A POTENTIALLY FAST, FLEXIBLE AND ACCURATE EARTH-CONTACT HEAT TRANSFER SIMULATION METHOD

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ABSTRACT

It is a basic premise of this paper that accurate earth-contact simulation is important and that the rapid *parametric* analysis of a structure can help designers pinpoint critical aspects of a structure early in the design stage. Numerical tools are an attractive option for this role in that they are potentially flexible and accurate. However, their application to such a tool is limited by their lack of speed. A new tool for use in paramteric analysis is proposed which incorporates a numerical model with elements of the response factor method. Details of the model are given, the testing of the model described and the results presented. The new tool appears to be able to reproduce the accuracy and flexibility of the numerical model whilst operating by up to a factor of 1000 more rapidly.

INTRODUCTION

This paper describes fundamental modifications to a numerical (finite volume) model which improve the speed at which it is able to undertake dynamic earth-contact simulations by a factor of up to a 1000 whilst not significantly affecting the accuracy of the simulations. Critical assumptions driving this work are listed below:

- *Earth-contact heat transfer is complex and it is important for earth-contact heat transfer to be modelled accurately:*
    - In order to exemplify one aspect of the complexity of earth-contact heat transfer, Davies *et al.* (1995) reinforced the importance of *multi-dimensional* heat flow modelling. Unfortunately, most of the works undertaken on this subject simplify the problem to a one or in the best case to a two-dimensional process.
    - The significance of this heat transfer path was shown by Claridge (1987) for example, who noted that in the USA a waste of about $5-$15 billion per year is attributable to heat transfer to the ground from buildings.
    - An improved understanding of the overall dynamic thermal response of a structure should lead to *the improved thermal comfort* of the occupants.

- *There are many different earth-contact simulation tools available but no current tool offers, accuracy, speed and a general flexibility:*
    - An extensive review by Adjali *et al.* (1998a) deals with the many types of earth-contact simulation tools ranging in complexity from simple manual methods to numerically based techniques.
    - One of the most useful current tools is that of Krarti *et al.* (1990). This *semi-analytical* method is accurate, fast, and to a large extent flexible. However, it deals with a prescribed (albeit comprehensive) set of geometry types.

- *Numerical models:*
    - have the potential to offer the greatest flexibility in terms of the geometry that they are able to cope with
    - have the potential for accuracy
    - are relatively slow

- *There is a need to incorporate an accurate and flexible earth-contact tool into a simulation model which is capable of the rapid parametric analysis of a structure*:
    - The method should provide an accurate and rapid yearly simulation of the earth-contact heat transfer in situations where the effect of repeatedly varying *other* aspects of the design is required. These aspects may include the type of heating, ventilating, and air-conditioning system to be used, the location and orientation of the building, the number of stories, construction materials and techniques, window

    spacing and construction, schedules of internal gains, shading, passive solar heating and insulation

- *The combination of a conventional numerical method with elements of the response factor method has the potential to produce a flexible, fast and accurate earth-contact tool suitable for rapid parametric analysis:*
    - Both of these techniques are individually already well described and widely used but it is their *combination* for the application of earth-contact heat transfer simulation that is novel.

THE NEW TOOL

Essentially, the new tool increases the speed of a dynamic numerical model by incorporating aspects of the response factor method. Some 'pre-processing' is carried out with the existing numerical (finite volume) code in order to produce the time series response of a structure to known driving pulses of energy. This time series is then used to *rapidly* generate the hourly heat transfer of the structure for a full year using the response factor technique. Note that for a one-dimensional simulation it is possible to *analytically* determine such time series responses. However, for the more complex two and three-dimensional geometries involved in earth-contact heat transfer the analytical development of the time-series is generally not possible - hence the role of the numerical code.

Note:

- Because the method requires that the finite volume technique be initially used to generate a certain number of simulated hours, this first part of the procedure takes a certain time. However, assuming that the earth-contact domain remains unchanged from then on, every subsequent simulation that is performed to calculate the effect on the earth-contact heat transfer of changing *another* parameter takes only a few seconds. Reductions in run-time for the successive simulations are of the order of 1000 times faster than the full finite volume technique whilst still retaining the flexibility and accuracy of this method.
- Only a *portion* of a year's finite difference simulation need be carried out to generate a valid time series. Because of the high degree of thermal mass involved in earth-contact heat transfer, many more hours of the time series will be required than would be the case with above ground elements. The benefits of extrapolating the shape of the time-series response curve in order to reduce and optimise this 'pre-processing' run-time will be briefly discussed in this paper.
- If so desired the time-series method can rapidly simulate *successive* years in order to allow the thermally massive earth domain to achieve an annual dynamic equilibrium. This can be a significant effect (Davies, 1994) and the original finite volume technique would be impractical in these circumstances due to the run times required to simulate several years.
- The new method does not, and indeed fundamentally cannot, improve the *accuracy* of the numerical model. Indeed it attempts to *reproduce* the accuracy of the existing numerical model and hence there is an assumption that the accuracy of such models is adequate. Work by Adjali *et al* (1998b, 1999) for example has tended to suggest that this is a valid assumption.

