North America on superinsulated timber-framed houses[1–3]. The result of this work has established the technological basis for the routine construction of timber-framed houses with an air leakage measured at 50 Pa below 3 ac h^{-1}. A significant number of these houses have air leakage rates of 1 ac h^{-1} or less¶. These levels of airtightness are combined with essentially unlimited thicknesses of insulation using the double wall techniques developed in Canada, or the variety of fabricated timber beams developed in Sweden.

Comparable air leakage figures for traditional British dwellings constructed since the Second World War are many times higher — in the region of 15 ac h^{-1}[5]. This has been coupled with a reluctance to construct walls with cavities wider than 50 mm, thus limiting the thickness of insulation that could be included in a masonry construction ||.

IThe central argument of this paper is that the observed performance of masonry dwellings in the UK is a poor guide to the potential performance of this construction method. Masonry itself can be extremely airtight. Leakage through junctions between masonry and other components can be reduced using simple methods, and it is therefore possible to construct airtight masonry dwellings with relatively minor modifications to traditional UK construction practice. This position will be supported by measurements made both in the laboratory and in the field.

†This paper is a revised version of one presented to Building Research Establishment Workshops on Airtightness in Dwellings, Garston and Stirling, October 1993.

2 Laboratory pressurisation testing of building elements

2.1 Airtightness of plain masonry walls

The *sine qua non* for airtight masonry construction is the airtightness of the masonry wall. If this can be assured, it then becomes necessary to consider the airtightness of junctions between walls and other components. The first question that must therefore be addressed is 'How airtight is a masonry wall?'

Laboratory measurements have been made and reported on several occasions. Lecompte[10] took measurements on both plastered and unplastered masonry walls by constructing sections of wall in one face of a plenum which could then be pressurised with a small fan.

A similar test rig was constructed at Leeds, and was used between 1990 and 1991 to test both plain masonry walls and window-wall combinations. The test rig consisted of a plywood plenum, a small centrifugal fan, and a flow measuring device. The plenum was constructed of 12 mm thick plywood, screwed to a softwood frame and painted inside and out with an oil-based paint. A hatch in the back of the plenum provides access to the test element without disturbing the seal between the plenum and the test element. Figure 1 is a diagram of the plenum. Air flow was measured with a laminar flow sensor designed for flows of up to 200 l min^{-1}. The output of this device is a pressure difference of 15.55 Pa l^{-1} s, which was measured with a Furness Controls micromanometer (precision 0.001 Pa, accuracy ±1% of reading). The connections between the fan and the laminar flow sensor and from the latter to the plenum were made using PVC tubing with an internal diameter of approximately 33 mm. A second micromanometer was used to measure the pressure dif-

¶ From 1983 the Swedish Building Regulations required 3 ac h^{-1} for detached and terraced houses, and lower leakage rates for other dwelling types[4].

|| In the 1980s many architects erroneously understood that the maximum wall cavity allowed under the code of practice for masonry was 100 mm. This was the main argument advanced for restricting wall cavities to 100 mm in the Linford and Pennyland houses[6, 7]. Although the code of practice makes it somewhat easier to construct narrower cavities, there is *de facto* no such restriction. In the late 1970s the Salford houses were constructed with a 173 mm cavity using double triangle stainless steel ties[8], while in Denmark at about the same time an experimental masonry house with a 200 mm cavity was constructed using plastic wall ties [9].

