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BUILDING DESIGN IN COLD CLIMATES

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Introduction

Buildings in cold climates must provide an indoor environment that is markedly different from that outdoors during most of the year and, in conjunction with the heating, ventilating and air-conditioning system, must maintain indoor conditions within relatively narrow limits. The exterior envelope of the building is thus subjected to large temperature and moisture differences and greater demands are made on the heating, ventilating and air-conditioning system.

Freezing conditions add another dimension, with cyclical freezing and thawing being the dominant influence in some cases and the existence and duration of below-freezing conditions the primary concern in others.

Cold climates are also hot: the solar energy falling on the outside of buildings in summer is almost as great as in areas much closer to the equator. Many occupancies require cooling in summer and solar radiation in winter further increases the thermal variation on and through the building envelope.

The greater demands placed on buildings in cold climates and the more extreme and variable conditions to which they are exposed have provided a series of accelerated tests on traditional designs and concepts. Evidence indicating imperfections or deficiencies in the design has been more obvious and remedial measures more urgent.

By way of illustration, the development of principles and practices for building design and construction in Canada will be reviewed with reference to links with other northern countries. Some suggestions as to how the principles might be applied in warmer climates will be ventured.

Wall Design and Construction

Thermal Insulation for Walls

The wood-frame wall, commonly used for residential construction in northern countries, offers a cavity in which some form of thermal insulation can be installed. Early building research work in Norway and Canada (1,2) focused on this feature. Loose-fill insulations made from waste materials such as sawdust and planer shavings or natural plant materials were installed by hand during construction.

In subsequent years, mineral-fiber and cellulose-fiber fill insulations were developed and pneumatic application techniques were employed to fill the wall cavities in existing residences. Pre-formed batt and blanket insulations of glass and mineral fibers or paper or plant materials, made to conform to the standard spacing of framing members, became more popular for new construction. Reflective insulations, consisting of one or more curtains of aluminimum foil, were also offered in prefabricated rolls for installation in standard stud spaces.

Air Space Convection

Problems of frost formation on the room-side surface of exterior walls with reflective insulation were experienced in houses in the prairie region of Canada in the 1950's. These houses had vented crawl space foundations and were heated with single oil- or coal-fired space heaters. The problem was not as severe or was non-existent in similar houses having mineral-fiber batt or blanket insulation. Field and laboratory studies demonstrated that air space convection and insulation fit created surface temperature gradients that could precipitate problems in colder climates (3,4).

Such "convective loops" can also reduce the overall thermal resistance of walls with other types of insulation (5), and became of concern with the subsequent use of lower density "friction fit" mineral-fiber insulations (6,7).

The significance of the fit and location of batt and blanket insulations on surface temperature and overall thermal resistance was also demonstrated by early studies on reflective insulation (5). Although surface condensation was usually avoided, large variations in surface temperature due to insulation fit, convection, and the low relative thermal resistance of the framing members led to undesirable dust marking. Re-examination of such features were undertaken with the subsequent introduction of metal studs (8) and are currently of interest with the increasing use of metal studs for exterior walls in commercial construction in Canada (9).

Vapour Diffusion and Condensation

The early batt and blanket insulations used in North America incorporated a paper backing that provided an integral "vapour barrier" to guard against the problem of condensation in walls due to vapour diffusion. This was based on the work of Rowley (10) and Teesdale (11) in the U.S.A. and Babbitt (12) in Canada who had applied the theory of gaseous diffusion to the movement of water vapour through the insulated envelope. Concern with the butt joints between batts led to requirements for an additional vapour barrier in colder regions in Canada.

The principle of controlling water vapour migration with low permeance materials on the warm side and higher permeance materials on the cold side of a wall became the basis for standards and design practices in most countries. In Canada and Norway the influence of air exfiltration was beginning to be appreciated as a more important mechanism in cold climates (13,14).

Air Leakage and Infiltration

Cases of excessive frost and ice accumulation in roof spaces in buildings in cold climates in which conventional vapour barriers had been installed confirmed the idea that air exfiltration and building stack effect were significant contributors (13,15). In cold climates, prolonged periods of below-freezing temperatures and greater rates of exfiltration due to stack effect increased the rate of accumulation and decreased the potential for moisture removal by sublimation.

