THERMAL LOADS - A STRUCTURAL ENGINEERS PERSPECTIVE

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ABSTRACT

From a structural perspective, the question is whether temperature changes during the lifetime of a building are sufficient to affect its integrity. Changes in average temperature and temperature differentials are the key thermal loading parameters. Ile purpose of this paper is to show bow computer models have been used to construct design charts for thermal loading. Firstly, the models were calibrated from temperature measurements of actual structures. The field tests cover several years and a range of climatic conditions. The next step is to simulated the behaviour of structural elements for each day of the weather record for a particular site. Finally, statistical analysis of the simulated data is used to construct the charts. The charts cover a wide range of structural elements and only samples are given in the paper.

INTRODUCTION

The mention of thermal loading in a building context usually invokes thoughts on its heat load for air conditioning. For the structural engineer, it raises the problem of whether the applied strains from temperature changes affect the structural integrity. In Australia, the structural loading code (AS 1170-Part 1 1989) provides guidance on the range of climatic change and solar radiation intensity expected during a building's life. Translating that data into structural effects on a particular building or building element is left to the structural engineer. The purpose of this paper is to show how a computer model has been calibrated and then used to construct design charts for the thermal loading of a variety of concrete structural elements.[1]

For the exposed parts of a building solar radiation is the key cause of thermal loading. The resulting non-linear temperature profile shown in Figure 1 can conveniently be subdivided into three components; namely:

a uniform or effective temperature, T_E producing overall expansion or contraction,

a uniform gradient defined as a differential temperature, T_D producing bending,

a residual non-linear temperature profile that may produce a self-equilibrating stress system.

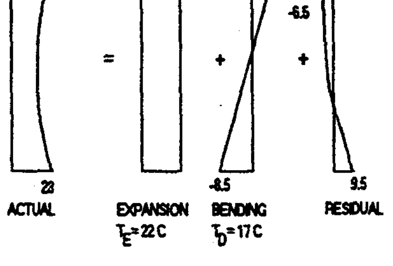

Figure 1. Temperature Profiles for Thermal Loading

The key task for the structural engineer is to evaluate the extreme values of T_E and T_D likely to

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occur during the structure's life. These extreme values can then be compared with the values occurring in the structure on the day the concrete cures. The resultant stresses in the structure are computed from the temperature differences using the principles of structural mechanics. The self-equilibrating stress system is usually relieved by creep or cracking in a concrete structure and has no effect in its ultimate strength.

Using computer simulation, it has been possible to produce design charts for the principal Australian climate regimes defined in AS 1170. For design, the Code stipulates that a value with a 1 in 25 year return period is appropriate for the serviceability limit state. For the ultimate limit state, the 1 in 25 year value must be factored by 1.25 as specified in Clause 2.2.3 of the Code.

These charts allow the structural engineer to easily compute thermal loads without the need to call in the specialist advice of someone skilled in heat transfer analysis. A further advantage of the charts is that they allow the thermal loads for alternative designs to be determined at a glance. This is especially important at the preliminary design stage.

PROCEDURAL OVERVIEW

Thermal loading is a function of climate and particularly in Australia can show great variation from year to year as well as the obvious geographic diversity. Given this variation, short term calibration experiments may not be truly representative of the loads likely to occur during a building's life. Any procedure must account for the long term variation of the thermal loads.

A fundamental methodology in the work has been to bring together relatively short term field measurements on actual buildings, computer models and the long term records of the Commonwealth Bureau of Meteorology.

Firstly, a theoretical heat transfer model is established to compute the temperature variation with time for a concrete element. The model uses the structural properties of the element and standard daily meteorological data. Short term field measurements are then used to calibrate the model is so that its reliability is known for a range of meteorological conditions. Using the calibrated model and the meteorological database, the daily extremes of effective and differential temperature are computed for a given structural element and site. From these results the annual extremes are computed and from them the design values with a known probability of occurrence are found by simple statistics.

