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M J Cunningham

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Modelling of Moisture Transfer in Structures—III. A Comparison between the Numerical Model SMAHT and Field Data

M. J. CUNNINGHAM*

A comparison is made between the predictions of a numerical model of structural moisture behaviour and the experimental results from a field study in which the moisture performance of roofs of several newly constructed houses was monitored over one year of occupation in different New Zealand climate zones. There was good agreement between the model and the experimental results, with a maximum standard deviation of difference of 1.3% moisture content. Most of the difference is due to limitations in measurements rather than to deficiencies in the model. Both the field study and the model confirmed that air infiltration was a dominating influence in the moisture transfer.

INTRODUCTION

A COMPANION paper [1] describes a field study in which the moisture performance of the timber framing of the roofs of seven newly constructed houses was studied over one year of occupation in three different New Zealand climate zones. The principle aim of that study was to acquire data to check the performance of SMAHT (Simulation of Mass and Heat Transfer), a numerical model of structural moisture behaviour [2].

To use any model confidently, and to allow it to be used as the basis of an engineering design tool, it must be well checked against laboratory and field conditions. SMAHT has been checked against laboratory data [3, 4] and shown to perform well. It must also be able to predict adequately under field conditions where mechanisms come into play that are difficult to simulate in the laboratory, such as cross ventilation and night sky radiation, and when subjected to real driving forces generated by the external climate, and by the life-style of the house occupants.

Not many comparisons of this type have been undertaken, despite the fact that such studies are important to ensure that models under development accurately reflect the real world. Perhaps the most extensive earlier field study for model validation purposes is the Canada Mortgage and Housing Corporation study set up to validate the model WALLDRY [5]. Cleary and Sonderegger [6] report a shorter 4 month study done on one unoccupied house which was used to support a simple mathematical model.

This paper describes the comparison between the data obtained from some of the houses in the field study described in [1] and modelling results using the numerical model SMAHT.

* BRANZ, Moonshine Road, Judgeford, Private Bag 50908, Porirua, New Zealand.

COMBINING THE MODEL AND FIELD RESULTS

The field survey and its results have been described in an earlier paper [1]. The moisture performance of the timber framing of the cathedral (or skillion) roofs of seven newly constructed houses was studied over one year of occupation in three different New Zealand climate zones. The zones were classified as humid and cool, dry and cool, and humid and mild. Five of these houses gave data of enough completeness and quality to allow their reported results to be compared to predictions from a numerical model.

The numerical model SMAHT has been described elsewhere [2]. It is a finite-difference implementation of the continuity differential equations governing heat and moisture transfer in structures. The user is free to specify the number and placement of the nodes used within the model.

To use the model, the inital conditions and boundary driving conditions have to be specified.

The boundary driving conditions required are the internal temperature and vapour pressure, the external temperature and vapour pressure, and the roof top temperature. The field study measured the under-roof temperature and the internal and external temperatures and relative humidities from which the vapour pressures could be calculated. All houses modelled had metal clad roofs, the under-roof temperature of which would be equal to the exterior roof temperature to within a fraction of a degree.

The initial conditions were set equal to the experimental values read when datalogging commenced.

The model also requires air-change rates into and out of the roof structure from all relevant zones. A monthly average figure was acquired experimentally through the use of passive detection tubes, see [1], and this average figure was assumed to hold throughout the periods under

Table 1. Air exchange figures used in the modelling studies

	Modelled cavity volume m^3	Living space to cavity air flow m^3/h	Exterior to cavity air flow m^3/h	Cavity to exterior air flow m^3/h
House 2	0.021	2.1	1.1	3.2
House 3	0.045	0.27	0.30	0.57
House 4	0.069	0.15	0.52	0.67
House 7	0.028	0.012	0.019	0.031
House 8	0.138	0.23	0.93	1.16

consideration. For use in the model the data on air-change rates described in [1] has been modified in the following way:

(a) In [1] it was stated that the best explanation for the data acquired for houses 2 and 3 was given by ignoring the living space air change data and modelling only the skillion roof cavities. However, the model requires air change data from indoors and outdoors into the cavity, so that raw data acquired for these houses was used.
(b) House 7 had the two roof zones modelled as one—for modelling purposes it was assumed that the air exchanges from other zones distributed itself into each of the two zones in proportion to the cavity volumes.
(c) In house 8, for modelling purposes the air exchange between the first and second skillion roof zones was ignored.
(d) By comparing the geometries of the cavities measured in the field and those modelled, an estimate was made of an appropriate air exchange rate into the modelled cavity. Cavity volumes are calculated without insulation present.

The air exchange estimates used for modelling are contained in Table 1. Table 2 contains the vapour diffusion coefficients and thermal conductivities used in the model for the various materials found in the roofs under examination. Sorption data obtained by Cunningham and Sprott [7] was used to describe the hygroscopic properties of the materials. Sorption curves obtained by Cunningham and Sprott are similar to those found by other authors [8, 9].

Five houses (houses 2, 3, 4, 7, and 8, see [1]) contained sufficiently complete data sets to allow useful comparisons to be made with modelling results. House 1 did not have its ceiling lining installed until the end of the experiment, while houses 5 and 6 were not successfully instrumented for internal relative humidity and temperature.

Table 2. Values used by the model for material coefficients

Material	Vapour diffusion coefficient s	Thermal conductivity $W\,m^{-1}\,°C^{-1}$
Wood	1.0×10^{-11}	0.18
Woodfibre board	0.9×10^{-11}	0.054
Gypsum plasterboard	3.0×10^{-11}	0.22
Fibreglass batts	2.0×10^{-11}	0.05
Concrete tiles	1.1×10^{-11}	1.0

Among those houses that were modelled, the external relative humidity sensor in house 3 failed very early in the experiment, while that for house 7 failed after day 523. (In all cases, 1 January 1990 is taken as day 0.) The external humidity sensor for house 4 became noisy and erratic after about day 300. House 3 was modelled using the external relative humidity data from house 2, which was in the same town (Queenstown) and on a roughly comparable site. House 7 data was modelled only from day 261 to day 523 (less than a full year). House 4 results were modelled for the entire year but should be treated with caution beyond day 300. Indeed, in general, it is important to note that because of known drift performance of the relative humidity sensors [1], relative humidity data taken towards the end of the collection phase will be less accurate than that at the beginning, so that modelled results late in a run are less reliable than those earlier in the run.

Detailed cross sections of these skillion roofs are contained in the earlier paper [1]. Two nodal schemes were used to describe these roofs, one for roofs with a significant cavity above the batts and one for roofs without this, see Fig. 1. The scheme illustrated in Fig. 1(a) was used for houses 2 and 7 and the scheme illustrated in Fig. 1(b) was used for houses 3, 4 and 8.