Stack effect pressures in larger, multi-story buildings were first appreciated as the cause of excessive infiltration at lower floors. The approach of the HVAC designer was to pressurize the building in order to counteract these effects and the increased heating load was accepted or ignored. The resultant increase in air exfiltration did not result in condensation problems because the indoor relative humidity in commercial buildings in cold weather was very low.

Masonry Walls in Commercial Buildings

The potential for improved thermal comfort, energy conservation, and avoidance of surface condensation led to the consideration of thermal insulation for commercial and industrial buildings. The installation of batt-type insulation between wood strapping or the fixing of board-type insulation to the interior face was thought to be the most suitable method for solid masonry walls. For masonry cavity walls the space between wythes was regarded as a location.

The effects of thermal insulation in creating a different thermal and moisture environment between inside and outside components of a wall were discussed by Hutcheon in a paper in 1953 paper on wall design (16). Among the concerns at that time was the wetting of masonry walls by rain or melting snow and the subsequent freezing and deterioration. He suggested that the information and techniques developed in the soil science and materials science fields on moisture movement and freezing be applied to the situation in walls. Hutcheon developed a set of fundamental considerations for exterior wall design for cold climates that conceived of an exterior wall as a separator of two different environments, the performance of each element dependent on its location and environment in the assembly.

A wall design proposed by Johansson of Sweden in a 1946 paper (17) was recommended by Hutcheon as a practical model. Johansson had suggested, in translation,

> "However, it is clearly unwise to allow walls, whether of brick or porous cement, to be exposed to heavy rain. They absorb water like a blotting paper, and it would therefore be a great step forward if an outer, water-repelling screen could be fitted to brick walls, with satisfactory characteristics from the point of view of appearance, mechanical strength and cost.
>
> "This screen could be applied so that water vapour coming from within is automatically removed by ventilation of the space between wall and screen.

"If a rain screen of this type is used, the thermal resistance of the wall can be considerably increased for only a slight increase of expense, by employing one of the highly porous, thermally isolating materials now obtainable. With a highly porous layer between the actual wall and the rain screen, the house would retain its good characteristics with regards heat capacity, sound isolation and fire risk. At the same time it would be guaranteed free from moisture, even in the worst weather, and moreover be extraordinarily well isolated thermally."

On this basis, Hutcheon outlined a wall design consistent with Canadian practice, emphasizing the protection provided by the exterior insulation by stating:

"The main structural material is now maintained at conditions deviating little from those indoors, which will usually be determined by considerations of the comfort of occupants and therefore regulated within narrow limits. It is relieved of all but small temperature and moisture variations and gradients, and will not be subject to freezing action."

Hutcheon's paper provided the basis for most of the subsequent Canadian research into building envelope design and performance. The principles of wall design which he developed were later expanded (18) and applied in the development of window and roof design and construction.

Weathertight Joints for Walls

Another significant development toward improved envelope performance was the two-stage approach to the design of joints. The work of NBRI and that of the CIB Working Commission on Rain Penetration was reported by Birkeland at an International Symposium on Weathertight Joints for Walls in 1967 (19). In contrast to the then current North American practice of attempting to seal joints in the exterior cladding to prevent rain penetration, the two-stage approach concentrated on achieving a vented air space behind the cladding with a sealed joint inward of the air space. In Birkeland's terms:

"The rain and wind must be stopped separately. There must be an exterior rainscreen; behind the rainscreen there should be a vented airspace, ventilated so that there is no wind-pressure drop across the rainscreen. Behind the ventilated airspace there should be an airtight windstop, preventing air from penetrating into the insulation and through the wall.

"It is desirable that rain, which for any reason penetrates the exterior rainscreen, can flow out again through the air space.

"This principle is also valid for claddings; in this case, however, the differences in wind pressure along the surface of the building may be of importance; therefore it is advisable to divide the airspace behind the cladding by vertical windstops.

"It is comparatively easy to formulate the principle, but to design good practical walls according to the principle requires a knowledge of the influence of many details."