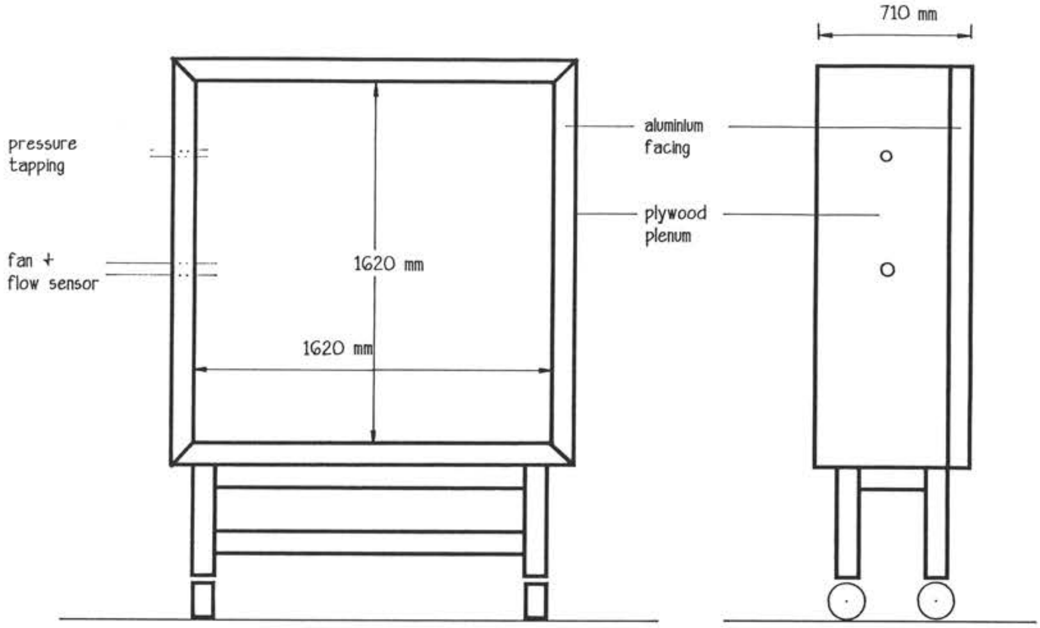

Figure 1 Diagram of element pressurisation rig

ference across the test element — that is between the plenum and the laboratory.

The authors experienced considerable problems in achieving a measurement rig which was airtight compared with plastered masonry. The background leakage rate of the plenum was measured by sealing a sheet of polythene to the open face, and pressurising. The results varied widely and are likely to have depended critically on the quality of the seal between the plenum and the test piece. The lowest background leakage measured at a pressure difference of 50 Pa was 0.09 l s^{-1}, corresponding to a mean face velocity of 34.3×10^{-6} ms^{-1}. This is of the same order as the face velocity through a plastered wall.

The procedure used was to hire a small local firm of builders to construct a test wall on the laboratory floor. The approximate dimensions were 2.5 × 2.5 m. The literature indicated strongly that the most important element in the airtightness of a masonry wall would be the layer of plaster applied wet directly to the inside surface of the wall. The additional resistance offered by the external leaf of a double leaf wall is likely to be negligible. The test wall was therefore constructed from medium-density clinker blocks as a single-leaf wall, supported by piers. The builders of the wall were not told the specific purpose of the wall. The initially unplastered test wall was pressure tested in October and November 1990. The wall was then plastered. The plastered test wall was pressure tested in November 1990 (shortly after plastering) and in April 1991.

It is common practice to express the results of such measurements by fitting a power law to the experimental data:

$$q = a\Delta p^b$$

where q is the mean air speed normal to the plane of the test element (m s^{-1}); Δp is the pressure difference across the test element (Pa); a is a coefficient related to the porosity of the sample (m s^{-1}); and b is a dimensionless pressure exponent dependent on the type of flow through the sample.

The measurements made at Leeds between 1990 and 1991 are summarised in Figure 2. Note that there was no significant difference between the results of the two sets of pressure tests conducted on the plastered wall.

Because of the problems in establishing the background leakage of the plenum, air flows through plastered walls measured at Leeds may be high by a factor of 2 or more. For this reason our results are presented without the normal error bands. There is, however, agreement between the results presented here and those presented by other authors on the fact that plastered walls are several orders of magnitude more airtight than unplastered. If anything, the uncertainties in the measurements strengthen the main conclusions of this paper.

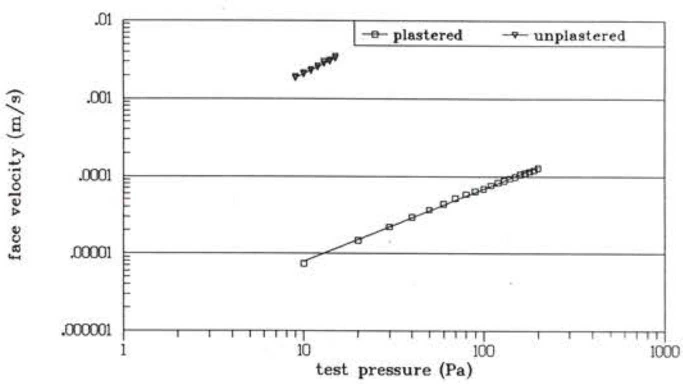

Figure 2 Air leakage through plane single leaf masonry walls

A better understanding of the meaning of these figures may be gained by estimating the 50 Pa leakage of a standard dwelling constructed entirely of 'wall' with the measured air leakage. A standard 100 m^2 two-storey dwelling would have approximately 241 m^2 of envelope surface area (measured at the inside surface of the envelope), and a volume of 250 m^3. The worst-case 50 Pa whole-house leakage rates for plastered and unplastered walls, based on measurements made at Leeds, would be 0.12 ac h^{-1}, and 26 ac h^{-1} respectively. The leakage rates based on Lecompte's[10] measurements would be 0.03 – 0.045 ac h^{-1} for plastered walls and 4.3 – 107 ac h^{-1}.

