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Energy Effective Design of Commercial Building Envelopes in the Sub-tropical Climate

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Abstract

This paper reports the analysis of the thermal performance of building envelopes of high-rise commercial buildings in the subtropical climate and their interactions with cooling system. Building constructions of commercial buildings in Hong Kong have been investigated and categorized. Their thermal performance and the resulting chiller load is studied with the building energy simulation tool DOE-2.1D. The characteristics of sub-tropical climate, coupled to high internal gains of commercial buildings, are discussed. Accordingly, an approach of assessing the year-round envelope heat gains summed for all hours of net heat flow into the building is proposed. Parametric runs are conducted to study the effect of individual envelope features on the heat gain. Sensitivities of the envelope parameters are determined, and proper design of envelopes for energy effectiveness are discussed. The interaction of envelope designs on daylighting and cooling requirement is also investigated. It is concluded that the possible range of cooling energy requirement subjected to influence of envelope designs is substantial. Professional input in the design of building envelopes for energy effectiveness is needed.

Introduction

Commercial buildings in Hong Kong are numerous. They are high-rise, enclosed and air-conditioned throughout the year. Curtain walls are common, but their constructions vary from light-weight to massive, reflective to absorptive, insulated or non-insulated, single or double glazing, and vary in the glazing areas. These commercial buildings are subjected to cooling requirement throughout most of the year, and the electricity consumption for operation of the air conditioning system accounts for about 60% of their total consumption. The cooling load is particularly dependent on the construction of the building envelope and the weather conditions. Here, a Building (Energy Efficiency) Regulation dealing with envelope construction designs stipulating a limit on the overall thermal transfer value (OTTV) has been enacted since 1995. The OTTV is defined to describe the maximum thermal transfer permissible into the building through its wall or roof, due to solar heat gain and outdoor-indoor temperature difference. It was initiated (ASHRAE Standard 90-1975, 90A-1980, 90.1-1989) as a cooling criteria to limit the amount of heat gain through the building fabric, hence the energy consumption for cooling could be reduced. Other Southeast Asia countries (e.g. Singapore Building Control Regulations 1979, Malaysia 1989) have also similar OTTV requirement stipulated in their building control regulation, but they have tropical climate where the outdoor air temperature is high throughout the year.

Design of the envelopes will significantly affect the heat gains and the cooling load on the air conditioning system, and consequently determine the required cooling capacity to be installed and the year-round energy consumption. Their thermal performance is characterized with a hot summer, mild winter, and intermediate seasons during which the outdoor air temperature may be close to but lower than the indoor air temperature. These commercial buildings are also characterized with high internal heat gains. This will mean that there will be a net cooling load on the system even on cool days, during which, the heat loss through the envelope will reduce the cooling demand and energy consumption. Proper design of the envelopes should be an optimization of both limiting the heat gains in hot days and taking into account of the desirable heat loss through the envelopes in the cool days. The conflicting interest of using reflective glazing to reduce solar load and utilization of daylighting should also be rationalized.

Parametric Study of External Wall Construction

Construction characteristic of commercial buildings in Hong Kong were reviewed by studying the existing buildings. A total of 57 buildings were investigated. The findings showed that the external walls can be classified into 5 types based on the construction methods, designated type I to V as illustrated in Figure 1. Local offices are also graded as A, B or C (Rating and Valuation Department 1995). Grade A offices have high quality finishes and good management, Grade C offices have basic finishes and minimal management, and grade B offices are average. The five types are:

(a) Type I external wall construction is traditional, and is found in most grade C and some grade B buildings. It has mass commonly exceeding 300 kgm^{-2}, and is characterized with high wall U-value and tinted glass. It is also found in some grade A buildings for external walls embracing non air-conditioned service areas.

(b) Type II and III are medium to heavy-weight construction, having inner heavy-weight concrete layer with spandrel glass or granite panel facade, with or without a fibreglass insulation layer in between.

(c) Type IV and V are non load-bearing construction, characterized with light-weight, thick fibreglass insulation layer giving low U-value, highly reflective vision glass, attractive spandrel glass or sometimes aluminum wall panel facade, and an innermost layer of gypsum board.

Grade A buildings typically have external wall construction of type II, III, IV or V, which in effect are various forms of curtain wall. Single pane reflective glazing with very low shading coefficient are common, though occasionally double glazing may be used. These curtain walls differ in the construction weight and the spandrel facade.

