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DYNAMIC THERMAL MODELLING AND PHYSICAL WIND TUNNEL TESTING – AN IMPORTANT PARTNERSHIP FOR BUILDING SIMULATION 2009 CONFERENCE

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ABSTRACT

The use of computer simulation has increased rapidly within the construction industry over the last few years and this trend is set to continue. However, it is important not to forget that physical testing methods still have a vital role in establishing the validity of and confidence in simulation modelling results.

This paper reports on the experience of modelling in excess of 10 large shopping centres where for the majority, natural ventilation and wind driven air movement was a principal means of ventilation and cooling. In all assessments, site-specific mean wind pressure coefficients from physical wind tunnel tests were used with an ESP-r simulation model in order to determine the feasibility of such schemes as well as to formulate design concepts and control strategies before construction.

The assessments have also led to an increased understanding of the seasonal air regime at entrances so that excessive draughts, local discomfort for retail kiosks and energy consumption can be reduced.

This paper clearly demonstrates the importance of physical testing and the increased accuracy of simulation assessments as a consequence. The confidence that the design team has had in the simulation results has enabled them to take decisions that have saved considerable amounts of capital expenditure.

INTRODUCTION

The use of computer simulation during the design process is now commonplace. This can be viewed as a positive step but only if the design team have the confidence to act on the results and improve the design.

It is still the authors' contention that too much faith is placed in computer simulation and that too often a miracle is expected by forgetting that the computer model cannot turn generic assumptions into site specific predictions.

The importance of quality input data into the computer model cannot be understated and CIBSE, BRE and BSRIA, for example, play an essential role in accumulating, considering and preparing data for use by the design engineer.

However, some data is so specific to a building and its site, that it is impossible to achieve accurate results by the use of a generic substitute. The data in question is that of mean wind pressure coefficients – which in simple terms is the effect of wind pressure at different wind directions on elements of a building.

Amazingly, it is still considered acceptable design practice by some clients and design teams to design a natural ventilation system without any recourse to site specific wind pressure data. The risk that this adds to the project and the client is huge compared to the relatively low cost (circa £8,000 to £15,000) of obtaining this data.

This paper will illustrate how vital and essential the results from a dynamic thermal model which uses wind tunnel data are and that to proceed without them is a high risk route.

The authors have been constructing large, complex dynamic simulation models for many years and have come to the conclusion that there is no substitute for building and site-specific mean wind pressure coefficients.

The knowledge and understanding gained from the analysis of mean wind pressure coefficients has also enabled effective remedial work for centres with post-occupancy problems. For example, where draughts are experienced at entrances due to the public using the centre in unexpected ways and sometimes because wind pressure data was not analysed in order to offer important benefits to the design team.

This paper will briefly describe the construction of the complex dynamic thermal model, the process of wind tunnel testing and how the test results are used within the model.

The main focus of the paper will be the design changes that were implemented for a wide range of shopping centres as a consequence of the simulation results.

The decisions made will clearly show the increased accuracy in the design team's understanding of how the building will work in practice.

This paper will show that the fees associated with a full scale physical wind tunnel test and in-depth dynamic thermal modelling are easily recouped by modifications made to the design which avoid unnecessary capital expenditure or costly under-performance issues.

THE WIND TUNNEL TEST

Wind tunnel testing is a physical testing method that is used to analyse the pressure field around a building as a result of the wind approaching from different wind directions. The pressure field around a building is determined by the height and configuration of surrounding buildings and the local topology upstream of the wind. The pressure field data is used to develop the mean wind pressure coefficients that are needed to predict how natural ventilation will work in practice within a particular building.

In isolation, the absolute values of the mean wind pressure coefficients are meaningless as far as natural ventilation is concerned. This is because for each wind direction, the applicable ventilation forces are a result of the wind pressure differences that exist *simultaneously* amongst the natural ventilation openings.

The first step of a wind tunnel test is to create a physical model of the development building. This is usually at a scale of 1:200 or 1:250 for exceptionally large developments.