Several points become obvious from the above - the very large range of values, and very high upper limit for air leakage through an unplastered wall, and the very high airtightness of a plastered wall. Early literature suggests that the performance of unplastered walls depends critically upon craftsmanship[11], as well as on the porosity of individual masonry units. In respect of such factors as the degree of filling of perpends and bedding joints, the performance of the craftsman may be discovered only by pressure testing, acoustic measurements, or by visual inspection following demolition of the finished wall. The quality, completeness and continuity of a traditional coat of plaster can however largely be determined by visual inspection. We believe that these considerations are largely responsible for the much smaller range of air leakage in the case of the plastered wall.

The authors did not test any of the dry alternatives to wet plastered masonry. The main reason for this is that the leakage of a masonry wall lined with plasterboard on dabs or battens depends on details at the edges of the sheets, at junctions of external walls and ceilings, internal partitions, floors and windows. The gap behind a plasterboard sheet acts as a plenum which potentially connects all parts of the envelope of a dwelling. It is hard to see how the problem of airflow across such an envelope can be modelled convincingly in the laboratory at anything less than full scale. Nevertheless, the results of our tests on unplastered masonry walls suggest that unless the plasterboard skin of a masonry house is sealed with the same degree of care that one would expect in a timber-framed house, the leakage rate through the walls of such a house cdould be unacceptably high. Even where the inner skin of plasterboard is successfully sealed to give an acceptably low air change rate, it is possible that the presence of a plenum immediately behind a very porous unplastered masonry wall will allow unacceptably high air movement to-and-fro through the insulation in the wall, thus degrading its U-value. These questions may be of some importance given the increasing proportion of dwellings constructed by dry techniques in England and Wales.

The overriding conclusion from the above is that, in principle, plastered walls are sufficiently airtight to enable dwellings constructed with them to meet any existing or foreseeable whole-building airtightness standard. As stated above, it then behoves us to look at the junctions between walls and other components, where much higher rates of leakage may occur.

2.2 Airtightness of window/wall junctions

The team at Leeds used the measurement rig described above to test two different window/wall details. The first was based on a detail used in a number of recent low-energy houses in Germany, and used a plywood timber box built into the inner leaf of the wall, and deep enough to project across the 150 mm cavity and out some 50 mm onto the brickwork of the outer leaf[12]. The window frame was then fixed into the plywood box, with an overhang of a further 25 mm. The outer plane of the window was thus recessed approximately 25 mm behind the outer face of the brickwork of the outer leaf of the wall. Timber lintels were used to support the inner blockwork and the outer brickwork leaves of the wall, following a detail developed by Vale and Vale[13]. The design of this window/wall junction was intended to minimise both air leakage and cold bridging, while being simpler and possibly cheaper to construct than the conventional detail. Construction details are shown in Figure 3.

The second window-wall was as close as possible to a conventional detail — steel lintel, 50 mm wall cavity with masonry returns at the jambs, and a conventional internal timber window board. Construction details are shown in Figure 4. The area of each window, measured inside the reveal, was approximately 0.59 m^2. The glazing ratio of the window-walls tested was approximately 23% — in the correct range for a dwelling. It should be noted that while the outer leaves of the test walls are not thought to have contributed to their airtightness, it is