THEORETICAL BASIS

Each of the theoretical models is described briefly and fully referenced here rather than repeat details that appear elsewhere.

For walls and slabs a simple one-dimensional computer model is sufficient as the heat transfer is essentially through the thickness of the element. The model used is a development of that first proposed by (Hunt and Cooke 1975). The equations for a multi-layer slab are solved by finite differences given the variation of the boundary conditions with time. For most walls and slabs in buildings a 15 minute integration period gives accurate results. Any shorter integration period gives essentially the same result as that using a 15 minute period. Details of the equations, the time variation of solar radiation and ambient temperature used in the model were given in an earlier paper (Hirst 1984a).

For columns, a two-dimensional finite element model is used to solve the heat transfer problem within the cross-section of the column since there is little variation of temperature along the column. The model used is a development of that first proposed by (Elbadry and Ghali 1984) for the thermal loading of bridges. Irradiance on any face of the column is calculated using the equation proposed by (Hay 1985) as a combination of direct, diffuse and reflected radiation on a horizontal surface. For the model, irradiance is calculated from the daily total using the method first proposed by (Collares and Rabl 1979) since Australian weather stations rarely report irradiance. The Collares model is an improvement over the power law used earlier to compute irradiance for the one-dimensional heat transfer model. Diffuse radiation is computed using the approach first suggested by (Orgill and Hollands 1977) and subsequently modified by (Spencer 1982) for Australian conditions. Finally, the reflected component is calculated by multiplying the irradiance by the ground reflectance. Although the computer model can allow for shading, extreme values of the thermal loading parameters are not associated with a column in the shade. Shading was allowed for when calibrating the model against field experiments since it was not always possible to located the test so that the specimens were in full sun.

CALIBRATION

Both computer models have been extensively calibrated against field tests which measured the temperature variation in actual structures for periods of up to one year. This length of time is needed to ensure a range of climatic conditions. It is not sufficient just to ensure the accuracy of the models for clear sky conditions.

The one-dimensional model was first checked against temperature measurements made on a model concrete roof slab located on the roof of the Civil Engineering Building at the University of Adelaide. Measurements of the temperature profile through the thickness of this 150 mm slab were made every hour using semi-conductor temperature sensors linked to a computer controlled data logging system. Monitoring began in November 1981 and ended one year later. Complete readings were taken on 315 days during the experiment. A simulation of the behaviour of the experimental panel was also carried out on a day by day basis for all 315 days. A wide range of climatic conditions occurred from hot summer days with clear skies to rainy days in winter. Comparison of the experimental data with simulated results showed the coefficient of variability to be 7.6% and 28.3% for the daily maximums of effective temperature and differential temperature respectively. Greater error was expected in the differential temperature since by definition the value is the difference of two quantities both of which could vary between measured and simulated values. The next step was to calibrate the model against temperature measurements in actual roofs.