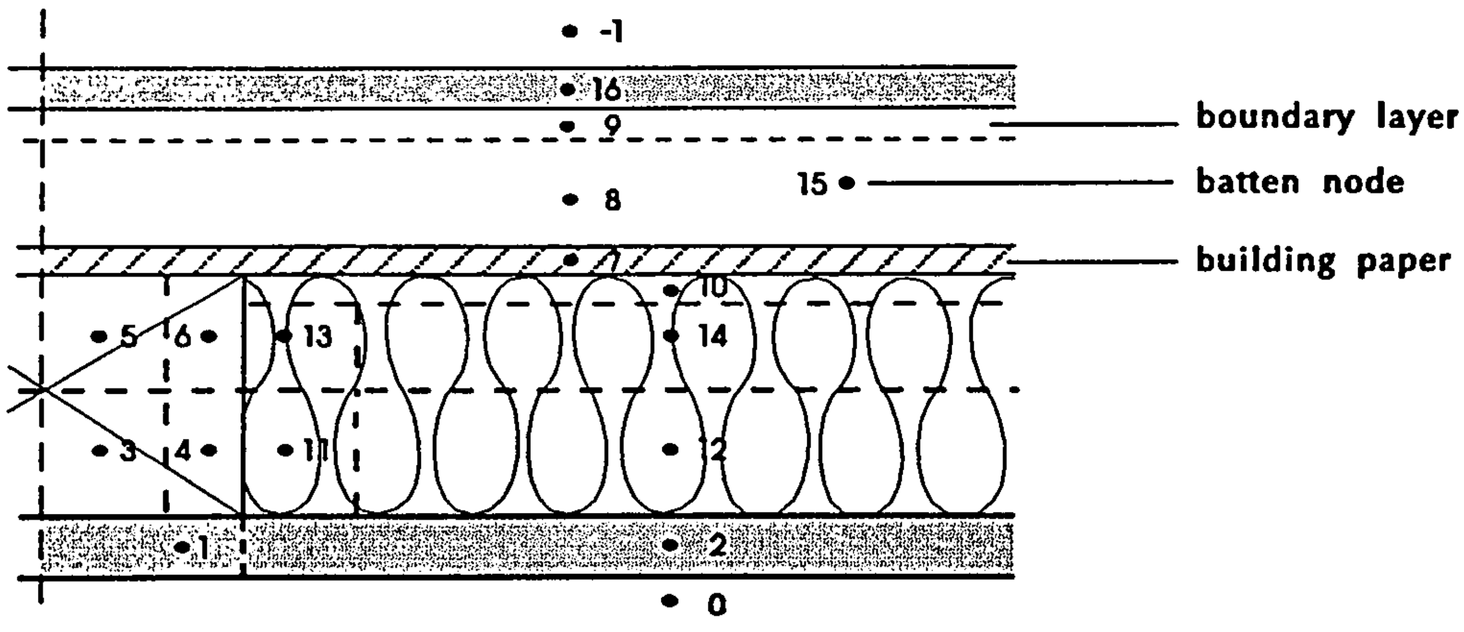
RESULTS

Some modelling runs were undertaken using the experimental hourly boundary condition driving data and then repeated using daily mean boundary conditions. The difference between the predictions was very small, never more than ¼% moisture content and never more than 3 days in phase difference in one year. Consequently all runs were done using daily means, as this allowed the model to run several times faster with no significant loss in accuracy.