Response factor technique

The response factor technique is well known and widely utilised (ASHRAE, 1997). It essentially relies upon the determination of the response of a structure to a known short driving pulse of energy. Because any driving function may be regarded as being a combination of a number of these known pulses, then the response to any driving function may be constructed. This is done via a method of superposition; the overall response is the sum of the weighted responses. It is a requirement then that the system being simulated is both linear and invariable. Generally, either these requirements are met or the errors associated with non-compliance are taken to be acceptably small (e.g. radiant effects and the variation of thermophysical parameters with temperature or moisture). These responses have been tabulated for a wide variety of wall types etc. (ASHRAE 1997) by the analytical solution of the one-dimensional heat conduction equation. However, the method is not ideally applicable to the solutions of earth contact heat flows due to the multi-dimensional nature of the flows resulting in the fact that the response factors are not generally determinable analytically. The method proposed in this paper however, utilises a finite volume technique to generate these responses numerically.

Details of the original numerical model

An extensive finite volume module has recently been developed by Davies (1994) and added to the whole building thermal simulation program APACHE to enable it to model multi-dimensional conductive heat transfer. Full details of the module, together with the tests applied to it (empirical, analytical and inter-model) may be found elsewhere (Davies, 1994). The numerical solution has been developed to solve transient linear problems, the governing equation being:

$$\nabla^2 T = \frac{rc}{l} \cdot \frac{\partial T}{\partial t} \qquad (1)$$

where:

T	temperature (K)
ρ	density (kg m^{-3})
c	specific heat capacity (J kg^{-1} K^{-1})
λ	thermal conductivity (W m^{-1} K^{-1})
t	time (s)

The governing equation is discretised using techniques based on the work of Patankar (1980) and the finite-volume model can solve either the explicit or implicit forms.

METHODOLOGY

The testing essentially then involves the comparison of simulated data produced by the original numerical model (APACHE) against that produced by the modified model. The purpose of this 'inter-model' testing then is simply to investigate whether the faster revised model is capable of replacing the original model in terms of achieving similar predictions. Two structures are used in this testing procedure and their earth-contact heat transfer is simulated by both the original and revised models. The hourly earth contact heat transfer values are compared for a period of one year. Note that no attempt is made to compare simulated results with measured data as the earth-contact heat flux was not directly measured in detail for either structure.

Generation of the time series responses for the two structures

The finite volume module within APACHE was used to generate the time series responses. The initial conditions assumed were 10 deg. C throughout. The responses were generated as follows:

1. The time series response of the internal surface heat fluxes due to an external pulse of 1 deg.C (from an initial 10 deg. C) for 1 hour was generated. The internal boundary conditions were kept constant at 10 deg.C.
2. The time series response of the internal surface heat fluxes due to an internal pulse of 1 deg.C (from an initial 10 deg. C) for 1 hour was generated. The external boundary conditions were kept constant at 10 deg.C.

Generation of the full simulation

For a given set of *variable* external and *variable* internal boundary conditions (see below) the time series are used to calculate the hourly earth-contact heat transfer for a period of one year. This was compared with the original numerical hourly simulation for the year.

STRUCTURES SIMULATED

It must be stressed that in principle the time series method is capable of dealing with *any geometry* - the only limitation being the capabilities of the associated finite volume method. The two structures simulated in this work are described below.

Japanese structure

The earth-contact portion of the structure simulated in this work is shown in figure 1 and is a simple basement configuration. It is located on the campus of Tohoku University in the city of Sendai, Japan. The authors gratefully acknowledge the help of Dr. Shin-ichi Matsumoto of Tohoku University for allowing access to the boundary condition data for this building. The surface resistances and emissivities were obtained from CIBSE (1986) recommendations. Further details of the structure are provided by Adjali *et al.(*1998b). During the year which is simulated, the internal air was maintained at a minimum of 20 deg. C by space heaters.
Finite volume domain: approximately 40,000 nodes were used, the time step was 10 minutes and the form solved was explicit.