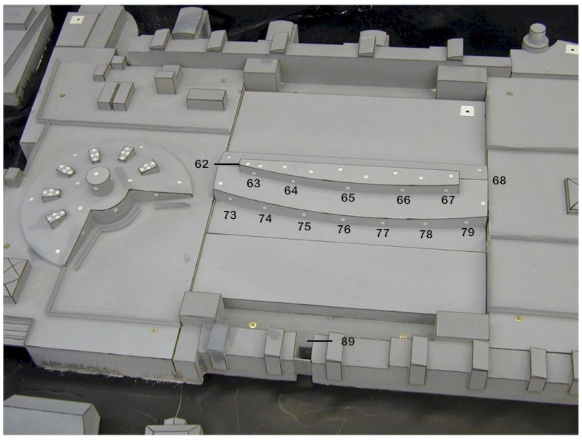

Figure 1 Typical wind tunnel model

Figure 2 Wind tunnel model with surrounding buildings

The buildings surrounding the site are also modelled but in less detail and these are placed around the development building in the tunnel.

The model contains pressure tappings at all the locations where a pressure reading is required. These comprise a fine hollow tube, rather like a hypodermic needle with a long plastic tube attached. The tappings are usually located in the centre of entrance doors, above entrance doors (where louvres could be located), and ANY location where a natural ventilation opening COULD occur.

It is important not to restrict the location of pressure tappings to existing openings if additional testing is to be avoided should alternative ventilation locations have to be considered. The individual pressure tappings are then numbered for ease of reference and the adjoining tube is also numbered to aid quality assurance. Like a large jigsaw, the development model and the surrounding buildings are then assembled onto a large turntable in the wind tunnel.

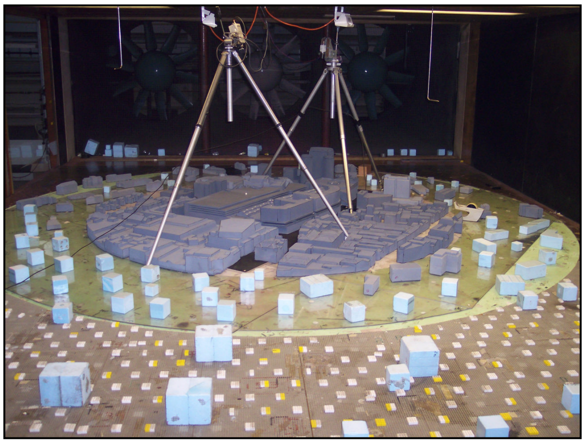

Figure 3 Wind tunnel model on the turntable

The tubes attached to the pressure tappings form a large stem, a little like a wiring harness, and are threaded through a hole in the centre of the turntable. (This group of wires is usually under the turntable but are on the top as shown for viewing only).

The tube ends are then attached to a correspondingly numbered transducer terminal that records the pressures on a computer.

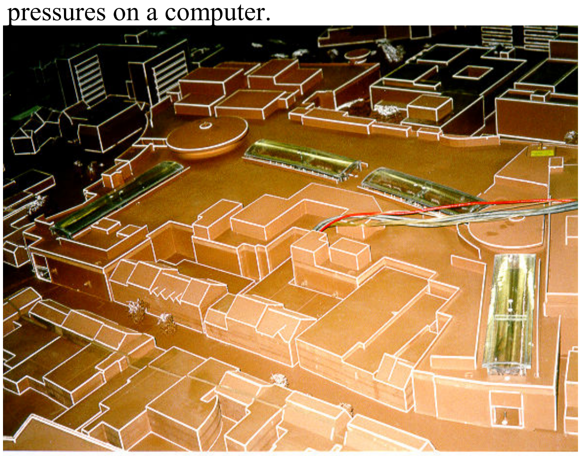

Figure 4 Wind tunnel model showing pressure tubes

The next step is to create the upwind ground topology in the wind tunnel and the appropriate wind profile (some tunnels use vertical vanes as shown in Figure 5).