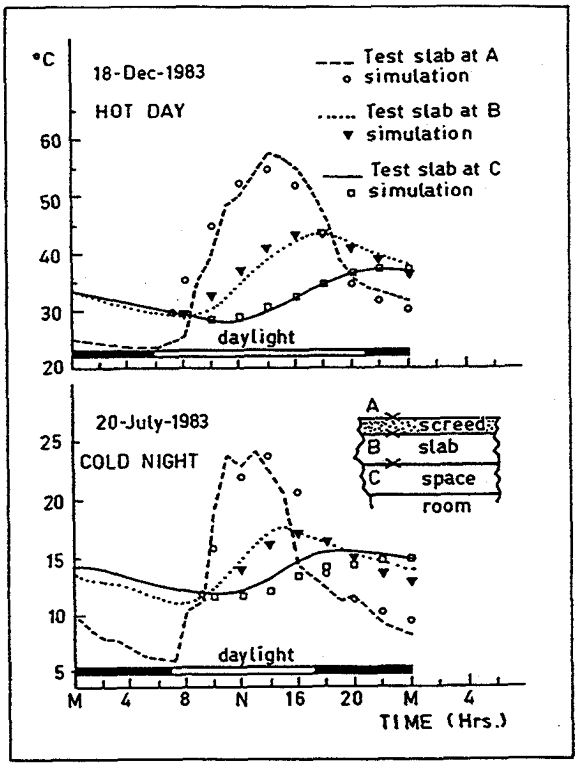

Figure 2. Temperatures in an Office Roof

From July 1983 to May 1984, hourly monitoring occurred of the temperatures in the roof of an Adelaide office building. The roof was a 220 mm thick prestressed concrete slab overlain by a dark coloured waterproof membrane. Figure 2 shows a comparison of measured and computed temperatures at different locations through the thickness of the roof for a summer and winter day. Similar results were obtained from a coincident field test measuring the temperatures in the roof of an Adelaide carpark (Hirst 1984b)

In 1984, temperatures were measured in an experimental wall panel located on the roof of the Civil Engineering Department at Adelaide University (Teicher et al. 1985). Figure 3 shows a comparison of measured and computed temperatures on the outside and inside faces of the wall.

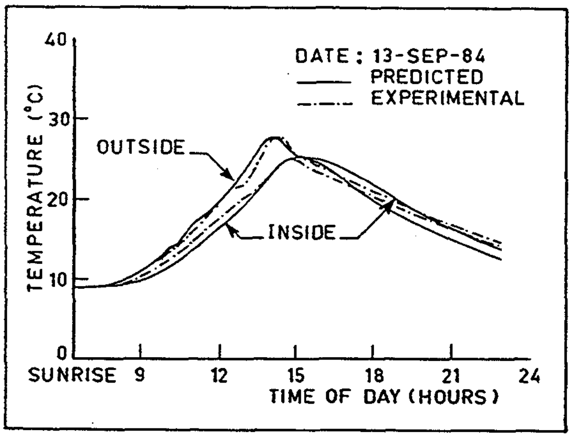

Figure 3. Temperatures in a Wall Panel

Taken together all these comparisons with field data show that the one-dimensional model can reliably compute the variation in temperature in a concrete roof slab or a concrete wall.

The two-dimensional finite element model had previously been checked against field tests on bridges and shown to accurately predict the temperature variation in bridges of complex cross-section (Hirst and Dilger 1989). Accordingly, it was felt that a less comprehensive set of calibration experiments were needed for columns than was the case earlier for roofs and walls. In addition, the cross-section of a rectangular column is much simpler than a bridge.

Temperatures were first measured in a 1.3 m high concrete column 250 mm square. The model column was set up on the roof of a building at Adelaide University and temperatures measured every hour during a series of days in the winter and spring of 1989. Figure 4 shows a comparison of the measured and computed surface temperatures on the four faces of the column for a typical day.