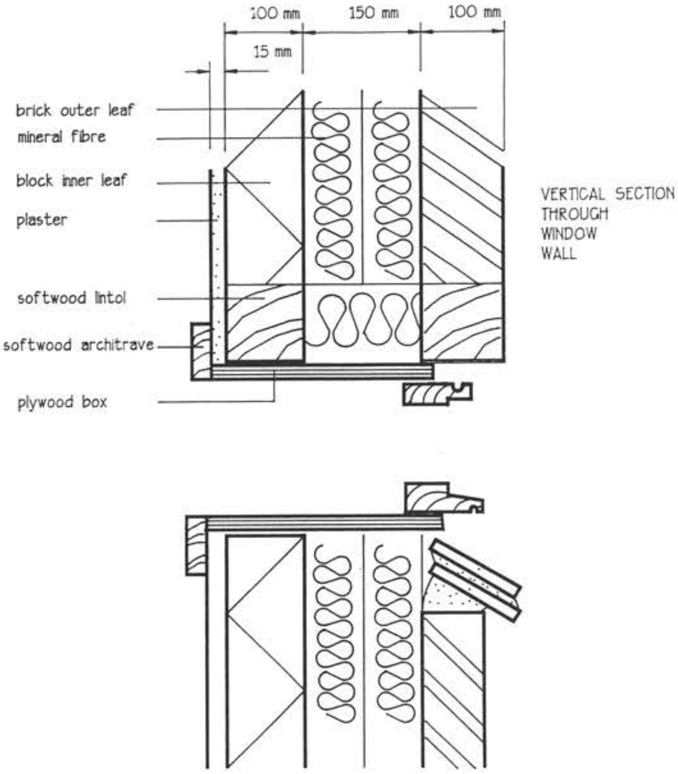

Figure 3 Window-wall detail —modified construction

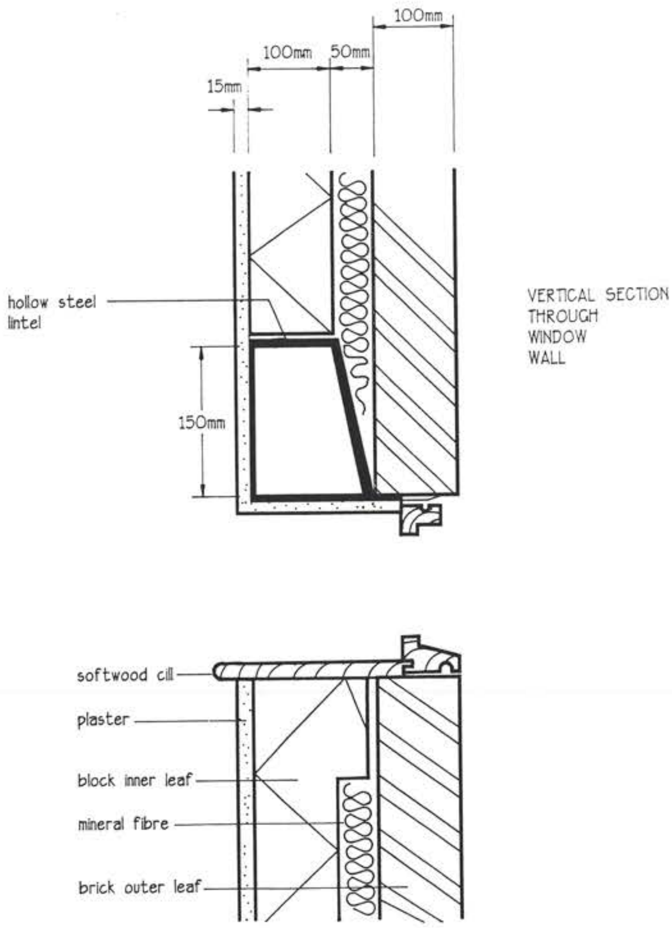

Figure 4 Window-wall detail — conventional construction

difficult to construct a window wall in cavity masonry without including the outer leaf of the wall. These were therefore included.

The pressure testing of the window walls proceeded slightly differently from the pressure testing of the plain walls described above. A sheet of polythene was sealed to the edges of the test piece, inside the plenum. The plenum was then pressurised to 50 Pa, and the pressure between the polythene sheet and the test piece was measured. This interstitial pressure was typically 1 Pa — very small compared with the pressure inside the plenum itself — suggesting that most of the measured flow was leakage through the plenum rather than through the window wall. The sheet was then removed without disturbing the seal between the test piece and the plenum, and the rate of air flow into the plenum was again measured. The difference between the air flow rate into the plenum with and without the polythene sheet is due to the additional airflow through the test piece. On unmasking the test piece the airflow increased by a factor of approximately 3 in both cases.

Air leakage through the two window walls, calculated by the method described above, is shown in Figure 5. Air flows have been normalised by the total area of the window wall. It is tempting to normalise by the actual area of window, but the quality of the data would lead to very large uncertainties in the resultant values.