Being of sub-tropical climate, there are intermediate seasons between summer and winter during which the outdoor air temperature is in the range of 18 - 25 °C. Even in the winter the weather is mild, so that cooling is still required in commercial buildings. At a particular hour, there can be conduction heat flow out of the building and solar radiation into the building. The algebraic sum of these components may be positive or negative, contributing to increase or off-set the overall cooling load, respectively. The thermal performance of an envelope construction can be indicated by the effective total heat gain obtained by summing the wall conduction gain, glass conduction gain and glass solar radiation gain for all hours with net envelope gain and normalized over the total exterior wall area, expressed in $kWhm^{-2}$. This term can be interpreted as an index for a particular form of envelope construction, telling the possible amount of heat gain per unit area of the exterior wall that constitute the cooling requirement throughout a year.

The thermal performance of various envelope constructions can be studied with the use of a hypothetical square shape high-rise office building with sides of 36 metres, having prescribed building operation characteristics given in Table 1. The internal heat gains are characterized with occupancy intensity of 7 m^2 floor area per person, lighting power intensity of 20 watts per m^2 floor area and equipment power intensity 12 watts per m^2 floor area. Outdoor air is provided at 7 l/s per person. Air conditioning is provided by a variable air volume system with cooling set point at 25.5 °C.

A base case having type II envelope construction is used as the basis for comparison. This base case building has single pane fenestration, window-to-wall ratio (WWR) = 0.5, shading coefficient (SC) = 0.45, opaque wall mass (M_w) = 312 kgm^{-2}, wall surface absorptance (α) = 0.58, and wall U-value (U_w) = 2.34 $Wm^{-2}K^{-1}$, which represents an average construction of local office buildings. The hour-by-hour heat conduction and solar radiation components through the building walls and windows, and the chiller load, are studied with the building energy simulation tool DOE-2.1D (LBL, 1981). The chiller load represents the energy extracted by the air conditioning system to offset the instantaneous cooling load resulting from external and internal heat gains, that passed onward as a load on the chiller plant. This chiller load is a cumulative amount for a year, and can be divided by the total treated floor area to give a normalized value. The calculated chiller load provides a reference only, as it is constrained by the prescribed specification of the air conditioning system and the building operation patterns. The actual load is expected to vary for different internal constructions and furniture, different building operation pattern and particularly different air conditioning system designs.

The effect of varying envelope parameters on the year-round heat gain from the envelope (Chow and Chan 1995) can be shown by parametric analysis, summarized in Figure 2. Among the parameters of envelope construction, the window-to-wall ratio and the glass shading coefficient have much larger impact on the envelope heat gains than the other parameters. The envelope heat gains can increase by more than four times as these two parameters are increased through their possible range. A point of interest is the thermal effect of double or triple glazing that has lower transmittance than single pane window. In contrary to the expectation of many architects and engineers that multiple glazing may help to cut energy consumption, the combined effect of local climate and high internal load characteristic of office buildings does not favour the use of double glazing for its low U-value. There will be an increase in the envelope heat gain summed for all hours of net gain, though minimal, for double glazing, as compared with single glazing of similar shading coefficient. Multiple glazing construction does not have thermal benefit by its low U-value, but may be advantageous for other design considerations, including noise attenuation and moisture condensation problem.

The opaque wall thermal mass has a counter-effect on the envelope heat gains and the chiller load. There is a significant reduction of heat gain of more than 10% when changing a light weight construction to heavy weight. However, this energy reduction credit is diminishing with increasing thermal mass, and there is virtually no extra benefit as the thermal mass is increased beyond 600 kgm^{-2}. An optimum wall construction may have thermal mass of about 300 kgm^{-2} by having a concrete layer of merely 100 mm thickness.

Changing the wall U-value from 0.5 to 3.79 $Wm^{-2}K^{-1}$ will bring about a reduction of envelope gain by 15.5%. The influence of the wall U-value on envelope gain has also a diminishing effect as its magnitude becomes smaller. Unlike many European countries that have cold climate and specification for wall U-value to be less than 0.45 $Wm^{-2}K^{-1}$, the local climate does not award low transmittance less than 1 $Wm^{-2}K^{-1}$. This suggests that if fiberglass is used as an insulating layer of the envelope, a thickness of 25 mm is adequate. Thicker insulation to bring the wall U-value below 1 $Wm^{-2}K^{-1}$ will not give extra energy credit. The absorptance of external wall surface has a proportional effect on cooling energy requirement, and its importance increases with the opaque portion of the envelope. As its magnitude is changed over its practical range from 0.2 to 0.88, there will be a reduction of envelope gain by 17.7%.

