CIBSE 1998

Practical Ceiling Solutions for Thermally Efficient Steel Frame Buildings

by Alex AMATO, *Consultant Architect to the Steel Construction Institute & Director of Dr Amato Ltd, UK*
Chris KENDRICK, *PhD Student at Oxford Brookes University, Oxford, UK*
Ray OGDEN, *The Steel Construction Institute Reader & Principal Lecturer in Architecture at Oxford Brookes University, Oxford, UK,*
Roger PLANK, *Holder of the British Steel Chair of Architecture & Structural Engineering at the University of Sheffield, UK.*

The need for energy efficient buildings is outlined, and the principal issues relating to commercial developments are discussed. The importance of natural cooling is highlighted, and the associated principle are examined. Some ways in which this can be achieved in conventional steel framed construction are presented. The suggestions include passive systems which rely simply on exposing sufficient thermal capacity of the building fabric, and active systems which provide greater control and improved performance. They represent an application of technology for sustainable development.

KEYWORDS

Environment, fabric energy storage, exposed structural soffit, suspended perforated ceilings, energy saving.

1. INTRODUCTION

Most buildings are designed to carefully controlled cost constraints. These have traditionally been based on initial cost, but there is an increasing recognition that cost in use should be considered and one very important element of this is energy consumption.(1) There is also an acknowledgement that in order to protect our environment we need to reduce both our consumption of raw materials and the production of greenhouse gases, in particular carbon dioxide.(1) Reducing our use of energy (based on the burning of fossil fuels) will help in both respects.(1) Since in the UK buildings account for approximately half our energy consumption and carbon dioxide emissions, building designers clearly have a significant role to play in this respect.(1) Reducing electricity consumption is particularly important in limiting carbon dioxide emissions since unavoidable losses in generation reduce efficiency significantly.(1)

Buildings 'consume' energy in a number of ways - the energy implicit in the production of the building materials and the construction process (the 'embodied' energy), incidental energy such as that used by occupants or users travelling to and from the building, and operational energy associated with lighting, heating, cooling, and ventilation. Studies have shown that in the UK the embodied energy consumed in the production of commercial buildings is relatively small in comparison to the operational energy over the notional life of an office building. Moreover, the expenditure of embodied energy is little influenced by the choice of structural form, although the potential inherent greater structural adaptability of steel framed construction may achieve a small advantage in comparison with less adaptable forms of construction.(1)

The significance of the operational energy consumed by the commercial sector is shown in Figure 1. From this information, it can be shown that of the approximate 50% of UK delivered energy that is consumed in buildings, approximately 25% of this is consumed in the services sector. Focussing on operational energy efficiencies and reductions in the commercial sector are, therefore, likely to yield significant environmental benefits.

The operational energy consumption of commercial buildings can be minimised in a number of ways. These include:

- reducing heat loss by high levels of insulation and a reduction of uncontrolled air infiltration by means of a well sealed envelope;
- optimising the use of day lighting, whilst avoiding glare and excessive solar heat gain by the use of appropriate external shading;
- using low energy installations where artificial lighting is necessary;
- using energy efficient office machines and reducing small power loads generally;
- reducing the need for air conditioning by grouping together high heat producing office machines away from general office areas.

Within the commercial sector, attention has recently been focussed on the importance of naturally ventilated, self cooling systems, and a small number of designers have incorporated the concept of storing coolth within the fabric of the building, potentially reducing both capital and recurrent costs and carbon dioxide emissions.(1) (Figure 2)

In simple terms the heat flow between a building and its environment is cyclical (Figure 3). During the day the heat flow is generally into the building. This may be due to increased outside temperatures, solar gain, and internal gains resulting from the heat emitted by occupants and equipment such as computers and photocopiers etc. At night the external air temperature falls and internal gains are significantly reduced, so heat is lost from the building. In Summer the daytime gains are typically dealt with by the use of air conditioning, whilst in Winter they may be inadequate to maintain comfort and there is a need for heating.

2. FABRIC ENERGY STORAGE

The thermal capacity of the building fabric, which is a measure of its ability to absorb and store heat, can be used as a thermal flywheel to minimise the daytime peaks keeping the internal ambient temperatures within the comfort criteria. This is achieved when heat is absorbed by the building structure during the day, reducing the peak Internal air temperature.(1) At night when the ambient temperature falls this stored heat can be released. This process can be assisted significantly if night ventilation of the building (night time purging) is possible. In this way a more even (Figure 4) temperature regime can be achieved during the Summer and the need for air conditioning reduced or eliminated.(1)

The mechanism for heat exchange between the room (occupants, contents, atmosphere) is a combination of convection and radiation. Although the relative significance of these can vary quite widely depending on a range of factors, both are of comparable importance. Heat transfer by convection can be improved significantly by increased air flow (preferably 'turbulent') across the surface of the building fabric, whilst radiation is affected by the nature of the surface.(8) The ability of heat to be absorbed depends on the availability of sufficient 'visible' thermal capacity. This is termed 'good thermal linkage'.

3. PASSIVE SYSTEMS

Systems which rely on natural heat exchange between the atmosphere and the structure may be classified as passive. In such cases floor slabs provide the most consistently available source of thermal capacity. On a diurnal basis only a relatively thin depth of concrete slab (50-75mm) is needed to provide adequate fabric energy storage.(8) Thicker slabs afford negligible improvement, and the key issue is to achieve good thermal access to the slab for efficient heat transfer.(1) The need for raised floors in modern commercial buildings means that direct access from the atmosphere to the slab can only effectively take place through the ceiling. This will require exposure of the soffit or a suitable suspended ceiling which permits good thermal access.