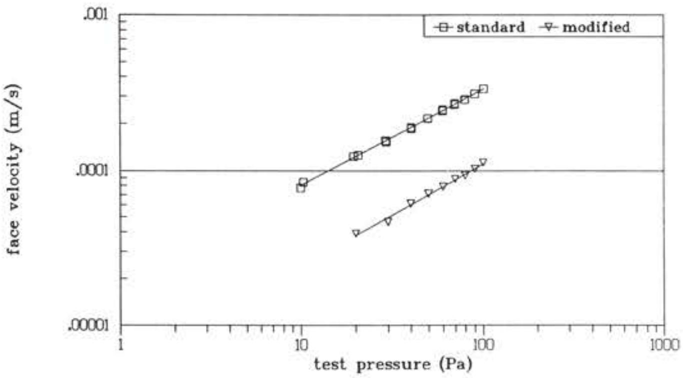

Figure 5 Air leakage through window-walls

It can be seen that the standard window detail is roughly three times less airtight than the modified, low-energy detail. The standard detail window wall had a 50 Pa leakage 6.1 times that of the plain plastered wall described in section 2.1, while the modified detail window wall had a leakage twice as high as that of the plain plastered wall.

The equivalent whole-house 50 Pa leakages for the two window walls are 0.75 ac h^{-1} and 0.24 ac h^{-1}. These figures are well below the leakage rates typical of UK housing, but are in the range of actual good European practice[14]. They indicate that reasonably well executed conventional window details are adequate for dwellings with a 50 Pa leakage of 3 ac h^{-1}, but that achievement of leakage rates below 1 ac h^{-1} would probably require modifications to present practice.

2.3 Airtightness of timber floor joist spaces

The next part of the programme of laboratory testing concerned joist spaces in conventional timber floors. A single-leaf block wall was constructed with a section of timber suspended floor abutting it. The joists of the timber floor were built into the wall in the conventional way, but were allowed to protrude on the outside face of the wall where they were attached to a wooden framework. This stabilised the floor structurally without modifying its leakage characteristic. Floorboards were fixed to the top side of the joists, and gypsum plasterboard was attached underneath. This had no direct effect on the leakage characteristic. The joists projected approximately 300 mm from the inside face of the wall, and the spaces between the joists were left open. The outer leaf of the wall was again omitted because it provides little additional airtightness compared with that provided by a skin of plaster. Except for the sections between the joists, the whole of the wall was plastered. The laboratory test specimen is shown diagrammatically in Figure 6.

The leakage of the joist space was tested using a perspex plenum made for the purpose. All other details (fan, flow and pressure sensing, and connections between fan and plenum) were as for the plywood plenum described above. The plenum was sealed to the wall using closed-cell epdm draught strip. The performance of the edge seal was tested using soapy water and was found to be airtight.

Initially the blockwork between the joists was poorly, though not unusually poorly, executed, and the pressurisation equipment was unable to maintain a pressure of more than 1 Pa across the joist space, at a flow rate of approximately 0.01 $m^3 s^{-1}$. The joist space was made more airtight by roughly rendering the blockwork between the joist ends with a cement render. This is an unusual treatment, which is likely to result in a joist space that is rather more airtight than normal. It was subsequently found possible to pressurise the joist space to about 18 Pa. The results of this test are shown in Figure 7.

The equivalent 50 Pa leakage rate for a house built entirely of joist space is some 79 ac h^{-1}. At 50 Pa, joist space performs some 640 times worse than plastered wall, and nearly twice as badly as unplastered wall. This difference is large and highly significant, both statistically and in terms of its implications for the construction of airtight masonry buildings. Any realistic analysis of the performance of this construction element has to take account of the fact that the resistance to air flow through the joist space is likely to be substantially lower than the resistance between the joist space and the occupied and heated volumes above and below. It must also be noted that a joist space would behave very differently for airflow at right angles to joists. It must nevertheless be concluded that joist spaces in suspended timber floors are likely to be a weak point in any building, and that measures to improve or replace this element of the construction should be a priority where an airtight construction is required. Even where ceilings and floors are sufficiently airtight to isolate the dwelling from its joist spaces, air flow through these spaces will result in significant heat loss through elements of the construction that are normally thought of as being entirely internal elements - namely internal floors and ceilings. For a dwelling constructed to the 1990 England and Wales Building Regulations[15], at moderate wind speeds, this could lead to an effective *U*-value across an internal floor or ceiling significantly greater than nominal *U*-values across external elements.