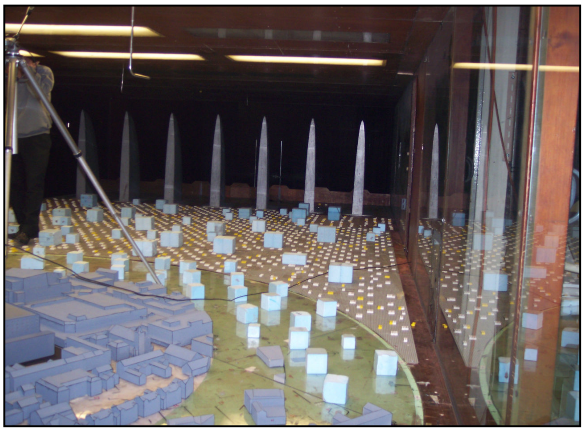

Figure 5 Creating upwind boundary profile

Wind profile data for different locations is available as recorded data and must be matched in the wind tunnel. An initial level of turbulence is generated by the use of vertical vanes at the far end of the tunnel. Coarse blocks are distributed randomly along the tunnel floor, refining the profile and closer to the model finer blocks may be introduced. This detail can be altered until the measured profile in the tunnel matches recorded data for the required location.

If the development is inland then usually the upwind conditions are similar for all wind directions. However, a coastal development such as Drake's Circus shopping centre at Plymouth or Gunwharf Quays at Portsmouth require careful consideration of upwind conditions that are over the sea. The wind tunnel tests for these locations are a little more involved because the upwind geographical conditions are not constant for each wind direction The wind tunnel is then run and pressure readings recorded on a computer for each tap location. The turntable with the building models is then rotated until data for all wind directions has been collected.

THE DYNAMIC THERMAL MODEL

All of the shopping centres assessed would be classed as Level 5 buildings had they been constructed in accordance with the Part L of the 2002 Building Regulations. These are buildings which may include features such as complex geometry, night cooling or internal atria.

All the models were simulated using a complex dynamic calculation method that enabled internal solar gain distribution and internal air movement was modelled explicitly.

The models generally comprised the common parts only i.e. the malls at ground and in some cases first and second floor levels. The individual retail units along the malls and the anchor stores were generally modelled as thermal boundaries although in some cases they also played a role in the overall air movement route. The heating and cooling contribution from the retail units is often difficult to quantify but usually offers some heating in winter and cooling in summer. In order to ensure a robust design, the potential heating and cooling contribution due to non-mechanical air movement from the retail units into the malls is never taken into account.

The capacious malls were modelled with occupied zones, 2m in height, at all levels that were to be temperature assessed and the temperature in these zones was used to determine the operation of the natural ventilation openings. The volume above the occupied zones was modelled as a zone without any direct thermal control but with associated heat gains such as solar or the convective element of any light fittings.

Entrance zones are defined as the space (occupied or otherwise) within 15m of external doors that are used by the public to access the building.

Construction information and internal gains due to occupants, lights etc are described in the usual way.

The key element of the dynamic thermal model is the air flow network. This network links the internal zones with each other and the external environment. The network describes the size of openings that exist between the zones and between the zones and outside. The user must indicate the ease with which air can pass through these openings. So for example a very large opening would have virtually no pressure drop associated with it compared to an opening with a small area or a large aspect ratio that would have a larger pressure drop associated with it.

The air-flow network needs to have a set of mean wind pressure coefficients for each entrance and each natural ventilation opening. A set of mean wind pressure coefficients for a specific point on a building comprises coefficients for at least 12 wind directions. The coefficients can be positive or negative

The presence of mechanical ventilation can also be represented in the air-flow network and this can be fixed or variable flow.

The next layer of detail is the controls for the ventilation openings and entrances that connect the internal air flow network to outside.

Entrance doors are usually controlled during occupied periods and the area of opening is profiled to match the occupancy density. Further detail may be added if the known or anticipated footfall ratios for each entrance are also taken into account.

Natural ventilation openings can be permanently open or controlled in a number of ways such as internal temperature, time or wind direction.

Once completed the model is run against suitable real hourly recorded weather data.

The results of the simulation are analysed in detail. Relevant result data for all 8760 hours of the year are extracted into an Excel spreadsheet so that potential problems with draughts, temperatures, natural ventilation opening sizes etc can be identified and addressed. The value engineering analysis to ensure that all components of the natural ventilation system (including controls) are working as intended and are not oversized can then take place. This analysis is different for every centre and is guided by the operating principles that have been developed for the design. This in-depth analysis and value engineering exercise is entirely dependent upon a comprehensive, holistic model that would not exist without the mean wind pressure coefficients unique to the site.