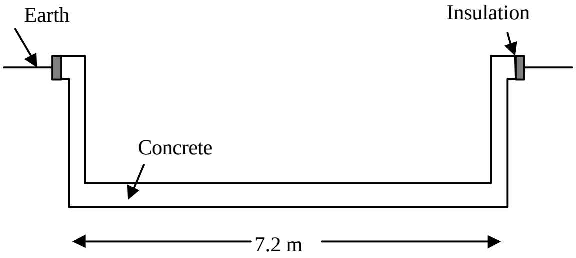

Figure 1. Schematic section of Japanese structure.

FTF Structure

The thermal performance of an uninsulated test module has been measured for a period covering four heating seasons. This experiment was carried out at the University of Minnesota, Minneapolis, USA and is known as the Foundation Test Facility (FTF); see figure 2. The floor of the structure is square (5.89 x 5.89 m^2) and the bottom of the walls is 2.03 m below the ground surface for a total height of 2.49 m. The floor and the walls are both concrete with a thermal conductivity of 1.82 W m^{-1} K^{-1}. The ceiling is well insulated and has been considered as an adiabatic boundary for the purpose of this study (U-value of 0.007 W m^{-2} K^{-1}). The module is heated by the means of 2 U-shaped electric resistances and the internal temperature is controlled to a minimum set-point of 20 °C and allowed to 'float' above this temperature. Further details of the structure are provided by Adjali *et al.* (1999).

Finite volume domain: approximately 40,000 nodes were used, the time step was 2 minutes and the form solved was explicit.

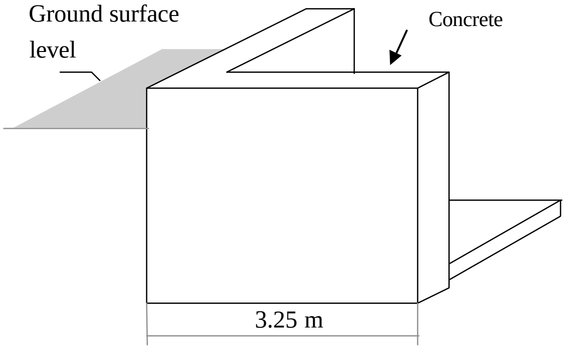

Figure 2. Schematic quarter of FTF structure.

BOUNDARY CONDITIONS

A set of measured hourly data for each boundary was applied to the simulations.

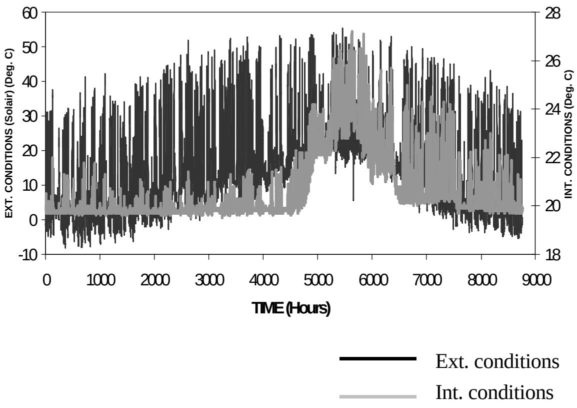

Figure 3. Japanese boundary data.

The boundary data for the Japanese structure is shown in figure 3. Details of the boundary conditions are given below.

Internal wall boundary

APACHE (incorporating the finite volume model) uses the binary star radiant-convective scheme as described by Davies (1990), in which each wall node is connected to both a radiant and air temperature point. For the purposes of this testing however, the radiant and air points were treated as a single temperature in order to clarify matters. Note that this does not invalidate the testing as identical boundary conditions are applied to both the time series and finite volume solution methods.

External surface boundary

The earth surface interacts with the external conditions via a ‘Solair’ temperature defined as follows:

$$T_{SOLAIR} = T_{OA} + SR[(DIR + DIF)a - e.RADLWS(SLP)]$$

where:

T_{OA}	measured external air temperature (deg. C.)
DIR	measured direct radiation incident on surface (W/m^2)
DIF	measured diffuse radiation incident on surface (W/m^2)
RADLWS (SLP)	a function which calculates the longwave radiation from a surface of slope SLP. It is a linear approximation based on the relevant equation from the CIBSE guide (1986).