Sensitivity Analysis

Relative impact of various envelope features on the effective year-round heat gains can be compared by plotting graphs of the relative heat gains against the envelope parameters, as in Figure 2. However, they do not allow direct comparisons of the slopes in those figures because of the varying ranges and units of the abscissa. This difficulty can be avoided with the use of a sensitivity coefficient (O'Neill, et al 1991) obtained by normalizing the envelope parameter during the calculation of the slope. The change in value of an envelope parameter can be normalized by expressing it as a multiple (or fraction) of its nominal value in the base case. That is, for an envelope parameter i,

$$\text{Normalized value change} = \frac{\Delta P_i}{P_{i,n}}$$

Also, the change in the amount of heat gains resulting from the change in magnitude of an envelope parameter can be expressed as a fraction of the nominal envelope heat gain in the base case. Then, the impact of an envelope parameter on the envelope heat gain can be indicated by a sensitivity coefficient S_{Qt}, which is defined as the percentage change of the relative envelope gain per unit normalized value change of that parameter. For a parameter i, $S_{Qt,i}$ can be expressed as:

$$S_{Qt,i} = \frac{\left(\frac{\Delta Q_t}{Q_{tn}}\right)100}{\left(\frac{\Delta P_i}{P_{i,n}}\right)}$$

The sensitivities of the six envelope parameters on the heat gains are compared in Figure 3. The glass shading coefficient has the largest sensitivity coefficient, followed by the window-to-wall ratio, both are relatively much more significant than the other parameters. If that of the shading coefficient is taken to be unity, the sensitivity of the others relative to the shading coefficient, called the relative sensitivity, can be obtained, in descending order of significance: shading coefficient (1), window-to-wall ratio (0.83), wall surface absorptance (0.152), wall U-value (0.13), window U-value (-0.091), followed by the wall thermal mass (-0.07). The negative sign indicates that increase in its value will reduce the heat gain and chiller load.

In these sensitivity analyses, the range of magnitude of envelope parameters must be defined to duly reflect the realistic and full extend of values. With a combined change of two or more parameters, the effect on the heat gains and chiller load will even be larger, though individual effects should not be added algebraically to give the combined effect. The combined effect of high shading coefficient and small heat capacity of wall on the chiller load will be prominent, so is the combined effect of high shading coefficient and large window-to-wall ratio.

Range of Heat Gains and Chiller Load Influenced by Envelope Constructions

The ultimate purpose of controlling the overall thermal transfer value of building envelope is to reduce the cooling load, hence cutting down the chiller load and consequently the energy consumption. Heat gains through the building envelope account for about 31% of the building cooling load during the hot summer seasons for an average office building (Chow and Chan 1995). The magnitude of this envelope load varies in individual buildings, and can be substantially higher or lower, depending on the construction of the building skin and the thermal/physical properties of the constituent layers. Hence, control of the thermal performance of the envelope is important as part of the overall scheme for building energy effectiveness.

To reflect the extreme, but possible, amount of envelope gains and chiller load of a building, a prototype energy effective envelope construction and a prototype energy intensive envelope construction are established. Their monthly chiller load profiles, compared with the base case, is shown in Figure 4, and their relative performance in heat gains and chiller load is illustrated in Figure 5. The energy effective form is obtained by favourable combination of envelope features found among the surveyed buildings, with double glazing, WWR = 0.24, SC = 0.14, M_w = 689 kgm^{-2}, α = 0.3, and U_w = 1.07 Wm^{-2}K^{-1}. Here, double glazing is adopted not because of its low U-value, but because of the extremely low shading coefficient which is available in the market from double glazing reflective glass. Its resulting normalized envelope gain and chiller load are 14.41 and 163.9 kWhm^{-2}, respectively. The energy intensive form comprises unfavourable combination of observed envelope features, with single glazing, WWR = 0.79, SC = 0.8, M_w = 302.8 kgm^{-2}, α = 0.85, and U_w = 3.46 Wm^{-2}K^{-1}. For this poor prototype form, the year-round normalized envelope gain is 284.8 kWhm^{-2}, and the chiller load is 264.5 kWhm^{-2}.