Gloucester Quays Designer Outlet Centre

Gloucester Quays is a designer outlet centre that opened in May this year. The malls are entirely naturally ventilated and are unheated. The roof mounted ventilation turrets are a principal design element. The centre has a very distinctive "gull wing" roof shape and the concern was that the turrets had to work without dominating the roof profile. The design intent was for the air to enter via the roof wind turrets located along the central ridge and to leave via the high level clerestory vents along the two sides of the central atrium. The wind tunnel model had large turrets so that pressure tappings could be placed at 2m, 4m and 6m above roof level. Analysis of this data indicated a significant improvement in the mean wind pressure coefficients on windward faces at 4m compared to the taps at 2m high whilst there was only a marginal difference between the data at 4m and 6m. This indicated that the optimal height was 4m and this was the data set used in the initial dynamic thermal model. The wind tunnel data was also used to optimise the orientation of the wind turrets to maximise the natural ventilation forces for no additional capital expenditure.

Figure 6 Roof turret in relation to Gull-wing roof

The outlets proved to be sub-optimal in that they also acted as inlets when subjected to the prevailing wind in spite of the location of a baffle in front of them to create a negative pressure. Therefore the baffles were redesigned using the wind tunnel to ensure that air was extracted for all wind directions. This also meant that the natural ventilation louvres could be used as smoke extracts. The control logic for the BMS was tested in the dynamic simulation model and condensed into a one page simple control settings guide for implementation by the Controls Contractor.

White City Shopping Centre, London

At planning stage an analysis was undertaken using the dynamic thermal model to evaluate two very different design concepts, both of which met Building Regulations, the Employer's Requirements and budget constraints. However, the scheme that integrated the tenant and landlord outdoor air supply required 40% less energy than the concept with separate systems. This energy saving was far in excess of what the client and the design team had anticipated and so BSRIA were tasked with the same exercise – and came up with the same conclusion.

The centre is mechanically ventilated and so it would be easy to overlook the benefit of a wind tunnel test to the design team.

However, the wind tunnel test results when combined with the dynamic thermal model were able to show which entrances were likely to suffer from the ingress of air during winter, mid-season and summer.

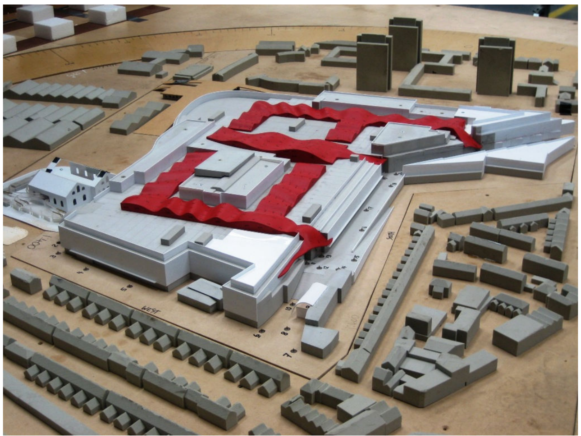

Figure 7 Wind tunnel model of White City

The data was sufficiently detailed that the draught analysis at each entrance could estimate the frequency and quantity of air movement at the entrances. The design was modified to address the problem of draughts and temperatures below the design target. Where draughts could not be alleviated, care was taken not to place sensitive tenants in these locations such as flower kiosks, cafes and newsagents.

The analysis was also able to identify the frequency of air flowing *out* of an entrance, wasting energy when over-door heaters were operating.

As a result of this understanding, a simple energy saving sensor turns the over-door heaters off when the air-flow regime is such that an entrance has air leaving from the centre.

The site-specific dynamic thermal model indicated that the proposed under-floor heating was only required for fewer than 20 hours a year. If the wind driven infiltration through the entrances had not been known, it would have been a riskier decision to remove this costly element from the scheme thereby saving an estimated £600,000.