3 Airtightness in existing housing

In 1990, Leeds Metropolitan University were appointed as technical design and monitoring consultants to the York Energy Demonstration Project. The project was funded by the Greenhouse Programme of the Department of the Environment, and its objective was to demonstrate the energy

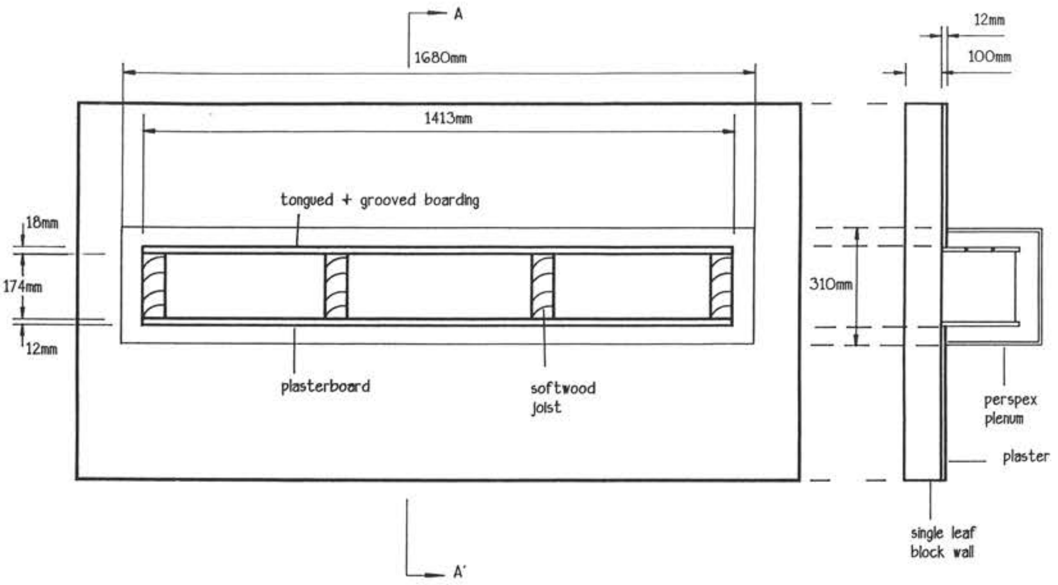

Figure 6 Wall–floor junction

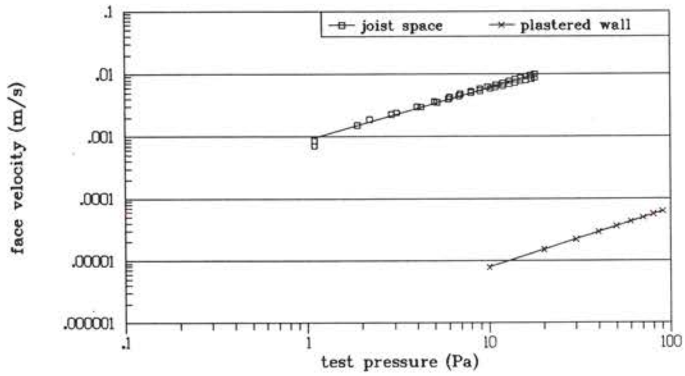

Figure 7 Air leakage through junction between masonry wall and suspended timber floor

savings that were possible in York City Council's existing housing stock using simple, cost-effective energy conservation measures. Further details and preliminary results from the project may be found in Reference 16.

It was possible to conduct before-and-after pressure tests in a small number of these houses, using the University's Minneapolis blower door. Tests were carried out in January, before improvement work, and in March and April 1992, after improvement work. In January it was possible to test only two of the houses under near-perfect weather conditions; in the spring it was possible to test all three of the houses, but under adverse wind conditions. The leakage rates at 50 Pa pressure difference are shown in Table 1.

Table 1 Leakage rates (ac h^{-1}) at 50 Pa in existing housing before and after improvement

Location	Before	After
Chapelfield B	19.3±1	7.5±0.4
Bell Farm B		6.8±0.3
Bell Farm A	16.9±1	4.9±0.33†

†In this house, it was only possible to measure directly the leakage rate with the mechanical ventilation system unsealed, and the effect of sealing this system has been estimated from measurements on the adjoining house.

These results show a 2.5 – 3-fold improvement in airtightness in both sets of houses. This has been brought about by a combination of measures, including draughtstripped replacement windows and doors, covering of tongued and grooved floors with 3 mm plywood sheeting (not sealed around skirting boards), and repair of obvious damage to plasterwork around doors and windows.