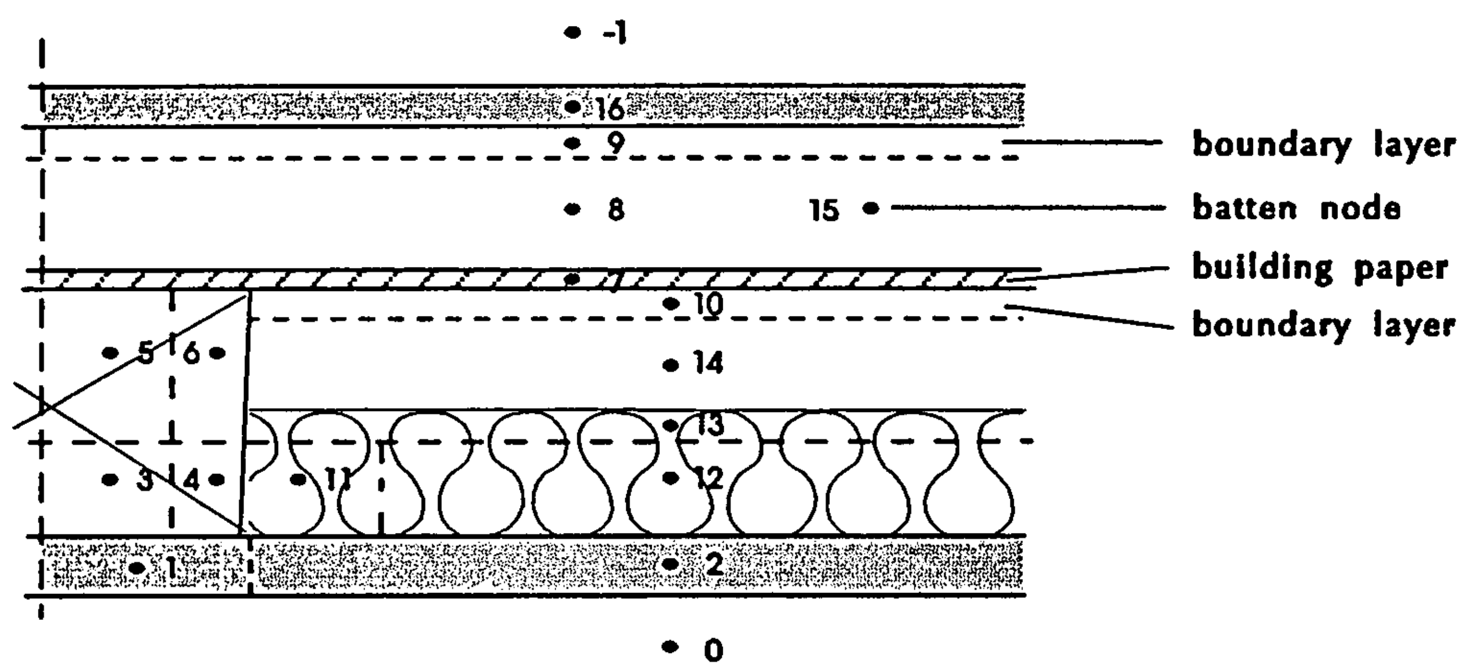
Figure 2 contains the experimental data for each house used for the modelling studies, showing all the moisture probes in the skillion roof under investigation together with the model predicted results. The presence of data from several moisture probes for each roof highlights the experimental variability to be expected in the field and emphasizes that models can only predict a space-averaged result.

Allowing for the variable nature of the quality of the boundary condition data used, see above, the agreement between the model and the experimental data can be seen to be good, and in some cases very good. Table 3 contains a quantification of the degree of agreement between the field data and the model.

Best agreement is given by house 4, despite the fact



(a) Model 1, houses 2 & 7



(b) Model 1, houses 3, 4 & 8

Fig. 1. Nodal schemes used for the modelled houses.

that the indoor relative humidity data is less reliable beyond day 300; worst agreement is probably given by house 2. However, as mentioned in the earlier paper [1], this house had a solid fuel stove inserted during mid-winter. While the stove was being installed, the driving forces being measured by the room sensors would not truly reflect the complexities of the opening of a hole in the roof and the subsequent firing up of the stove. Bearing this in mind the agreement observed is quite good.

The tendency for the model to predict low in summer for houses 2 and 3 can be explained by the fact that, for these houses, very low timber moisture contents were observed which are very difficult to measure under field conditions. As explained in [1], the moisture probes have a very high resistance under these conditions and so consequently are vulnerable to high impedance current leakage paths at all points from the datalogger to the transducer. Any current leakage path with a value as low as several Gohm will convert to a moisture content of about 8%, which becomes the lowest that the probes can report.

THE IMPORTANCE OF AIR INFILTRATION

All of the roofs studied were dominated in their moisture performance by air change into and out of the roof cavity. Vapour diffusion was in most cases an unimportant mechanism. To illustrate this requires first that air infiltration and vapour diffusion be put on an equal footing. There are a number of ways in which this can be done. Cunningham [10] has used time constants or equivalent total vapour diffusion resistance. In the latter approach, it was shown that the total vapour diffusion resistance due to the vapour resistances of the roof section internal and external linings is given by