Bradford Broadway (WSP)

The performance of the roof design was tested in the wind tunnel and again the turrets around the malls had taps at 2, 4 and 6m. We took data from the top of each turret to ensure extract and we used the set at 2m. In this instance the design team wanted the turrets as low as possible and so the 'weakest' set of coefficients i.e. the values for the 2m turrets were used in the simulation. The natural ventilation rates during the height of summer were sufficient to maintain acceptable temperatures and therefore the low turrets were incorporated into the design. The dry resultant temperatures were significantly higher than the air temperature and therefore solar shading was recommended for the glazed roof.

Figure 8 Bradford Broadway wind tunnel model

This project was located in a very windy location and the entrances experienced significant wind-driven infiltration throughout the year. Therefore, the principle of concentrating the heating at the entrances to was established. This proved a successful strategy and removed the need to install a significant heating system for the main malls whilst at the same time maintaining winter design conditions.

The Shires Shopping Centre

The Shires Shopping Centre has a new mall that interfaces to an existing mall. The objective was to upgrade the old mall (which had natural ventilation via clearstory louvres) and create a homogenous environment in the both malls. It was proposed that the new mall would also be naturally ventilated and a number of ideas were on the design table.

The first step was to create a wind tunnel model and to obtain the mean wind pressure coefficients for all the design options to be considered. The wind tunnel model included both square and round turrets, positioned alternately to allow the mean wind pressure coefficients for both options to be compared.

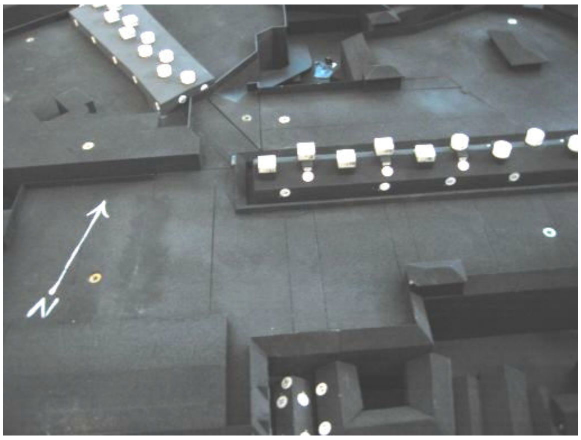

Figure 9 Ventilation options tested in the wind tunnel

There was concern over the effectiveness of the clerestory louvres in the existing mall and therefore the adoption of these for the new mall was initially dismissed. The first option in the dynamic thermal model, using data from the wind tunnel tests, was for the new mall to have wind turrets acting as supply and extract and for the existing mall to continue to be ventilated by clerestory louvres. The results showed that although ventilation rates were acceptable and that design temperatures were met, the different ventilation devices led to an air-flow regime with one mall acting as a supply and the other as an extract. This meant that there was no direct control over the mall acting as an extract. Two further simulations were run, using first turrets throughout and then louvres throughout. In both simulations each mall acted independently of the other and again met design conditions. This led to the conclusion that either natural ventilation device would work but a combination would not be possible.

As a result of the wind tunnel test results and the dynamic thermal model the least expensive option of clerestory louvres (with some modification to improve their performance) was adopted with confidence and significant capital savings were made as a result.

St. Davids Shopping Centre

The original design intent was to naturally ventilate this shopping centre. The centre was part of a mixed development comprising retail, residential, commercial offices and a hotel. The development was wind tunnel tested and the mean wind pressure coefficients were used to predict the natural ventilation regime using the dynamic thermal model. The original natural ventilation strategy proved to be unpredictable and alternative natural ventilation regimes were tested. Whilst all the natural ventilation options were able to achieve the required internal design temperatures, they also had significant air flow characteristics that were not directly controllable. This meant that the centre could not be reliably controlled in response to unexpected events.

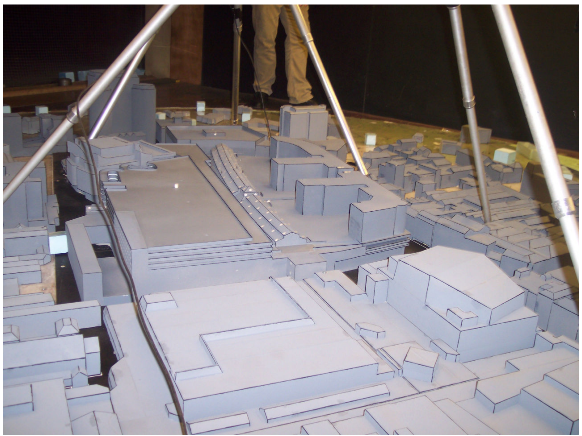

Figure 10 St. Davids surrounded by taller buildings

Since it was not possible to develop a natural ventilation strategy that was predictable and controllable, the decision was taken to mechanically ventilate the malls in order to produce an environment that was predictable and controllable.