The leakage rates after improvements are low compared with those measured made in other British houses built in the 1960s and 70s[5]. The estimate for Bell Farm A is below 5 air changes per hour, a value which approaches the 1980 Swedish standard of 3 ac h^{-1} for new housing. The fact that this level was achieved without significant attention to detail, workmanship or supervision, suggests that the decision to fill the wall cavities at Bell Farm with high-density polyurethane foam may be a reliable and effective way of reducing air leakage in traditionally constructed masonry houses. This result, and the fact that a number of obvious construction defects were evident at the time of testing, imply the possibility of achieving air leakage rates of 3 ac h^{-1} or less in existing masonry houses by a modest additional effort. A number of questions remain to be answered, not the least of which is how well the comparative airtightness of these houses will be maintained over the next 20 years or so. The authors intend to retest the houses in the spring of 1994, when the present monitoring programme comes to an end.

4 Airtightness in new housing

In 1991 a small Huddersfield-based firm of builders, Butcher & Slator, contacted the authors of this paper to discuss their plans to build a low-energy house of approximately 114 m^2 gross floor area in Huddersfield. The site at Longwood was an almost perfect passive solar site, steeply sloping toward the south. The intention of the builders was a carefully considered design, visually in keeping with the traditional Pennine weaver's cottage, but with very low space heat demand. The house was being built speculatively, with the low energy demand and careful selection of materials and finishes being used to gain a competitive market edge. The vernacular context dictated the appearance of the house — stone clad, stone mullioned windows, small eaves overhangs, and shallow plan. Construction was to be of load-bearing masonry.

Work for the Longwood House concentrated on achieving low *U*-values, and on designing all construction details to limit air leakage and to avoid cold bridging. The choice for the wall construction was a 150 mm fully-filled wall cavity, using Danish nylon wall ties. The Building Inspector was cooperative, and there were no problems in gaining approval for this construction. The roof was insulated at ceiling level with 300 mm of blown cellulose. The ground floor slab was cast on 100 mm expanded polystyrene insulation. The windows were timber, with 20 mm low-emissivity double-glazed sealed units. The inner leaf of the wall and all internal partitions were constructed of 100 dense clinker block to maximise internal thermal mass and to reduce sound transmission between rooms. Interestingly, clinker blocks also have a significantly lower embodied energy content than do lightweight aerated concrete blocks(17). The *U*-values expected from the chosen construction methods are: walls 0.21, roof 0.11, ground floor 0.23, and glazing 2.4 W $m^{-2}K^{-1}$. The avoidance of cold bridging means that actual *U*-values are likely to come close to those given.

The possibilities of an *in situ* cast or beam-and-block concrete first floor were discussed. Both options, but particularly the first, promised higher levels of air-tightness than the timber alternative. Eventually timber was chosen because of the greater buildability (avoiding the need for a crane), and familiarity of the builders with this method. The authors suggested that the edge of the first floor be sealed with in-situ foamed polyurethane foam. This was achieved by fixing firrings between the joist ends approximately 25 mm from the external wall, and foaming the space between the firrings and the wall from the underside before the fixing of the ground floor ceiling. The space between the external wall and the first and last joists was also sealed in the same way. A better seal may have been achieved if the foam had been applied after the fixing of the ceiling, through holes drilled in the floor above.

A number of steps were taken to achieve an airtight first-floor ceiling. The domestic hot water system is unvented and the header tank for the central heating system is situated in the first floor airing cupboard, thus eliminating all plumbing from the attic. The remaining penetrations are for the loft access hatch, wiring for first floor light fittings, and the soil and vent stacks. The loft hatch is a prefabricated draftproofed unit. Soil and vent stacks were boxed as they passed through the first floor ceiling, and these boxes were then filled with polyurethane foam. Finally, the plasterboard on the first floor ceiling was installed in a single continuous layer, before the construction of the first floor partition walls. This avoided the (frequently untidy and poorly executed) junctions between internal partitions and first floor ceiling.

Airtightness at window reveals was achieved by careful construction. The window reveals were thoroughly thermally broken — the inner leaf was not returned, and separate lintels were used for inner and outer leaves of the wall. Cavity closure at the jambs and head was achieved with plasterboard, which was bedded on a continuous bed of bonding plaster at the inner leaf, and into a continuous bead of mastic gunned into a channel in the timber window frame. The internal wooden window sill was treated in a similar way. Here again, the authors originally suggested a detail based on that shown in Figure 3. The builders preferred their own rather more conventional solution, which appears to have worked well.