In 1990 the south pier of a pedestrian bridge over

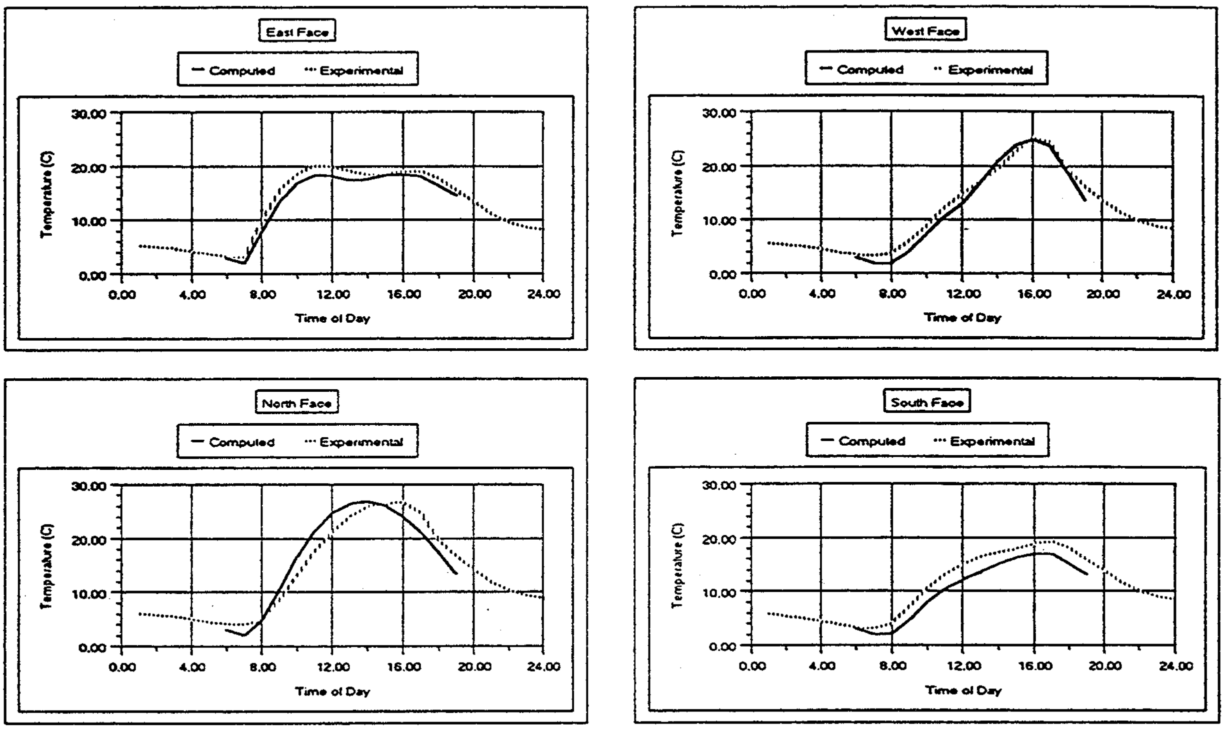

Figure 4. Temperatures in a Column

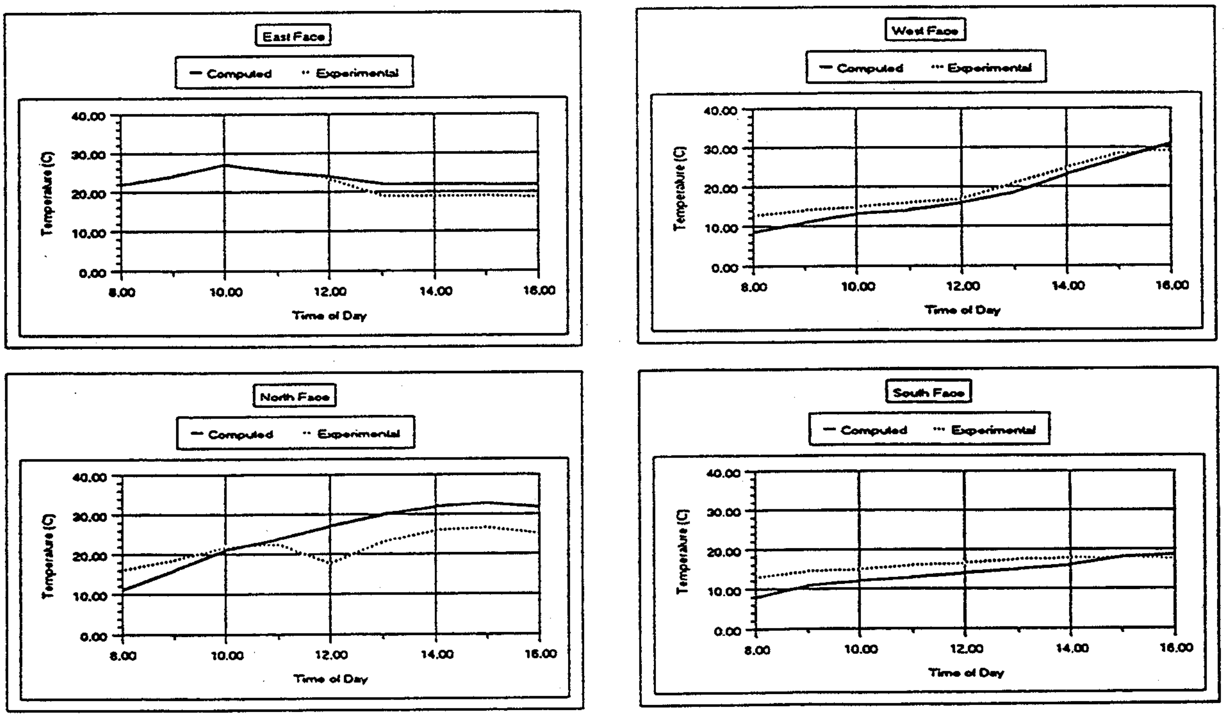

Figure 5. Temperatures in a Bridge Pier

the freeway near Adelaide was also instrumented to measure its surface temperature. Again readings were taken over a series of spring days. Figure 5 shows a comparison of the measured and computed surface temperatures for a typical day.

The two-dimensional model can predict the surface temperatures for columns. However, for the bridge pier the model does not predict the cooling of the north face as it shaded by the bridge deck around noon.

CHARACTERISTICS OF THERMAL LOADING

A number of important obsevations were derived from an analysis of the field data.

For roofs and walls maximum effective temperatures occur in the late afternoons on days of high solar radiation at the end of heat waves when the structure has warmed up over successive days. Conversely, minimum effective temperatures occur just before dawn after a clear night at the end of a cold spell. Maximum differential temperatures occur in the early afternoon of clear sky days that start cool and rapidly get warmer during the morning. For roof slabs such days occur in summer when the sun is overhead. For walls, maxima occur in either spring or autumn when sun angles are lower and there is a greater period during the day when the sun angle is approximately normal to the plane of the wall. Minimum differential temperatures are approximately zero just before dawn.