Practical Wall Details

The compatibility of the Norwegian two-stage approach with the exterior insulation plus rain-screen system had been recognized by Canadian researchers and incorporated into the set of principles initiated by Hutcheon (20). Considerable effort had been made to explain and promote these principles to the design professions and several papers at the CIB Symposium described major buildings that had been designed and built in Canada on the "open rain-screen principle" (19).

The CIB Symposium had also dealt with the performance of sealed double glazed windows, an envelope component that had received considerable attention in Canada.

Windows

Thermal Performance of Windows

It had been standard practice in many parts of Canada since the 1920's to use wood sash and removable exterior glazing panels or "storm windows" in winter. Frost buildup on the inner face of the storm panel was a common occurrence due to leakage of moist indoor air past the inner sash. Some frosting was also experienced at the bottom of the inner glazing but this was usually accepted unless melting and subsequent wetting of the sill resulted in deterioration of sill components.

Double "sashless" windows or units with metal sash as well as wood windows of the awning or casement type became popular in the 1960's for residential construction. Metal framed windows soon exhibited serious icing and "sashless" types showed evidence of higher rates of air leakage. The trend toward "picture windows" in house design and the use of curtain wall construction in commercial buildings led to the development and evaluation of sealed, double glazed window units in many countries.

Sealed Double Glazed Windows

Much attention was devoted to the edge seal design of hermetically sealed units and to the development of test methods to assess the durability of the seal (21). The wider range of temperature to which such windows were exposed in cold climates resulted in greater changes in pressure within the unit which, in turn, created a "rocking" action at the perimeter and additional stressing of the seal.

Water leakage from outside and condensation on the room-side surface increased the potential for water to accumulate at the sill and in the glazing rabbet. Subsequent deterioration of the seal coupled with the "pumping action" of the air space led to some spectacular failures, with the accumulated water drawn up into the sealed space to a considerable height, its level etched on the glass as a permanent record. Such observations showed the necessity of keeping the edge of the units dry and the two-stage approach was applied at the unit perimeter, venting the rabbet space through a protected opening to outside.

Window Sash and Glazing Design

Another major concern in cold climates was with condensation on the room-side surface and with the "cold edge" created by the metal spacer in sealed units. Their edge performance, in this respect, was inferior to the old non-sealed wood-framed windows. "Thermal breaks", developed for metal sash and curtain walls, were positioned after the manner proposed by Hutcheon for incorporating windows in externally insulated walls. The extension of indoor metal sills to increase the heat transfer to the window edge and the reduction in surface area of exterior sills to minimize their exposure was also recommended. The judicious use of thinner, more highly conducting glazing sealants on the room side and of thicker, more thermal resistant gaskets on the exterior was also proposed (22) as were arrangements using thermal insulation in exterior mullion and sill caps.

Thermal Breakage of Sealed Glazing Units

The introduction of heat absorbing and reflective glazing to reduce the summer cooling load in air-conditioned buildings contributed to another problem of window performance -- thermal breakage. The glass edge at the perimeter sealed glazing units tended to be at a lower temperature than the center portion. Under sunny conditions, the center portion was heated while the shaded edge or edges were not. With heat-absorbing glass as the outer pane, or with reflective surfaces within the unit, the temperature difference between the center portion and perimeter was increased further as were the tension stresses at the glass edge. Minute flaws at the glass edge allowed stress concentration and precipitated crack formation (23).

Similar concentrations of tensile stress could occur at the edge of the inner pane in cold weather when space heating units discharged warm air against the inner pane and "cold weather breakage" was experienced. This same effect may also result when interior "insulating drapes" are used during the night and opened in the morning to expose the glass to the warm, indoor air.

The approaches developed to improve the edge temperature of windows to avoid surface condensation were also beneficial to the reduction of glass breakage potential. Consideration of all these factors led to the development of a set of guidelines for the design of weathertight windows (24) and to the development of unique designs for special cases (25).

Roof Design and Construction

Roofs in Cold Climates

Cold climates are also characterized by snow and snow accumulation on roofs. Unlike rain that can be drained off, snow creates loads that vary with time, place, and building geometry. Snow accumulation is greatly affected by wind and wind direction and the aerodynamic characteristics of the building and its surroundings. Long-term records of snow depth on the ground modified by empirical relationships developed through observations on real and experimental buildings are used as a basis for predicting roof loads.