The values of the surface absorptivity α, emissitvity ε and resistance SR used are respectively 0.5, 0.9 and 0.06 m^{2}K/W. Note that the above does not take account of evaporative effects. This is because whilst the finite volume module within APACHE (which is used in this testing to generate the responses that the time series method requires) is capable of three-dimensional simulations, it is not *specifically* an earth-contact tool. Work by Adjali *et al.* (1998b, 1999) has shown however that it *is* capable of accurately simulating earth-contact heat transfer Whilst the final version of the tool will take such effects into account (Krarti *et al.* (1993), for example, suggest a simple method of so doing), the testing reported here does not do so. Note that again this does not invalidate the testing as identical boundary conditions are applied to both the time series and finite volume solution methods.

RESULTS

A sequence of yearly time-series simulations were carried out to calculate the hourly earth-contact heat transfer for each building for a period of one year. This was done with differing portions of the time series responses (varying from 100 to 1000 hours) - the remainder of the time series response for a period of 1 year (e.g. from 100 hours to 8760 hours) being set to zero. Figures 4 - 6 show the results of the 1000 hour runs for the Japanese structure. Figures 7 - 9 show the results of the 1000 hour runs for the FTF structure. The 'heat flux' referred to in these figures is the total predicted heat flux (for that hour) specifically via the *earth-contact* portions of the structure i.e. the relevant heat flowing into or out of the space; a positive heat flux indicates a heat flow *into* the structure. The hourly Root Mean Square (RMS) 'errors' (i.e. finite volume predictions - time series predictions) for the one year period were:

Japanese structure

100 hours	316 W
500 hours	104 W
1000 hours	29 W

FTF structure

100 hours	839 W
500 hours	261 W
1000 hours	107 W

DISCUSSION

As expected, the more of the time series response to internal and external pulses that is used, the better the simulation (note that the higher RMS errors for the FTF structure as compared with the Japanese structure correspond with the higher average heat transfer associated with this building). This is because if one uses only 100 hours (say) of the time series, then one is discarding information relating to the thermal response of the structure. In theory, to simulate one year, then one should use 8760 hours of the time series response. However, the significance of the time series response reduces as one moves away from the initial hours and hence it is possible to utilise only a portion of the reponse and still achieve a simulation which, whilst not theoretically perfect, is satisfactory. It is argued, for the cases described here, that the use of approximately 1000 hours of the time series response produces an acceptable simulation. The generation of these time series is done using the finite volume technique and takes a certain time. Whilst this issue will not be discussed at any length here, it should be possible to reduce this requirement by extrapolation techniques. In other words, only two or three hundred hours (say) would be generated, the remainder would be extrapolated. Work is currently being undertaken to investigate this issue; initial results are promising and will be reported at a later time.

CONCLUSION

The details of improvements to a numerical model have been given. These changes were intended to increase the speed of the model whilst retaining its accuracy and flexibilty. The inter-model tests reported in this paper indicate that this has been achieved. Further work is continuing to optimise the model.

ACKNOWLEDGEMENTS

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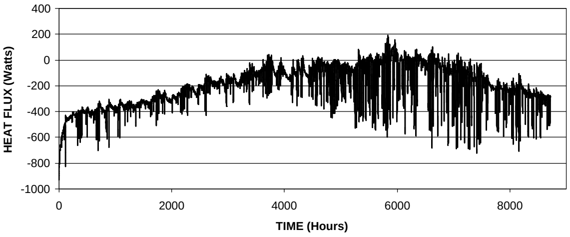

Figure 4. Japanese structure (finite volume):
see 'RESULTS' section for an explanation of 'HEAT FLUX'.

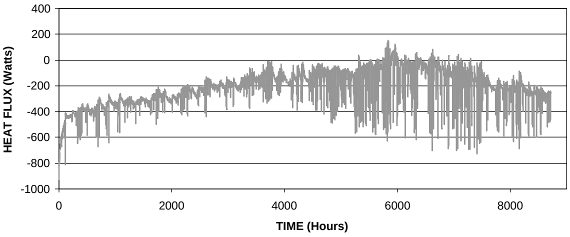

Figure 5. Japanese structure (time series).