For columns extreme effective temperature patterns are similar for walls. For maximum differential temperatures the situation is a little more complex. There are two temperature differentials between each pair of faces. For a column whose cross-sectional axes are aligned north/south and east/west the maximum temperature differential between the east and west faces will occur in the morning as the sun warms the east face on a hot summer day. The maximum for the north/south faces will occur in the early afternoon of an autumn day when sun angles are lower and there is more time for the sun to shine directly on the north face of the column. Although the west face will reach a high temperature in the late afternoon the whole column has also warmed up and the temperature differentials are not as high.

DESIGN CHARTS

Using the calibrated models, the thermal behaviour of a specific building element was analysed for every day of the actual meteorological record available at a given site. A series of sites was studied in each of the three climate regimes defined in the Australian Loading Code AS 1170. From this analysis, the daily extremes of effective and differential temperature were calculated for each day of the meteorological record. The annual extremes were then found from the daily values. Statistical analysis of this data showed the annual extremes to follow a normal distribution and hence it was easy to derive the 1 in 25 year design values. The whole analysis was then repeated for different building elements and alternative climate regimes.

While the computing task has been large it was not unmanageable. The result is a set of design charts that the structural engineer finds easy to use.

The charts shown in Figure 6 give the maximum effective temperature in a concrete wall with an off-form finish located in the three climate regimes defined in AS 1170 Part 1. Design temperatures are obtained by simply reading from the chart knowing the thickness and orientation of the wall. A wall on a bearing of zero degrees faces true north with the angles increasing to the east.