The accumulation of snow at sloping roof edges can initiate the formation of "ice dams" and icicles. Water from the melting of snow due to heat or warm air leakage from the building interior or from solar gain is intercepted and held by capillary action. On extended eaves the water may freeze immediately and that held by the snow will subsequently freeze at sub-zero temperatures. The ice layer in the snow may build up progressively until a dam is formed and melt water may back up under the overlapping shingles and leak into the house. The melt water, slowed down by the snow, will tend to form icicles that can subsequently create a hazard to people or objects below.

The use of waterproof membranes extending up from the roof edge under the tiles or shingles can prevent leakage problems and on low buildings sheet metal roof edges can inhibit the buildup of snow. For sloping roofs on higher buildings, fences have traditionally been used to hold the snow and ice in place or electrical heating cables utilized to prevent their accumulation. Both of these techniques are now being employed to deal with the more potentially serious problem with current architectural features such as atriums and glass roofs on high-rise buildings.

Ventilated Roofs

Sloped wood-frame or timber roofs with a space ventilated to outside are the most common type used in residential construction in Canada. In most instances light, factory-prefabricated wood trusses are used although some rafter and joist systems are employed with load-bearing interior partition walls. Soffit vents are almost universal, with additional vents in gable ends, on the roof slope, or along the top ridge.

Ventilation is provided to remove moisture that migrates through the ceiling by diffusion or air leakage. Sizing of the vent openings has been rather arbitrary, based on early work in the U.S.A. when vapour diffusion was thought to be the only mechanism. Larger vent openings are suggested for colder regions, but this fails to recognize the rapid decrease in rates of sublimation at low temperatures. In Canada, the effectiveness of venting has frequently been questioned, particularly when blowing snow conditions result in substantial snow entry, or when flat wood-frame roofs are used.

Flat Wood-Frame Roofs

For reasons of appearance, economy, and ease of insulating, flat wood-frame roofs became popular for low-rise housing in central Canada in the late 1960's and early 1970's. The principles of venting with outdoor air common to sloped wood-frame construction were applied but serious moisture problems occurred, particularly in electrically heated houses.

Air leakage through unintentional openings in the ceiling due to stack effect was identified as the primary factor (26). The lack of an operating chimney lowered the air leakage rate and tended to allow higher indoor humidities to be maintained. For the same reason, larger stack effect pressures upward across the ceiling increased the rate of movement of moist indoor air into the roof space. Dispersion of water vapour and rates of ventilation through the confined roof space were inadequate to handle the increased moisture load.

Similar problems had occurred in flat-roofed frame buildings in northern Canada (27) and consideration was given to the approach of closing the roof vents in winter to reduce the outward flow of moist indoor air through the roof space. Reducing or counteracting this outward flow using fans to exhaust air from the house or to supply outside air to the roof space were other measures considered (26,27). These experiences led to requirements by central housing authorities to seal openings at partition locations and other identifiable places in ceiling construction.

The role of an operating chimney and of house stack effect had been investigated by Wilson and Tamura (28) and the problems in flat wood-frame roofs led to a renewed interest in identifying the air leakage paths and patterns in contemporary construction (29). The influence of stack effect in combination with wind and fans on the air leakage patterns of low-rise buildings was also of interest in Sweden (30).

Built-up Roofing Membranes

Application of the principles of wall design advocated by Johansson and Hutcheon led to the development of the "protected membrane" roofing system whereby an insulation layer "protects" the membrane from solar radiation and temperature extremes (31). It has become a popular roofing system for cold climates, particularly for roof terraces where surface treatment acts to hold the insulation in place while performing other functions. The "double drained" roofing system, following the same principles, relies on a "protected" membrane as the primary membrane and allows the use of any type of roof insulation under a second, conventional roof covering (32).

Both the "protected membrane" and "double drained" roof systems offer an opportunity to make the waterproof membrane continuous with the wall vapour barrier at the wall to roof junction. This approach was promoted in Canada in a seminar series on construction details for airtightness in 1978 (9). Methods to improve the airtightness at other junctions in the envelope were also dealt with and suggestions solicited from the industry.