It is clear that the frame itself has little influence on thermal capacity, and ways in which designers can optimise fabric energy storage in conventional steel framed construction have been studied. Initially, attention has been focused on the most common methods of floor construction - composite decking and precast concrete slabs. Simply exposing the soffit will provide for a heat transfer between the atmosphere and slab of approximately 20W/m^2. This is generally sufficient to reduce the air temperature by about 2°C compared with conditions in which the soffit is effectively isolated from the internal space, for example, by a suspended ceiling.(8) A visually acceptable ceiling can be achieved by simple finishing treatments such as painting the underside of a composite deck, or specifying a fair faced finish to the concrete. Together with suitable treatments for fire protection - if required - of beams and columns, and integration of lighting, an attractive and thermally efficient ceiling can be easily realised. (Figures 5-9)

In the case of a composite slab with a soffit formed by profiled decking, heat exchange is slightly better than for a flat soffit because of the increased surface area. This is true for both conventional and curved soffits, which use profiled decking curved to form a vaulted ceiling. It is supported at its ends on the bottom flanges of steel beams, which are therefore provided with a significant amount of implicit fire protection. The recently introduced deep form composite deck system also offers these twin advantages of improved thermal efficiency due to increased surface area, and shielding of the steel beam in fire conditions.

Where a conventional plastered ceiling is required, plasterboard can be fixed directly to the underside of the slab, but this will reduce the efficiency with which heat can be transferred between the internal space and the slab. For a re-entrant profile composite deck where most of the deck is in direct contact with the plasterboard, analysis indicates approximately 6 W/m^2 compared with the fully exposed condition. For deepdeck flooring systems, there is significantly less contact between floor structure and ceiling, and thermal linkage is much reduced.

However, a suspended ceiling has many advantages in addition to masking a visually unacceptable soffit and providing a void for service ducts, pipes and cables. For example, it can include sound absorbing panels for reduction in reverberation time and noise transmission and it provides convenient mounting for luminaires, signage, and full-height partitions. It is possible to retain these advantages, whilst allowing thermal linkage with the slab soffit above, by using a perforated or open grid ceiling tile.

Circulation of air is allowed through the open grid or perforations, enabling convective heat exchange between the air and slab to occur, as with a fully exposed slab. Previous research has suggested that percentage open areas as low as 15% could be enough to allow significant air circulation and hence modulation of peak internal temperatures.(1) Open grid tiles will allow some direct radiative heat exchange between the soffit and surrounding surfaces in the room, but perforated tiles will act as a radiation shield, suppressing radiative exchange. If a metal tile is used, there will be indirect radiative exchange with the room in two stages: between the slab and the tile, and between the tile and other surfaces/occupants in the room.

There are various issues still under investigation, including optimum tile layout and the effect of perforation size on thermal linkage. A test room has been constructed at the Steel Construction Institute (Ascot, UK) which uses a 600mm ceiling grid 400mm beneath a re-entrant profile composite steel/concrete deck. Different ceiling tiles are currently under test to establish quantitative performance data for each type. The room is subjected to a heat input of 55W/m^2 for a nine hour period to replicate office occupation, followed by a period of 15 hours of controlled cooling. The thermal response of the room is monitored over the cycle: air temperatures at different heights, surface temperatures (walls, floor, soffit, and tile) and black globe temperature are logged at ten minute intervals, as is ceiling heat flux. Some preliminary results are presented in Figure 10.

No.	Tile type	Description	% open	Max air (deg C)	Max DRT (deg C)	% Cooling Effect
1	Exposed ceiling	No tiles in grid	100%	28.66	28.11	100%
2	Plain steel	No perforations, no acoustic backing	0%	30.60	29.89	60%
3	Mineral board	No perforations	0%	31.82	31.06	0%
4	Perforated steel	2.5 mm round holes, 5.5 mm square pitch, no acoustic backing	14.5%	29.20	28.62	83%
5	Perforated steel - 'microperf'	1.5 mm round holes, 5mm diagonal pitch, no acoustic backing	19.9%	29.59	29.00	70%
6	Plain steel	No perforations, with acoustic backing	0%	31.49	30.74	11%

Table 1

The performance of each ceiling configuration can be compared by assigning a percentage effectiveness, based on the performance of the exposed ceiling (Test 1) at one extreme, and that of a completely closed ceiling (Test 3) at the other. For example, percentage performance of the perforated tile in Test 4 is given by:

$$\frac{\text{Max DRT (Test 3) - Max DRT (Test 4)}}{\text{Max DRT (Test 3) - Max DRT (Test 1)}} \times 100\% = \frac{31.06 - 28.62}{31.06 - 28.11} \text{X } 100\% = 82.7\%$$

Table 1 summarises the maximum temperatures reached in each case. It is interesting to note that a ceiling open area as low as 14.5% can provide 83% of the cooling effect of a completely exposed structural soffit. However, decreasing the size of the perforations introduces additional flow resistance to convective circulation, and counteracts an increased percentage open area, as is shown by Test 5.

It can be seen that use of closed fibreboard tiles isolates the thermal mass of the soffit and results in a maximum temperature over 3°C higher than the room with the exposed soffit. However, a perforated ceiling tile, with acoustic blanket removed, using 2.5mm diameter holes to give a 14.5% open area achieves approximately 83% of the cooling performance of the exposed soffit, equivalent to 14 W/m^2.