Interaction of Envelope Designs on Daylighting and Cooling Requirement

Electric usage for lighting in local commercial complex has been found to be in the order of 30% of the total electricity consumption (Lau and Chan 1992). This will also impose load on the cooling system, meaning a further energy implication. The energy requirement for lighting and air conditioning is an inter-related issue, in particular if daylighting is taken into consideration. Greater window-to-wall ratio and shading coefficient of fenestration will certainly provide more natural lighting and reduce lighting power requirement, but it will also increase the heat gains through the building envelope. The energy impacts of daylighting in some geometrical regions have been reported (e.g. Sullivan et al. 1992), and suggested that the visible transmittance of the glazing and the orientation are critical. The impacts of daylighting and the interaction of envelope designs on illumination and cooling requirement under the sub-tropical climatic conditions as in Hong Kong are yet to be investigated.

An integrated envelope and lighting system together with lighting control strategies is established to investigate the energy impact of daylighting and envelope design. The base case office building, with construction and cooling system described above, is designed to have illuminance level of 500 lux (CIBSE 1994) and provided with movable interior drapes. Visible transmittance of glass is important for using daylighting to offset internal electric lighting load and associated cooling load. In this test the visible transmittance is 0.3 at normal incidence, and the interior shading device has a shading coefficient and visible transmittance multiplier of 0.6 and 0.35, respectively. Daylighting saving is investigated with perimeter zones of depth 4.6 metres, with photocell that controls the continuously dimmable electric lighting system respond to the light level at a reference point placed two-thirds of the zone depth from the window to maintain a lighting level of 500 lux. The shading device and the lighting control system will be deployed if direct solar gain transmitted through one square metre window area exceeds 95 watts or the glare index at the reference point exceeds 22 (CIBSE 1994).

Results of simulation with the base case building and the described lighting control system indicate that daylight can often provide illuminance of 500 lux at the perimeter zone without the use of installed electric light. In this prototype building the peak space cooling load normalized over the floor area is reduced by 8.3% from 51.2 Wm^{-2} to become 46.5 Wm^{-2}. This would enable the use of smaller installed cooling plant and fan capacity. The amount of lighting energy reduction by daylighting is 27% on an annual basis. Associated with this is a reduction of the annual chiller load by 7.7% from 204.1 $kWhm^{-2}$ to become 188.4 $kWhm^{-2}$ of air-conditioned floor area. As a result of the reduced electric lighting, reduced chiller load and smaller fan power consumption, the year-round energy saving is 12.6%.

The above finding supports that there is significant opportunity of energy saving through utilization of daylighting with deployment of shading device and appropriate lighting control system. However, the overall thermal transfer value (OTTV) of an envelope design, which is a legislative requirement under the building regulation to be lower than a prescribed limit, does not account for the effect of daylighting. This will discourage the use of skylight and state-of-the-art fenestration of enhanced visible transmission because that may boost the calculated OTTV. On one hand it is reasonable to exclude any interior shading in assessing the thermal performance of building envelope, as the interior shading device is not a fixed installation and is subjected to probability of not being deployed by the occupants. However, the promising energy saving from daylighting coupled with appropriate lighting control scheme suggests that a proportional relax in the OTTV can be granted for envelope designs that are beneficial to utilization of daylighting. For this, further investigation on the visible solar gain with relation to the integrated envelope and lighting design is needed, and the incremental electricity consumption with respect to the solar aperture $WWR \times SC$ and the effective aperture $WWR \times t_{vis}$ (Sullivan et al 1992) has to be analyzed for the local meteorological and building characteristics. Another window performance parameter, the luminous efficacy constant (t_{vis} / SC) that indicates the relative performance of window in rejecting solar heat while transmitting visible light (Shepard et al 1995), can be compared with the incremental energy use. This parameter will be complementary to the OTTV that, otherwise, can be made low by simply having highly reflective glazing with extremely small shading coefficient but blocking the visible light as well.

Conclusion

Different envelope constructions have substantial effect on the magnitude of the cooling energy requirement. The extent of influence has been illustrated by parametric analysis with the practical range of each parameter identified from existing buildings. The influence of individual envelope features on heat gain is weather dependent, making the design considerations for building envelopes under the sub-tropical climate to be different from that under the topical or cold climate.