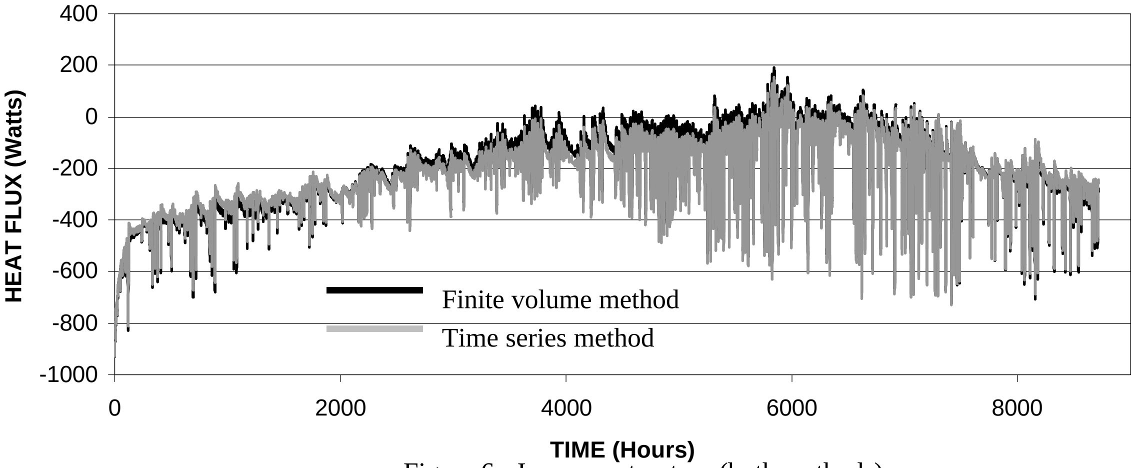

Figure 6. Japanese structure (both methods).

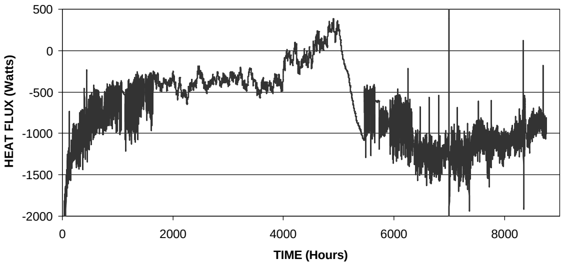

Figure 7. FTF structure (finite volume).

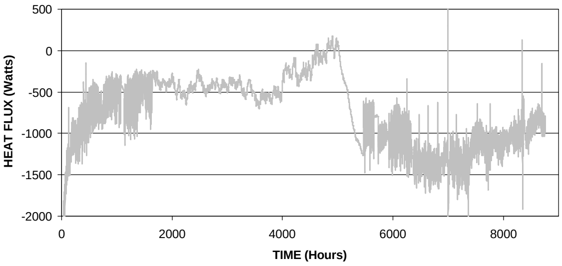

Figure 8. FTF structure (time series).

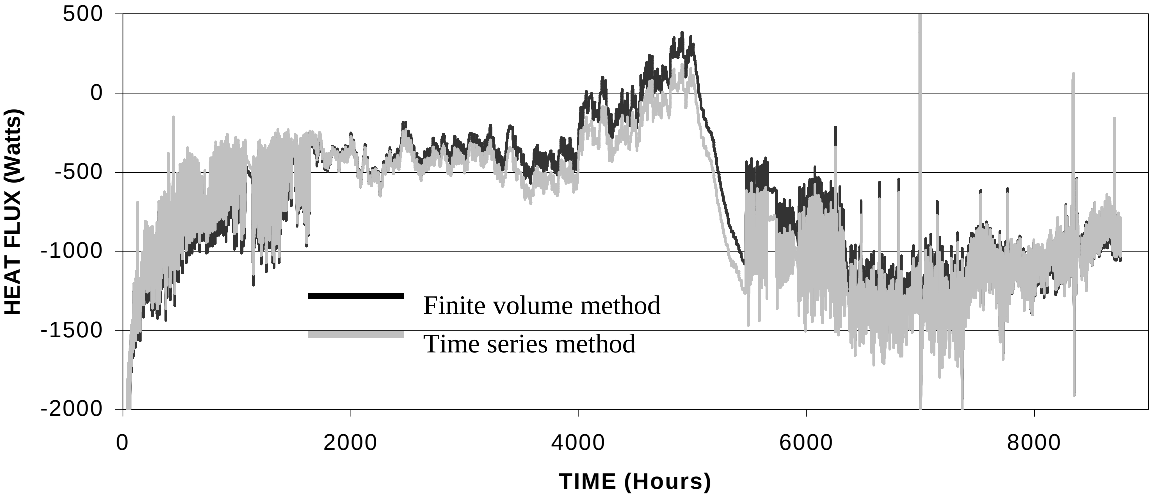

Figure 9. FTF structure (both methods).