In addition, computational fluid dynamics (CFD) modelling is being used to extend the physical testing and investigate convective air flow patterns in a room with multiple heat sources (lighting, electronic equipment, etc). A typical CFD pictorial output is shown in Figure 11: warm air rises as a convective plume through a suspended ceiling with 30% open area, and contacts the slab where heat exchange occurs and the cooled air falls back into the occupied volume.

Perforated ceiling tiles provide the best solution for the typical office environment, concealing the soffit better than the larger cell open grid tiles. The latter leave soffit and service runs visible from directly beneath and hence may require them to be painted black to aid concealment. Perforated metal tiles are available, usually for use with an acoustically absorbent blanket on the upper side, being intended to improve the acoustic environment in the office. However, the "micro-perforated" variety, although having sufficient percentage open area, will present a larger flow resistance to the relatively slow convective plume above heat sources, and will thus discourage air movement into the ceiling void. Larger perforations are better, such as the 11mm square hole steel tile offered by one manufacturer. This design gives an overall percentage open area of 37%, allows relatively unrestricted air movement through into the ceiling void, and hides the soffit effectively.

The use of such ceiling tiles offers the possibility of a multi-functional suspended ceiling, where different tile types are combined to best effect. The full range of aesthetic expression is open to the designer, whilst fabric thermal storage is achieved, acoustic criteria are met, artificial and natural lighting is facilitated, and additional cooling can be supplied if necessary by chilled ceiling tiles.

4. ASSISTED SYSTEMS

The performance of these systems can be improved by encouraging air movement across the surface of the slab, for example by using a simple ceiling fan with a bare soffit (Figures 12 and 13). Air can also be drawn through the raised floor void above the slab, or the ceiling void below. Mechanical ventilation of this nature not only improves performance but also provides some degree of control. However, because the air movements are relatively gentle, the improvements in heat transfer are modest. For example, a raised floor void with ducted air in between the raised floor and the upper surface of the slab fan and bare soffit might provide a heat exchange of about 10 W/m^2. Systems based on a space fan might perform little better than a simple exposed soffit if a suspended ceiling is installed, but total flexibility of ceiling treatment is achieved.

5. ACTIVE SYSTEMS

Passive systems are effective in reducing cooling requirements but control and performance can be improved by using a hybrid solution in which air is directed across the surface of the ceiling or floor and released into the atmosphere in a controllable way. This is the principle of hollow core systems which create significant turbulence where air is forced around corners in ducts within precast concrete floor units. A variety of generic design solutions have been devised taking advantage of the natural air paths available when using profiled slabs. A composite deck with a plasterboard ceiling attached directly to the underside provides a system of potential air ducts, and because these are relatively small, turbulent air movement can be readily achieved. The same principles can be applied by fixing decking to the top of the floor slab within the raised floor zone. With a suitable arrangement of supply ducts and outlets this can give a performance of about 32 W/m^2 and good control. Such a system can also be used for existing buildings during refurbishment.

A further option is to use a liner tray arrangement fixed to the underside of the slab providing a flat finish (Figure 14). If the ducts so created are not sufficiently small, improved turbulent air flow can be achieved by introducing baffles.

The deep deck profiles with a plasterboard ceiling create natural voids through which air can be directed. However the size of the ducts is rather large and needs to be reduced to improve turbulence. This can be achieved by introducing a liner inside the deck (Figure 15).

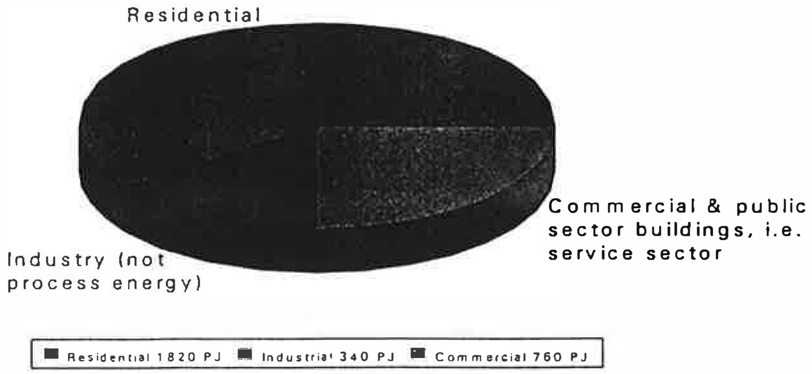
These systems combine the full advantages of fabric energy storage, user control, and the design freedom to use any ceiling treatment. The challenge is then to provide the necessary controlled air flow, and this can be done most effectively using distribution fans. Whilst this consumes some energy this is relatively small, and potential problems associated with totally natural ventilation - security, noise and inadequate cooling during extreme weather conditions - are eliminated.

6. CONCLUSIONS

As energy costs and concerns for the environment grow, architects and engineers will increasingly need to incorporate energy efficiency as part of building design. In commercial developments this will often focus attention on reducing or eliminating air conditioning by using the concept of cooling by exploiting fabric energy storage (FES). This can be ‘passive’, relying simply on exposing sufficient thermal capacity of the building fabric. Such approaches, however, have limited performance and offer the user little control. This can be improved by enhancing the heat transfer from the internal space into the floor structure. This is achieved by encouraging air movement in contact with the exposed surfaces, but maximum effect is obtained by using an active system in which air is routed through specifically designed ducts or voids in a turbulent flow.