Chapelfield Shopping Centre, Norwich

At the early design stage, it appeared an impossibility to naturally ventilate the Chapelfield Shopping Centre. There was a shortage of low-level air supply routes, many spaces were occupied at more than one level and had spaces with high floor to ceiling heights.

An optimistic natural ventilation strategy was proposed which would require careful design of natural ventilation openings.

A physical wind tunnel model was constructed and the mean wind pressure coefficients produced were used in the dynamic thermal model. The initial design comprised one long clerestory style supply turret to a large double height hall, wind supply turrets in other malls and a mixture of natural and mechanical ventilation to terraces dining areas.

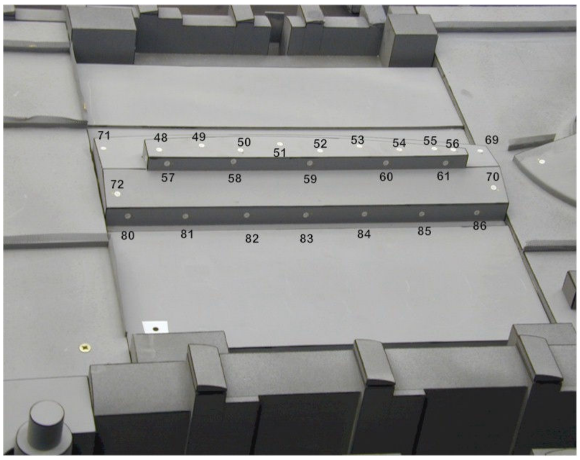

Figure 11 Chapelfield with clerestory turret tapped for testing

Early simulations indicated that some of the wind supply turrets were contributing little to the performance of the centre and these were removed from the design reducing capital cost.

The interaction between the areas served by mechanical ventilation and those served by natural ventilation was closely analysed in order to ensure that throughout the year, the environment in all occupied areas could be directly controlled by adjustments to the natural or mechanical system serving that area.

The performance of the long clerestory style supply turret was optimised using CFD as well as the dynamic thermal model.

Drake Circus, Plymouth

Drake Circus is a naturally ventilated shopping centre at Plymouth. The coastal location meant that the wind tunnel model had to take account of the effect of the wind approaching over the sea for much of the year.

The centre is essentially in three sections and the design intent was for each to ventilate independently of the other areas.

The early simulations indicated that dry resultant temperatures were too high and eventually it was possible to convince the architect that reducing solar gain was the only answer having proven that the natural ventilation was already optimal.

The centre has bespoke ventilation chimneys that are similar to icebergs in that most of the chimney is below roof level.

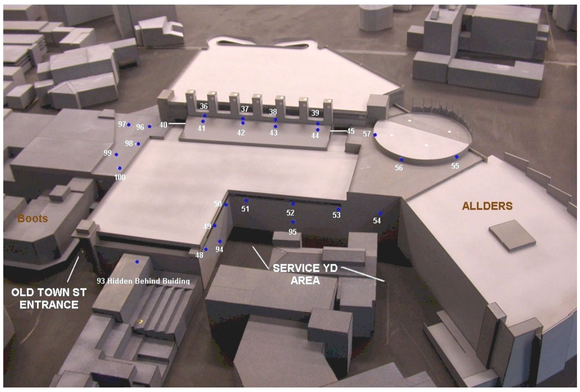

Figure 12 Drake Circus with wind chimneys

Whilst the ventilation chimneys look simple, their internal design was developed using the mean wind pressure coefficients and the dynamic thermal model. This means that each chimney was able to extract warm air form high level in a mall whilst at the same time introducing make up air to the lower levels.

Touchwood Shopping Centre, Solihull

Touchwood was the first naturally ventilated shopping centre in the UK. It was decided at a very early design stage that wind tunnel modelling and computer modelling would be used to optimise natural ventilation performance of the centre.