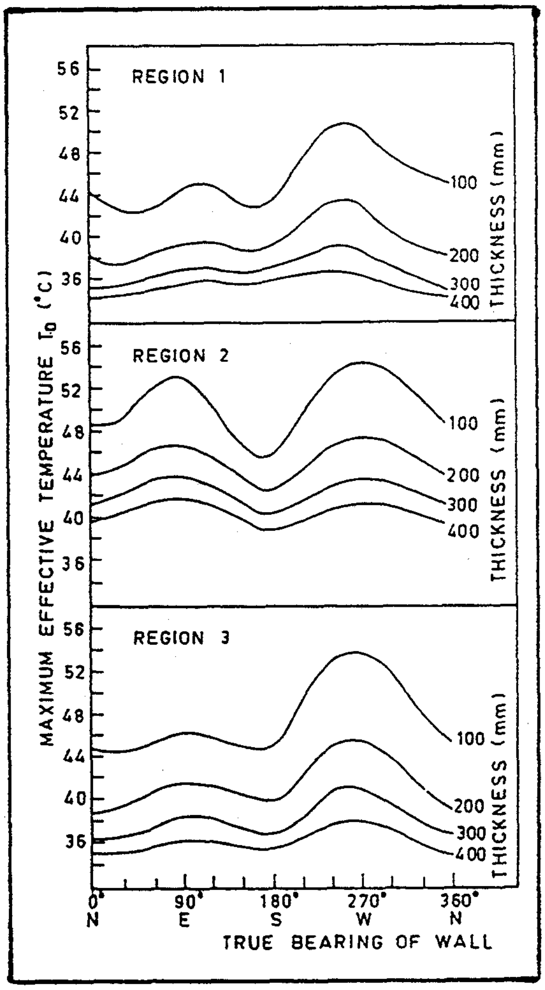

Figure 6. Chart for Maximum Temperature in a Wall

The charts shown in Figure 7 apply to columns and were derived using the same basic procedure.

Further charts are given in (Hirst 1991) for roof slabs and walls and in (Hirst 1992) for concrete columns. The selection given in this paper illustrates the form and ease of use of the charts not their full scope

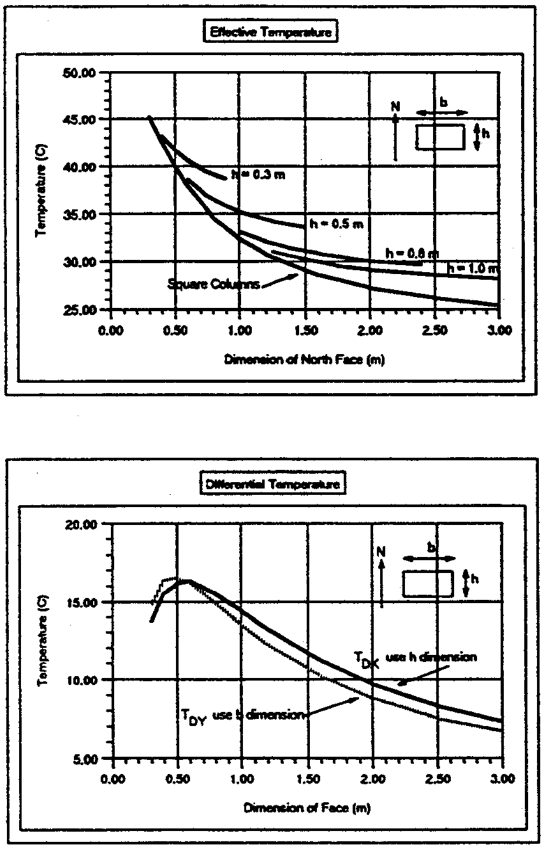

Figure 7. Charts for Columns located in Central Australia

CONCLUSIONS

The paper presents a review of the author's use of computer simulation to produce design charts for engineering professionals unfamiliar with heat transfer theory.

Extensive comparison with field observations has shown that the computer models are capable of simulating the thermal behaviour of building elements for a wide range of climatic conditions.

While the results apply to Australian conditions the techniques are not climate specific. Indeed the two-dimensional model was first calibrated against temperature measurements from Canadian bridges.

From the structural engineering perspective the computed temperature profiles were processed to determine thermal loads. With alternative computation, the differential temperature charts can easily be modified to show heat loss or gain through building elements.

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