Passive systems are likely to require the soffit of the floor slab to be exposed, and a number of simple treatments can be given to those floor systems typically used in steel framed construction to achieve a visually acceptable finish. Alternatively open grid or conductive ceilings can be installed, although these will in some cases reduce thermal performance. Active systems will also generally perform best with exposed soffits, but can provide good performance with a conventional suspended ceiling.

The important design aspect is enabling heat transfer between the internal space and slab, directly or indirectly, and the form of the supporting structural frame and its mass is of lesser importance. Designers can therefore use steel framed construction, and still achieve energy efficient buildings that exploit all the benefits of fabric energy storage. Perhaps the optimum solution is to use a mixed mode approach, maximising the use of passive systems, but supplementing these with active control when necessary.



Source: from CIRIA Environmental Issue in Construction Volume 2.

Figure 1: Delivered operational energy consumption by sector (1987)

Figure 2: The Ionica building is a recent example of an energy efficient steel frame building

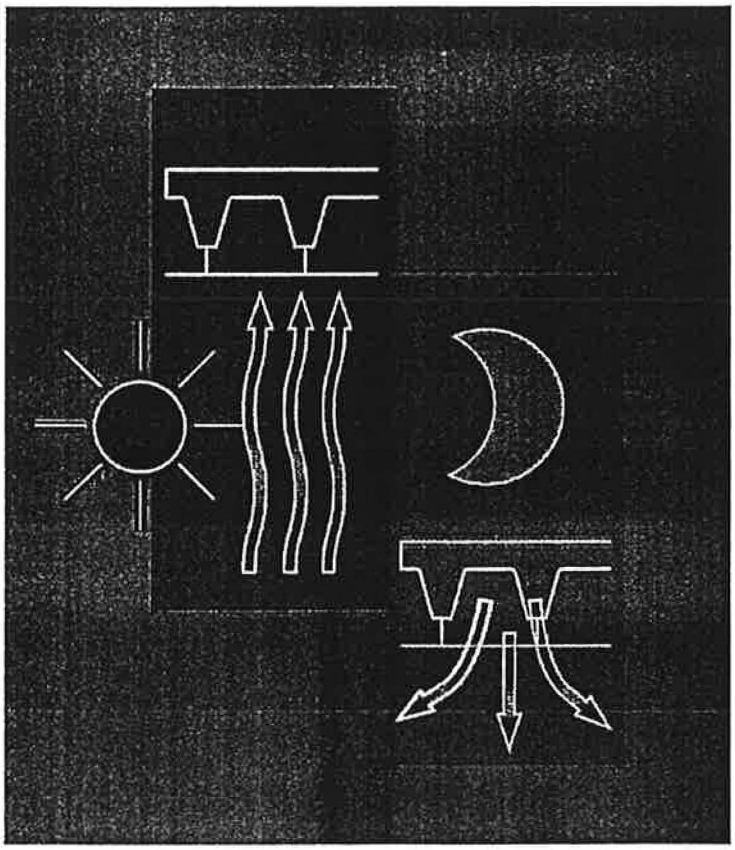


Figure 3: Diagrammatical representation of diurnal heat transfer

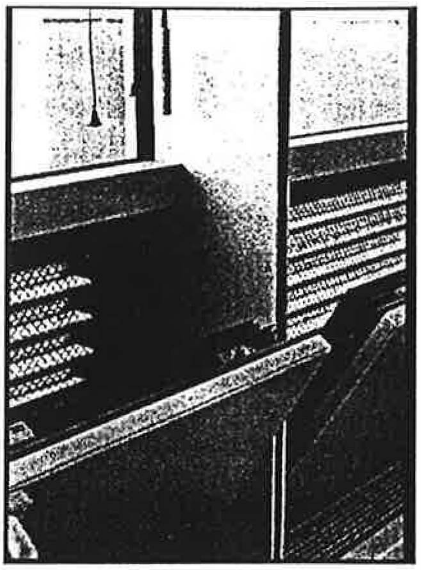


Figure 4: Example of perimeter ventilation hoppers for night time ventilation

Figure 5: Slimdek - exposed soffit

Figure 6: Composite deck - exposed soffit

Figure 7: Steel frame and precast flat slab - exposed soffit

Figure 8: Exposed soffit with curved metal decking (N.B. last structural bay may require ties)