The Building Envelope

Commercial Construction

Although the principles of envelope design for cold climates have been recognized for over thirty years in Canada and efforts made to introduce and apply them to practice, problems continue to arise and remedial measures are costly and not always effective (33,34). Inadequate or inneffective communication between the designer and builder have been cited as one factor (35). Lack of understanding of the construction process by designers and lack of appreciation by the builder of the designer's objectives are often involved. Fortunately, the emphasis given to improving the airtightness of the envelope for energy conservation has helped to promote this singular, most important principle.

Wood-Frame Construction

Initiatives to promote the construction of low-energy houses have resulted in new techniques for building tighter wood-frame houses (36). Air leakage testing during construction and post-construction evaluation of larger, commercial buildings have resulted in re-evaluation of traditional details and the application of new materials and techniques to create tighter joints between components (37).

An apparent resurgence of moisture problems in wood-frame houses in Canada, evidenced by high indoor humidities, window condensation, mildew on interior walls and some cases of rotting of wood components was attributed to lower natural ventilation rates due to improved airtightness of the envelope (38). The most serious cases occurred in areas of the country with a climate characterized by wind-driven rain, high outdoor humidities, and relatively little sunshine. As a result, the implications of rain penetration and of moisture storage in walls are being reconsidered in regard to wood-frame wall construction and drainage provisions as used in commercial construction are being advocated (29,39).

The promotion and development of low-energy dwellings in Canada have resulted in marked improvements in the airtightness of the envelope and recognition of the need for mechanical ventilation systems to control air quality (40). The achievement of envelope airtightness has both prompted and permitted the integration of central air recirculation with ventilation supply and exhaust systems and heat recovery units.

Building Services

Freezing of HVAC Systems

Low outdoor temperatures require the use of anti-freeze solutions in solar heating applications and special features for heat pump refrigerant control. Defrosting requirements interfere with the operation of air-to-air heat pumps and exhaust air heat recovery devices.

In regions with long periods of sub-zero temperatures, condensation and freezing of water vapour effluent from plumbing vents and chimneys sometimes occurs. The use of larger diameter exhaust sections and the insulation of those portions extending outside or through unheated roof spaces usually prevents complete closure.

Condensation of moisture in exterior portions of masonry chimneys can lead to deterioration from chemical reaction and by freeze-thaw action, particularly with conversion to natural gas because of the lower temperature and high water vapour content of the flue gases. Such problems have led to the use of stainless steel liners and insulated chimney construction.

Stack Effect in Tall Buildings

The concern with stack effect as a contributor to condensation problems in cold climates increased with the growth of high-rise building construction. The early measures to reduce infiltration into lower floors of commercial buildings had to consider the much higher pressure differences created and the difficulties with the operation of doors and noise induced by air flow through openings. Of even greater concern was the recognition that the structural loads on walls and windows could exceed those due to wind and that the high sustained pressure differences resulted in substantially increased energy requirements due to air leakage.

Smoke Movement and Life Safety Concerns

Building stack effect in cold weather also became recognized as a significant factor in the movement of smoke and resulted in a major effort by building research and fire authorities in Canada to examine the problem of smoke control and life safety in high-rise buildings. Measures were developed for the guidance of regulatory officials and building designers and these have been incorporated into building codes (41) and design handbooks (42).

The research on smoke control focused attention on the air leakage characteristics and performance of building separations as well as the building envelope. The development of computer models to predict the movement of air and smoke required that measurements be undertaken in real buildings to establish flow coefficients for floor and shaft separations as well as for the exterior envelope (43,44). Initially, the installed air-handling equipment was utilized to measure envelope and shaft wall leakage, but large, transportable blowers were also used to evaluate the boundary characteristics of compartments and shafts.

The extreme variability between buildings and the critical influence of construction practices became apparent. The recognition of stack effect and the need for improved air tightness to control the movement of air through and in buildings was given added emphasis by the growing concern to conserve energy.

Air Movement in Buildings

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Air Movement in Buildings

The envelope of a building with no separations between floors and with leakage openings uniformly distributed with height experiences a pressure difference equal to one-half the total stack effect pressure acting inward across the ground floor in winter with an equal, outward pressure acting across the top floor envelope. If airtight floor separations could be achieved, the total stack effect would be divided equally between the floors and the pressure differences acting across the exterior envelope would be reduced to that for a one-story height.