$$\frac{1}{R_v} = \sum_i \frac{A_i}{r_i}$$

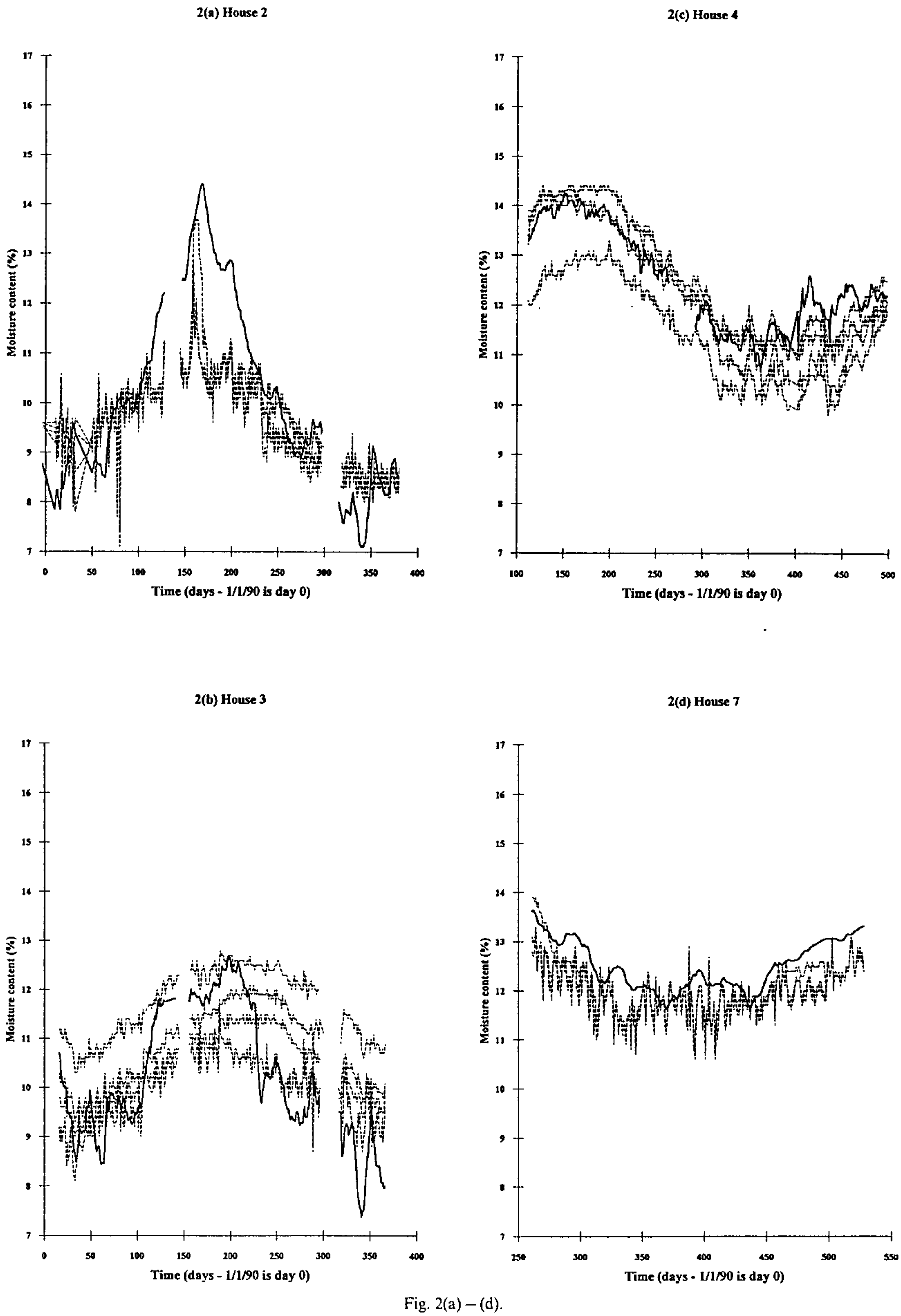

2(a) House 2
Moisture content (%)
Time (days - 1/1/90 is day 0)
2(c) House 4
Moisture content (%)
Time (days - 1/1/90 is day 0)
2(b) House 3
Moisture content (%)
Time (days - 1/1/90 is day 0)
2(d) House 7
Moisture content (%)
Time (days - 1/1/90 is day 0)

Fig. 2(a) – (d).