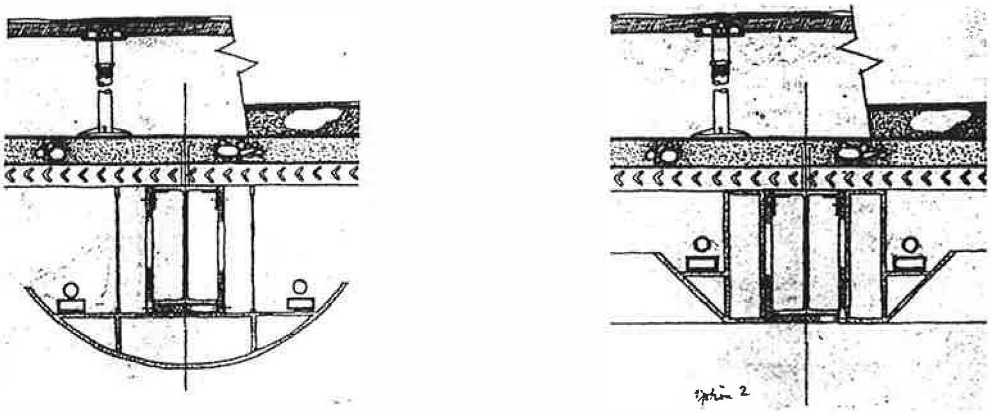


Figure 9: Integration of cornice uplighting into composite deck, exposed soffit

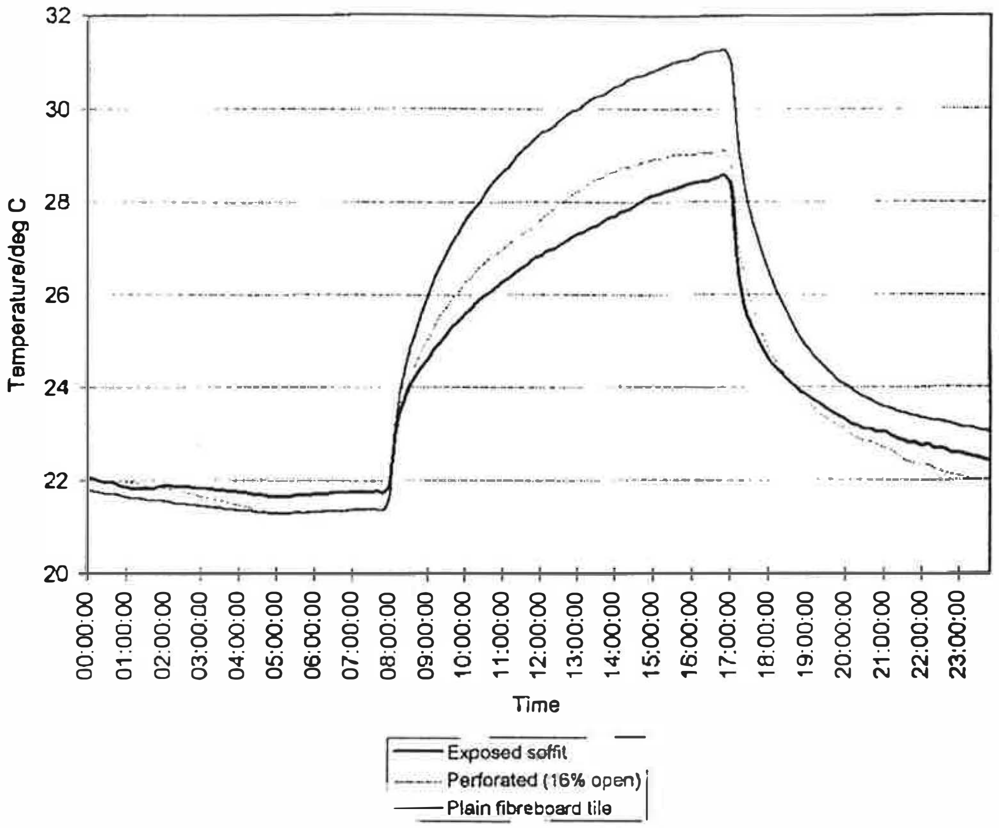


Figure 10: Ascot test room: thermal response for stated ceiling arrangements

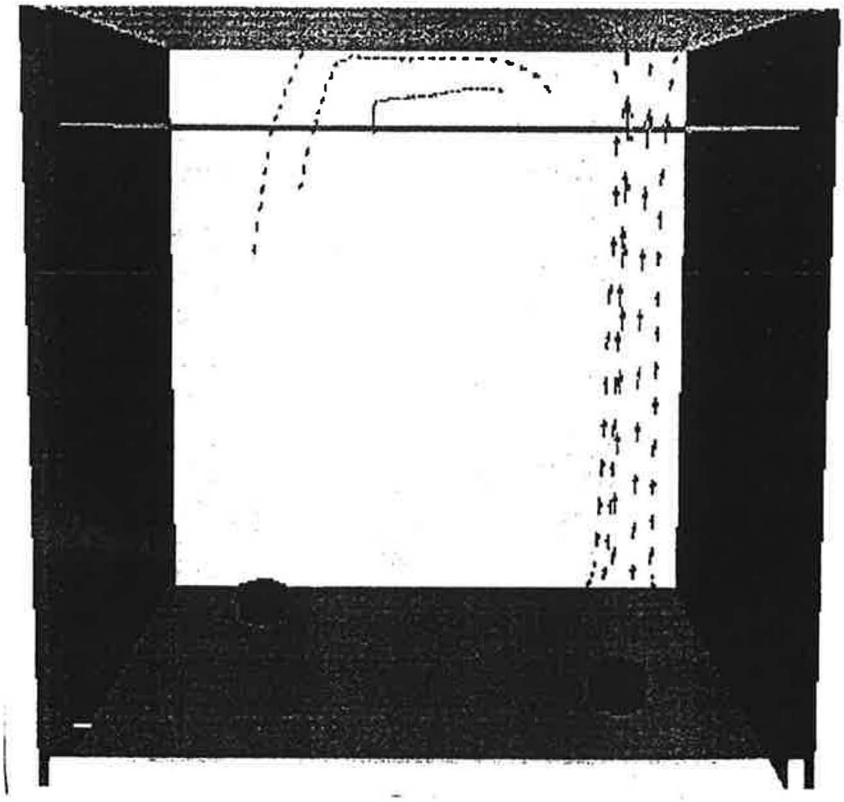


Figure 11: CFD plot of test cell with perforated ceiling

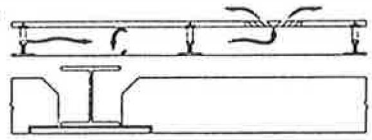


Figure 12: Heat transfer by means of mechanical air movement within raised floor

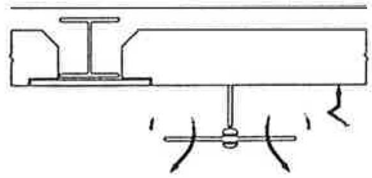
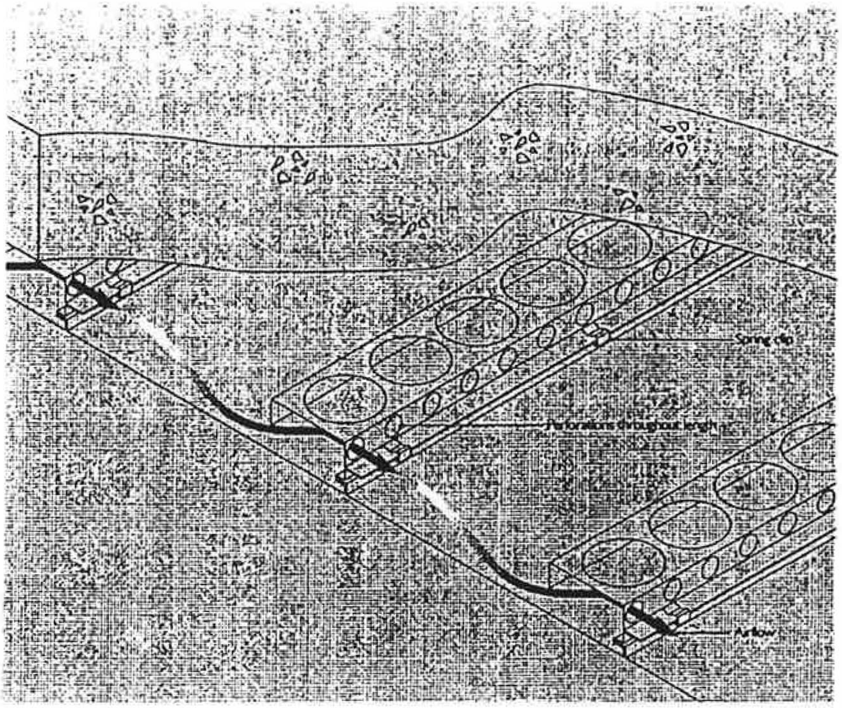


Figure 13: Heat transfer by means of space fan and exposed slab soffit

AIR CEILINGS

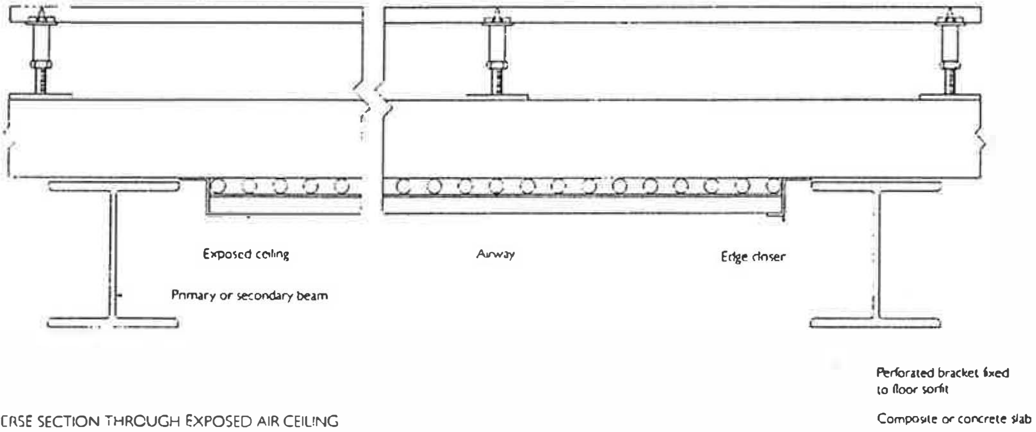