Owing to the varying ranges and units of the envelope features, their relative impacts on the heat gains and chiller load for changes in magnitude cannot be compared on equal basis. This can be overcome with the use of a sensitivity coefficient obtained by normalizing the amount of change of the envelope parameters and their corresponding heat gains. The impact of an envelope parameter on the thermal performance of envelope, on a comparative basis, may than be indicated by an envelope gain sensitivity coefficient defined as the percentage change of the relative envelope gain per unit normalized value change of that parameter. It provides insight and guidelines to the building designers on the effective means to optimize the thermal performance of envelope constructions, and possible trade off among the parameters in gearing the designs to meet with any criteria on envelope heat transport and energy target.

There is good opportunity of energy saving through integrated envelope design and utilization of daylighting. Resulting from appropriate daylighting scheme design and proper implementation, the reduced electric lighting, reduced chiller load and smaller fan power consumption amount to 12.6% year-round energy saving of a typical office building.

From this analysis, it can be concluded that the range of thermal performance indices resulting from differences in the envelope construction is substantial. The year-round envelope gain resulting from the prototype energy intensive envelope is 16 times as high as the prototype effective form. Using the base case building as the baseline, the difference in the heat gains between the energy effective and energy intensive forms is

272%, and for the chiller load the difference is 51%. These indicate the possible range of cooling energy requirement subjected to influence by the envelope design under the local climate. It supports the need for professional input in the design of building envelopes for energy effectiveness.

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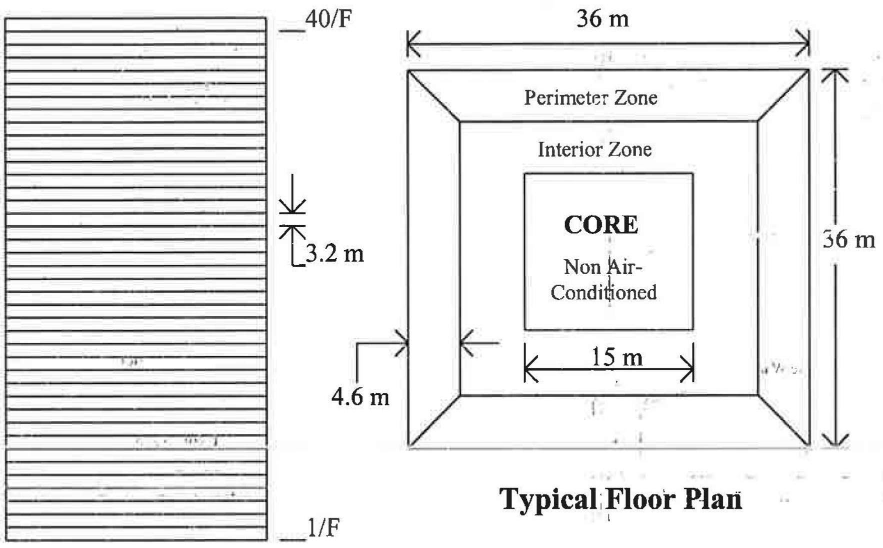
Table 1 Operating Schedule of Buildings



Typical Floor Plan

Days	Hours	Occupancy*	Lighting * (Perimeter)	Lighting* (Interior)	Fans
Weekday	1-7	0	0.05	0.05	Off
	8	0.05	0.1	0.1	Off
	9	0.4	0.5	0.5	On
	10	0.95	0.9	1	On
	11	0.95	0.9	1	On
	12	0.95	0.9	1	On
	13	0.95	0.9	1	On
	14	0.45	0.8	0.9	On
	15	0.95	0.9	1	On
	16	0.95	0.9	1	On
	17	0.95	0.9	1	On
	18	0.5	0.8	0.8	On
	19	0.25	0.5	0.5	On
	20	0.1	0.3	0.3	Off
	21	0.05	0.2	0.2	Off
	22-24	0	0.05	0.05	Off
Saturday	1-7	0	0.05	0.05	Off
	8	0.05	0.1	0.1	Off
	9	0.3	0.5	0.5	On
	10-13	0.6	0.75	0.8	On
	14-17	0.1	0.2	0.2	Off
	18	0.05	0.1	0.1	Off
	19-24	0	0.05	0.05	Off
Sunday	1-9	0	0.05	0.05	Off
	10-17	0.05	0.1	0.1	Off
	18-24	0	0.05	0.05	Off

* The decimal fractions denote percentage of maximum occupancy or lighting power.