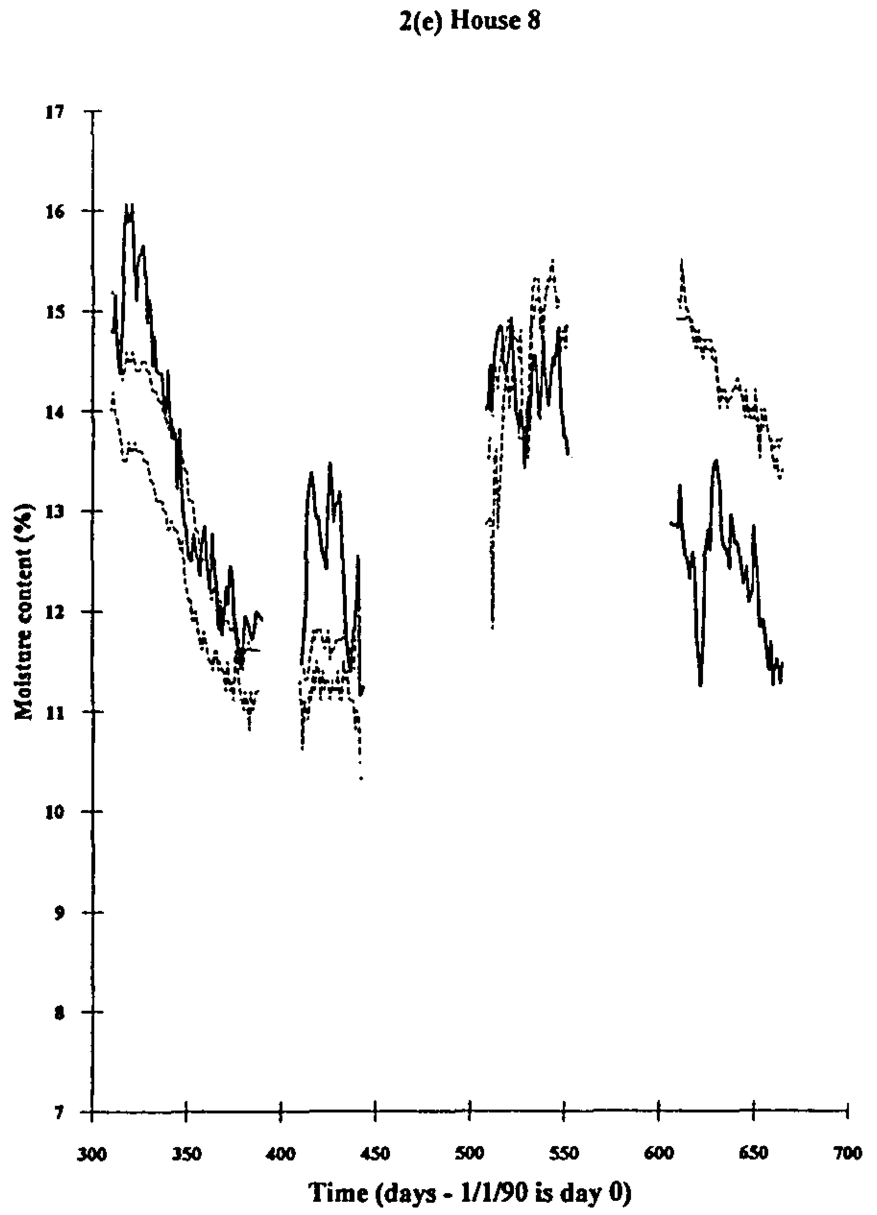


Fig. 2. Experimental and modelled 24 hour mean moisture contents. --- experimental moisture contents; —— model prediction.

where:

R_v is the total vapour diffusion resistance due to vapour diffusion flow paths (N s kg^{-1} m^{-2})
A_i is the area of the ith lining (m^2)
r_i is the vapour resistance of the lining (N s kg^{-1})

while the equivalent total vapour diffusion resistance of air infiltration is given by

$$\frac{1}{R_a} = \sum_i \frac{\Phi_i W}{RT}$$

where:

R_a is the total vapour diffusion resistance due to air infiltration flow paths (N s kg^{-1} m^{-2})
Φ_i is the total volumetric air flow into the cavity from the ith external region (m^3 s^{-1})
W is the molecular weight of water (18 kg $kmole^{-1}$)
R is the universal gas constant (8310 J K^{-1} $kmole^{-1}$)
T is the average Kelvin temperature in the structure (K).