This approach uses profiled steel sheeting applied to the underside of a slab to form an air path between the sheeting and the slab. Key characteristics are:

- Cooling may be provided both by heat transfer through the ceiling panels and chilling of the supply air
- Partial modulation of output can be achieved by varying air flow rate
- Suitable for new and retrofit applications
- Shallow construction depth
- Ceiling is fully demountable for cleaning/maintenance



ISOMETRIC VIEW

DETAIL SECTION THROUGH EXPOSED CEILING



TRANSVERSE SECTION THROUGH EXPOSED AIR CEILING

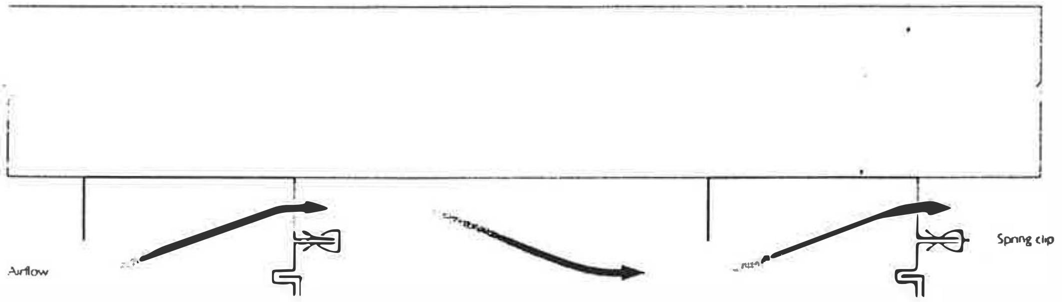


Figure 14: Extract from British Steel/SCI publication entitled ‘Environmental Floor Systems’ illustrating air ceilings