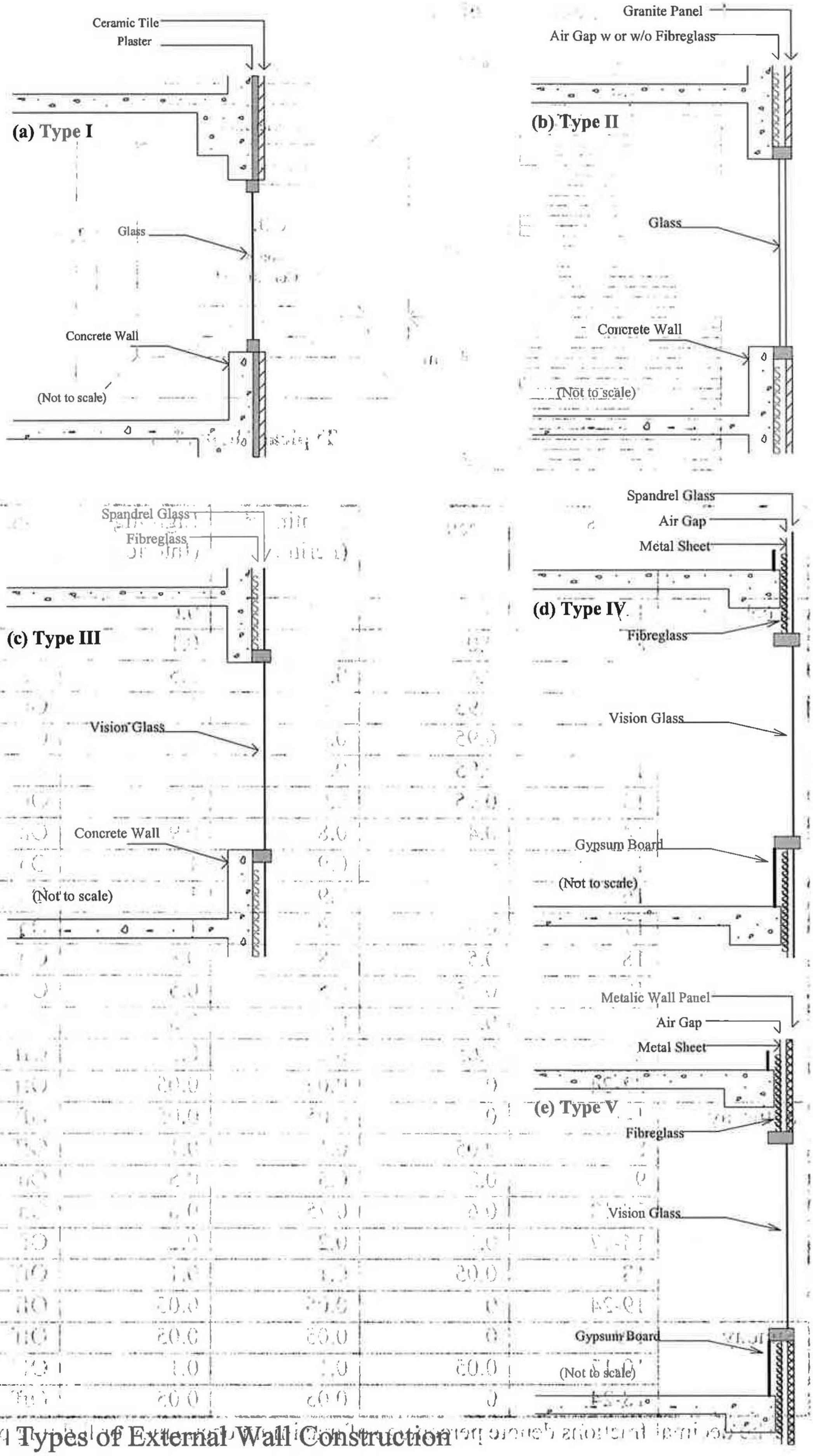


Fig. 11 Types of External Wall Construction

Fig. 2 Effect of Envelope Parameters on the Year-round Envelope Heat Gain (relative to the reference case)

Fig. 3 Parameter Sensitivities on Envelope Heat Gain

Fig. 4 Comparison of Chiller Load Between Energy Effective and Energy Intensive Envelopes

Fig. 5 Range of Envelope Heat Gain and Chiller Load Influenced by Envelope Constructions