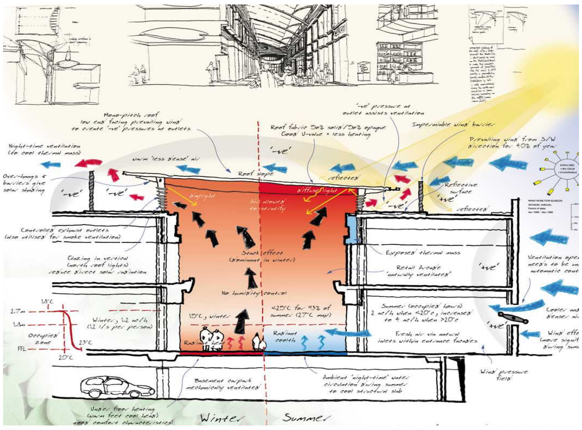

Figure 13 Concept Schematic for Touchwood

The initial roof design was tested in the wind tunnel and using these results the roof design was modified to maximise the use of natural ventilation.

The internal performance of the shopping centre was assessed with the dynamic thermal model and once again a predictable and controllable control strategy was developed for each mall. The original natural ventilation design had numerous stages of control that added capital cost to the project. The dynamic thermal model was able to value engineer the controls and identify how often the centre was within each control mode. This enabled the control strategy to be simplified and capital saved without any adverse effect on performance.

The proposed design was simulated and the entrance environment assessed. However, the *anticipated* low pedestrian footfall through potentially draughty entrances suggested that remedial design measures were unnecessary. However, *in practice*, pedestrian use was higher than anticipated and remedial measures were subsequently implemented.

Blue Water Shopping Centre, Kent

This shopping centre was designed to operate with mixed mode ventilation in order to take advantage of natural ventilation when external conditions allowed. This centre also had vast double deck car parks surrounding the centre that due to their size required mechanical ventilation.

The centre was located within a chalk pit bowl that generated unusual wind effects around the centre. A wind tunnel model was constructed and the results used in the dynamic thermal model.

An objective was to naturally ventilate the car parks and therefore the mean wind pressure coefficients were also used in computational fluid dynamic (CFD) models of the car parks.

It was observed in both the physical (wind tunnel) and computational (CFD) models that the light wells within the car parks were a key element to achieving natural ventilation. Using the CFD model the design of these openings was refined to enable Carbon Monoxide levels to meet the Building Regulations and only 10% of the car park was installed with mechanical ventilation that only operates at peak periods. This saved in the region of £750,000.

Figure 14 Bluewater with large naturally ventilated car parks and iconic ventilation turrets

The natural ventilation design for the malls was simulated and the entrance environment assessed. However, as at Touchwood, the *anticipated* pedestrian footfall through the secondary entrances suggested that no remedial design measures were needed. However, *in practice*, the pedestrian use was different to what was anticipated and remedial measures were subsequently implemented.

The size of the iconic ventilation turrets was optimised to provide the required internal air distribution during the natural ventilation period without being excessively large which would have added cost and structural weight loading on the roof.

CONCLUSION

The wind tunnel test data when combined with the dynamic thermal model provide site-specific performance results that avoid design mistakes and remove redundant capital items.

The cost of the wind tunnel model and the dynamic thermal model are recovered many times over by savings in capital costs and/or energy costs. In spite of this, many naturally ventilated projects still rely on generic rules of thumb.

The extent to which the natural ventilation schemes required modification is testament to the importance of site-specific performance information at an early design stage. It also demonstrates that whilst natural ventilation can deliver low energy buildings, it does not follow that design fees can be saved by assuming that natural ventilation will always work as intended.

The authors' experience is that the lack of site-specific information leads to "just in case" extras to provide back up ventilation. It is the authors' experience that had a comprehensive analysis been undertaken the "just in case" extras would have been shown to be unnecessary. A much better use of resources would have been to allocate *some* of the costs for "just in case" backup systems for a comprehensive analysis and to confidently pocket the difference!

REFERENCES

The Building Regulations 2000, Conservation of Fuel and Power, Approved Document L2.