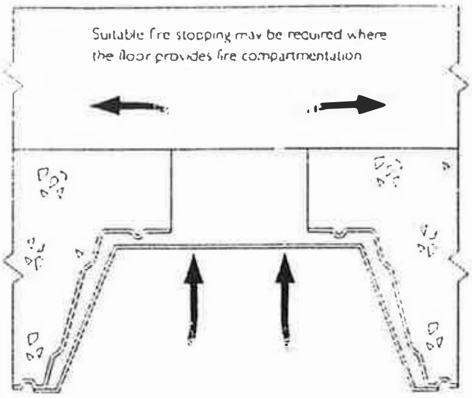
SLIMDEK®* AIR CORES

The approach uses a steel liner to form a narrow airway along ribs on the underside of slimdeck floor constuction.

Supply and extract air may be channelled through distribution ducts either beneath or below the floor slab. Ducts positioned above the floor slab are connected to the ribs by sleeves cast in the floor slab. Where compartmentation is required, supply and extract ducts may require fire protection specialist advice should be sought.

* Slimdek® is a registered trademark of British Steel and is covered by patent

- Supply and extract ducts may be contained within the raised floor void thus minimising high level ductwork.
- A single damper arrangement may control the supply route on each floor.
- The floor slab may be cooled during the night without cooling to internal spaces.
- High rates of heat transfer can be achieved between the slab and the air supply ribs in the Slimdeck profile increase air turbulence.
- Air path may be cleaned easily by removing steel liners.



SECTIONAL DETAIL OF PENETRATION INTO DUCT THROUGH SLIMDEK PROFILE

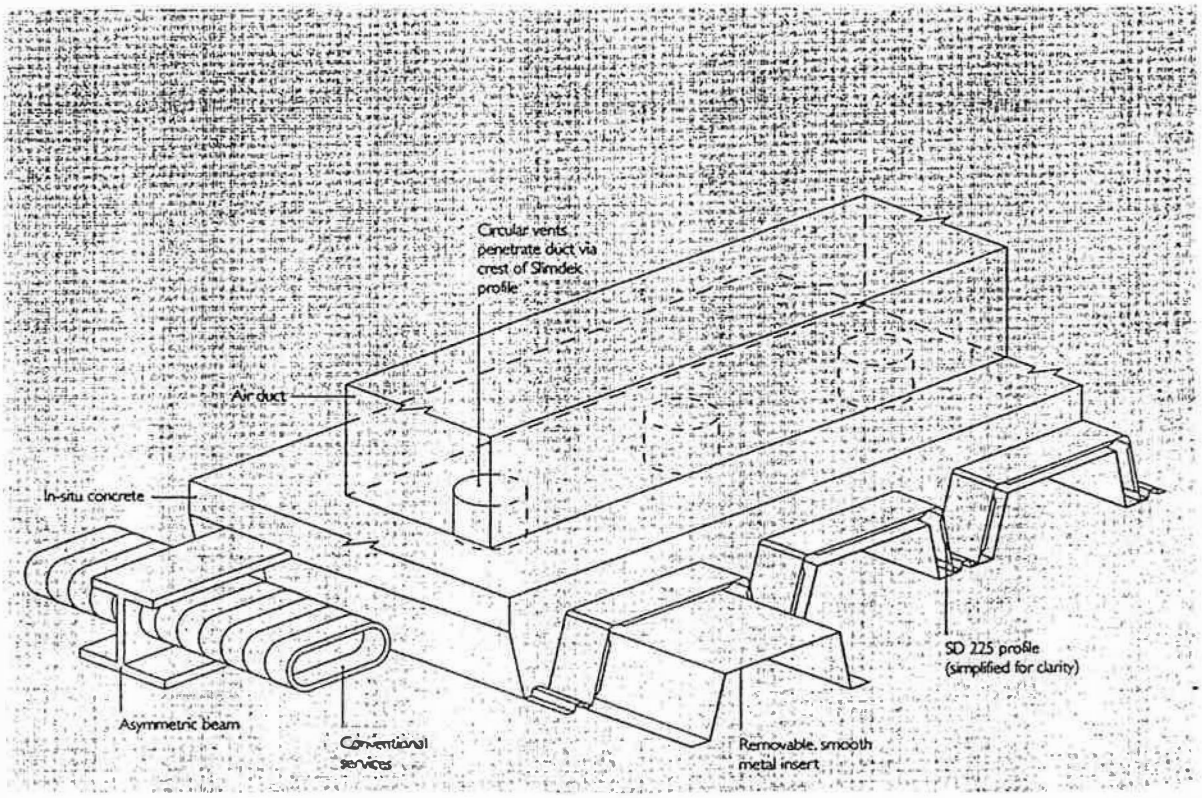
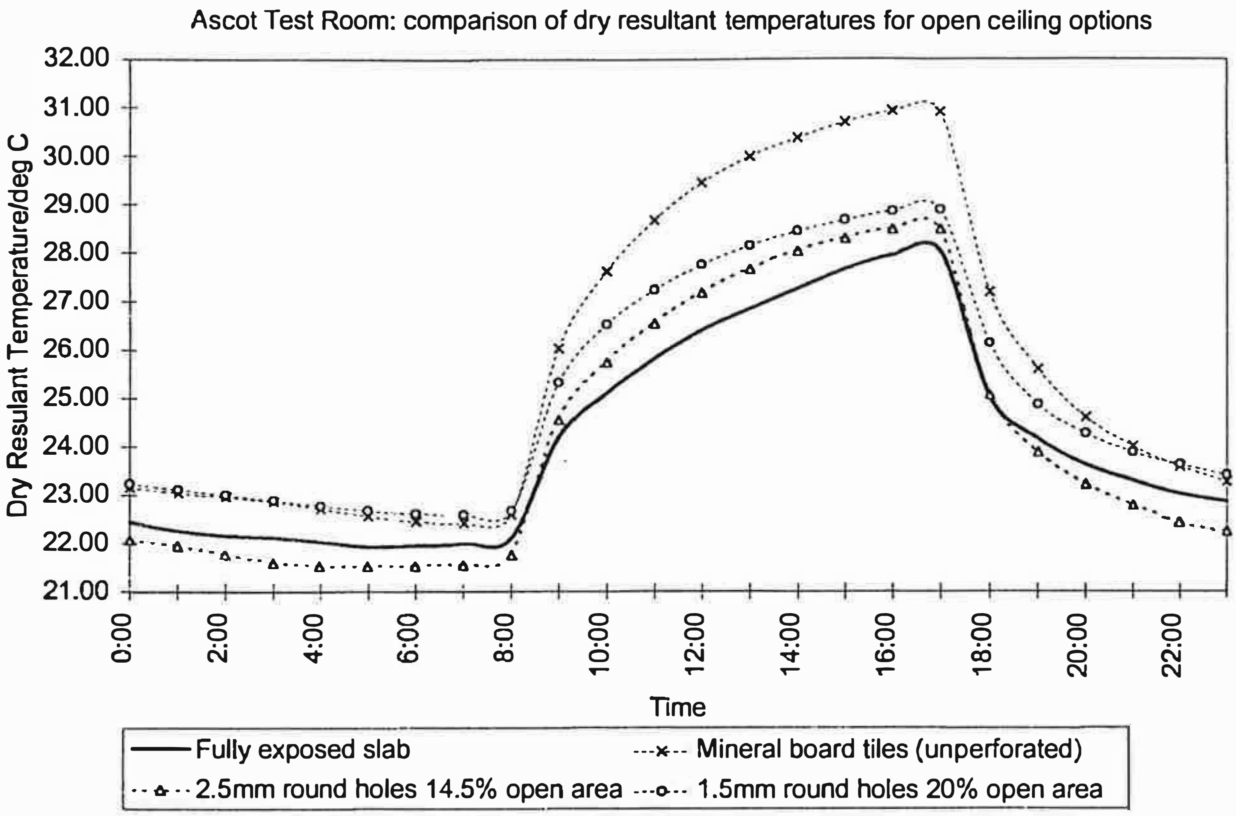