Taking the properties of materials used and the air flows measured for each roof, these formulae yield approximate values for the equivalent resistances through a 1 m^2 roof section of each house as given in Table 4. This table shows clearly that only in the case of house 7 does vapour diffusion become a mechanism of the same importance as air infiltration—in all other cases vapour diffusion could be ignored as a transport mechanism with very little effect on the modelled result. The table also says that all houses except house 7 have "loose" roofs implying that they will respond quickly to the driving forces and will have fast transient drying rates. Even house 7 could be judged as only moderately "tight". These conclusions are born out in both the experimental and modelled moisture content values.

Since air infiltration dominates the moisture performance of these roofs, it might be inferred that accurate modelling predictions could only be expected if accurate air infiltration rates had been measured. However, it is quite clear that the air infiltration measurements are very approximate, see [1], mostly because the assumption of complete mixing in the building cavities is unlikely to be correct. In fact, at the levels of air infiltration measured in the field study, it is found that the timber moisture contents predicted are insensitive to quite large changes in the values of air change used in modelling; this is so firstly because the cavities are "loose" so that the structure already responds to external conditions fairly directly, and secondly because the indoor and outdoor air moisture concentrations never differ by more than 30% so that changing the proportion of indoor and outdoor air entering the cavity does not make a large difference to its moisture content.

CONCLUSIONS

A comparison has been made between the predictions of a numerical model of structural moisture behaviour SMAHT (Simulation of Mass and Heat Transfer), and the experimental results from a field study in which the moisture performance of the timber framing of the roofs of seven newly constructed houses was monitored over one year of occupation in three different New Zealand

Table 3. Degree of model agreement with the field data

% moisture content difference = model mc − rafter mean mc

House number	Mean % moisture content difference	Magnitude of maximum % moisture content difference	Standard deviation of % moisture content difference	Comment
2	−0.5%	3.7%	1.2%	Model low in summer, high in winter
3	−0.5%	2.6%	0.9%	Model low in summer, high in winter
4	0.3%	1.7%	0.4%	Less reliable beyond day 300
7	0.5%	1.7%	0.4%	Model consistently slightly high
8	−0.2%	3.3%	1.3%	Model high initially, low later

Table 4. Approximate values for the equivalent resistances for each house through a 1 m^2 roof section

	House 2	House 3	House 4	House 7	House 8
Vapour diffusion equivalent resistance (N s kg^{-1} m^{-2})	11.0	110.0	14.0	14.0	11.0
Air infiltration equivalent resistance (N s kg^{-1} m^{-2})	0.2	0.9	2.0	17.0	0.4

climate zones. Not many comparisons of this type have yet been undertaken, despite the fact that such studies are important to ensure that models under development accurately reflect the real world.

Agreement between the model and the experimental results was quite good, with a maximum standard deviation of moisture content difference of 1.3% moisture content. Most of the difference between modelled and experimental results seems due to limitations in measurements rather than to deficiencies in the model. Measurement error will affect both the experimental results and the boundary conditions used for driving the model.

Both the experimental results and the model confirmed that air infiltration is a dominating influence in moisture transfer. Air infiltration into a building structure is a complex issue, and is not simply air passing through the cavity from indoors to outdoors as is often assumed. The actual process involves interchange with several zones of air in both directions, including indoors, outdoors and other building cavities. Since air infiltration is such an important mechanism in the moisture performance of structures, it seems imperative that more experimental effort, particularly under field conditions, be devoted to quantifying it.

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