Ventilation of the house is by a combination of passive stack, trickle vents, and mechanical extract in kitchen and WCs.

Leeds Metropolitan University were able to pressure test the house before occupation approximately one year after construction (the house took some 18 months to sell in a difficult market). Pressurisation and depressurisation tests were carried out on 8 April using the University's Minneapolis blower door, under near perfect conditions. Inside and outside temperatures were 11.5 and 7.5 °C respectively, and wind speed at a height of 2 m was less than 2 m s^{-1}.

The 50 Pa leakage is estimated as 2.95 ± 0.3 ac h^{-1}. This was achieved blind, without the need for remedial work, making the Longwood house one of the most airtight to have been constructed in the UK. Pressure test data are presented in Figure 8.

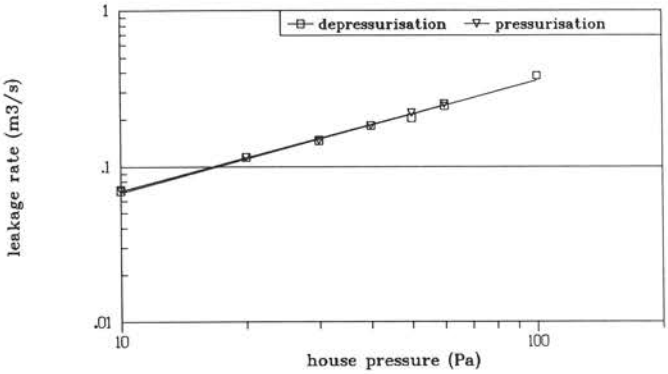

Figure 8 Pressurisation test of Longwood house, Huddersfield

The location of leaks was investigated using a smoke pencil. Leakage was predominantly around the edges of the two floors. Leakage around the edge of the ground floor slab was somewhat unexpected. It is likely to have been exacerbated by the insertion of a thin layer of expanded polystyrene between the floor slab and the inner leaf of the wall, which was intended to minimise cold bridging. There was very little leakage around the windows. Leakage was noticeable around ceiling roses (these were not caulked), and from electrical sockets. At a test pressure of 150 Pa, leakage was noticed from behind the wall-string of the staircase. If these residual leaks were caulked, it is likely that the leakage rate of the Longwood house could be reduced substantially — but with passive stack ventilation there is little point in going further. The 50 Pa leakage rate with the trickle vents open was approximately twice as great as that measured with all vents closed. This suggests that operation of the trickle vents can exert considerable control over the ventilation rate of the house.

The pressure tests reported above were undertaken roughly one year after construction was completed, and after the initial drying-out period had elapsed. Nevertheless, the long-term performance of the Longwood house remains an important question. The authors hope to be able to return within the next two years to retest the house.

4 Conclusions

The detailed conclusions from this paper are:

- that wet plastered masonry walls are very airtight;
- that conventional window reveal detailing is reasonably airtight, but can be improved considerably with minor modifications;

— that a suspended timber floor is likely to be a serious weak point in an airtight masonry envelope;

— that filling of wall cavities with *in situ* foamed polyurethane foam appears to improve the airtightness in houses with timber first floors.

The paper offers evidence, from work on a small number of houses in York, that great improvements in airtightness are possible when traditionally built existing houses are renovated. These improvements are such as to demand positive steps to ventilate the house after renovation, but also offer the very clear possibility of improving the airtightness of such houses to a point where techniques such as mechanical ventilation with heat recovery (MHVR) might become viable.

Finally we have reported on measurements made on the Longwood house, which has a 50 Pa leakage of 3 ac h^{-1}. This was achieved with some minor modifications to normal construction practice, and confirms that very airtight dwellings are possible in the UK, in load bearing masonry construction.

Acknowledgements

The laboratory work on airtightness was supported with a grant from the National Advisory Board for the Polytechnics, and by Borall Edenhall Concrete Products Ltd., Ibstock Building Products Ltd., and George Clark Ltd. The work in York was supported by the Department of Environment. The Longwood house was constructed by Slator & Butcher of Huddersfield, with advice from Curwell and Lowe. Susan Hardisty prepared the drawings for Building Control. At the time of writing Leeds Metropolitan University and British Gas North Eastern intend to monitor the house over the first heating season.

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