Figure 15: Extract from the forthcoming British Steel/SCI publication entitled 'Environmental Floor Systems' illustrating slimdek air cores


Ascot Test Room: comparison of dry resultant temperatures for open ceiling options
Dry Resulant Temperature/deg C
32.00
31.00
30.00
29.00
28.00
27.00
26.00
25.00
24.00
23.00
22.00
21.00
0:00
2:00
4:00
6:00
8:00
10:00
12:00
14:00
16:00
18:00
20:00
22:00
Time
Fully exposed slab
Mineral board tiles (unperforated)
2.5mm round holes 14.5% open area
1.5mm round holes 20% open area

8. REFERENCES

---

1. Connoughton, J., Life-cycle Energy Costing, Building Services, London, October 1990

1. Indicators of Sustainable Development for the United Kingdom, Department of the Environment, London, HMSO, March 1996

1. Protection of the Atmosphere and Agenda 21 Chapter 9, United Nations Conference on Environment & Development, June 1992

1. Supply and Demand in a Greenhouse Economy, Royal Institute of British Architects Energy & Environment Committee, May 1992

   Towards Sustainable Design, Royal Institute of British Architects Energy & Environment Committee, July 1995

1. Pout, C.H., Relating CO_2 Emissions to End Uses of Energy in the UK, Building Research Establishment, Watford, May 1994

1. Amato, A., A Comparative Environmental Life-cycle Assessment of Alternative Framing Systems for Offices, Oxford Brookes University, September 1996

1. Evans, B., Summer Cooling: Using Thermal Capacity, Architects Journal, 12 August 1992
   Bisler, A., Body Building, Building Services Magazine, 18 April 1993

1. Barnard, N., Dynamic Energy Storage in the Building Fabric, BSRIA, Bracknell, Berks, January 1995

1. Wilks, S., Recent experiences of monitoring night cooled buildings, Summary of presentations at the 'Current Activities in Night Cooling' seminar at the Building Research Establishment, 23 February 1995
   Kolokotroni, M., Research strategy for night cooling, Summary of presentations at the 'Current Activities in Night Cooling' seminar at the Building Research Establishment, 23 February 1995
   Tridal, A. et al, Developing a calculation method, Summary of presentations at the 'Current Activities in Night Cooling' seminar at the Building Research Establishment, 23 February 1995

1. Eaton, K.J. & Ogden, R., Thermal & Structural Mass, Architects Journal, 24 August 1995

1. Bruggema, H.M., Making use of the thermal inertia of the building using thermal open ceilings, Energy, Climate and Moisture in Buildings, CIB W67, Rotterdam, 1990