Under such conditions, not only would the air exchange with outdoors be reduced but the movement of air and contaminants between floors would be prevented and the charges for energy more equitably divided. Air and smoke movement between floors would not constitute a problem, and the effect of openings through the envelope on one floor would not affect other floors.

Access to each floor would have to be provided by means of a stair or elevator shaft with tight fitting doors or vestibules. Compartmentation of multi-occupancy floors would have to be dealt with by similar means, but the advantages to be gained in the control of smoke, fire, air quality, and use of energy could be substantial.

Implications for Design

A building design approach that involves tight floor separations in high-rise buildings is incompatible with a central air handling system and separate systems for each floor level or for a group of floors would be necessary.

Separate systems on each floor or unitary systems for different occupancies on a single floor have a number of advantages. The problems involved in providing fire and smoke dampers are minimized, the balancing of systems should be simplified and the opening of windows or ducts to outside for ventilation would not be disrupted by stack effect.

Even small openings in floors, fire separations, partitions, and around interior doors are important from the standpoint of air quality control, smoke movement, fire resistance, and sound isolation in buildings for all climates. The airtightness of all such separating elements is fundamental to their satisfactory performance. Methods of measurement that were developed to obtain information on air leakage and air leakage paths through the envelopes of small buildings can been adapted to measure the leakage characteristics of partitions and floors during construction. These techniques also provide an opportunity to locate, characterize, and seal air leakage paths and openings.

Any and all efforts toward improving the airtightness of the assembled building components will be advantageous. Improved airtightness allows for better control of the air distribution in buildings, reduces uncontrolled air leakage due to wind and stack effect, and renders unnecessary the complex and inherently approximate calculations of infiltration and exfiltration.

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SUMMARY

G.O.P. Handegord: Building Design in Cold Climates. Buildings in cold climates must provide an indoor environment that is markedly different from that outdoors. The materials and components of the exterior envelope are subjected to large variations in conditions and greater demands are placed on the indoor environmental control system. Air pressure differences across building elements are augmented by buoyancy forces that influence air movement and indoor air quality. The potential for moisture condensation on and within the envelope is increased as is the danger of freezing in liquid systems. The influence of these factors on the design and construction of buildings for cold climates is discussed and consideration given to applications in other regions.

RESUME

G.O.P. Handegord: Conception des bâtiments pour les régions froides. Dans les régions froides l'intérieur des bâtiments doit assurer un environnement qui fait contraste avec le climat extérieur. Les matériaux et les composants des parois extérieures sont soumis à des variations considérables de conditions atmosphériques. Les systèmes de réglage de climatisation doivent satisfaire des demandes exigeantes. Les différences de pression atmosphériques entre l'extérieur et l'intérieur sont augmentées par les forces de poussée qui ont un effet considérable sur l'écoulement et la qualité de l'air intérieur. Le danger de condensation à la surface et à l'intérieur des parois extérieures d'accroit, ainsi que le danger du gel des conduits. L'auteur discute des effets qui influencent la conception et la construction des bâtiments pour les régions froides et de certaines applications pour d'autres régions.

ZUSAMMENFASSUNG

G.O.P. Handegord: Bauprinzipien für kalte Regionen. Für kalte Regionen müssen Gebäude ein Innenklima gewährleisten, das vom Aussenklima stark abweicht. Baumaterialien und Bestandteile der Gebäudehülle sind starken Bedingungsschwankungen ausgesetzt, und auch die Ansprüche an die Klimatisierungssysteme sind entsprechend erhöht. Die auf die Gebäudehülle wirkenden Luftdruckunterschiede werden durch Auftriebskräfte vergrössert, welche auch den Luftaustausch und die Luftqualität beeinflussen. Die Gefahr von Kondensation, an und in der Gebäudehülle, und des Einfrierens von Leitungen ist verschärft. Der Einfluss dieser Faktoren auf den Entwurf und die Ausführung von Bauten für kalte Klimata wird beschrieben, wobei andere Klimaverhältnisse auch berücksichtigt werden.