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DESIGN OF LARGE BUILDINGS FOR SAFETY AND HEALTH

BY

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DESIGN OF LARGE BUILDINGS FOR SAFETY AND HEALTH

Large and complex building arrangements, which are appearing in ever-increasing number, are not well handled by traditional approaches to public safety, particularly with respect to fire. In this review of design in relation to safety, the special problems of fire are emphasized, and developments leading to more rational regulations and design concepts are anticipated.

CONCEPTION DE GRANDS BATIMENTS EN PREVISION DE LA SECURITE ET DE LA SANTE

Les approches classiques de la sécurité publique, particulièrement celles qui concernent le feu, ne répondent pas très bien aux agencements de grands bâtiments complexes qui apparaissent en nombre de plus en plus croissant. Dans la présente revue de la conception au regard de la sécurité, nous soulignons les problèmes spéciaux du feu, et nous anticipons des progrès de réglementations et de concepts plus rationnels.

Design of Large Buildings for Safety and Health

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This paper deals with *safety* considerations in the design of *large* buildings in the future. This implies some attempt on my part to make forecasts about the nature of large buildings. Forecasting is a difficult task, if one is concerned about accuracy. Fortunately it is sufficient to make only general predictions in order to deal with the subject of the future needs and directions for the design of buildings for safety.

The building industry has been characterized by a slow but steady introduction of change so that a revolution in the technological nature of buildings in the next 10 to 20 years would hardly be anticipated. Changes in the design professions and the design process, and in the regulation of safety, are likely to be equally important considerations. One can anticipate an increase in factory fabrication of major building components, the continuing refinement of mechanical and other services providing amenity for the user, and the introduction of new materials and composites, particularly those employing plastics, in competition with more traditional elements.

Increasing urban populations, higher costs of land and services, more complex and interrelated activities, and the preference of inhabitants for convenience and comfort in leisure hours will no doubt lead to an increased number of large and complex enclosure arrangements. These are already in evidence: high buildings, both for commercial and residential purposes, up to 60 storeys in height; large shopping complexes with enclosed malls, some with over 25 acres under one roof; and complex interconnections between a variety of buildings serving various activities such as offices, shops, restaurants, residences and transportation terminals.

There will be an increasing demand to create buildings with large, unencumbered spaces which can be manipulated for a succession of alternate arrangements and activities; and for special purpose space frames and air-supported or other tent-like structures for the enclosure of sports and other public events, or for factory, commercial and construction operations where low, first cost is important. It is difficult, however, to take seriously at this point the schemes sometimes put forward for the covering of entire towns and cities, which though highly imaginative, generally disregard or fail to provide solutions for a number of serious technological, social, and economic problems that they present.

These large and complex arrangements of buildings and activities, along with new materials and systems, will present, indeed are already presenting, problems not well handled by traditional approaches to certain aspects of safety. In addition, the trend toward increasing concern for user or consumer standards may be reflected in increasing regulation or control over other aspects of buildings associated with durability, habitability, or the well-being of occupants. These trends will inevitably affect the responsibilities of the design professions, as well as others involved in ensuring the safety and adequacy of buildings.

National Building Code

Minimum requirements for safety and public health in buildings are matters which are dealt with in law by building codes and other safety regulations. They are intended to ensure that a building and the activities associated with it do not present an undue hazard to occupants, or to neighbouring buildings. Traditionally, they are concerned with hazards of structural collapse, fire and spread of disease, the latter primarily in terms of the safe handling of water supply, sewage and waste disposal within buildings. These regulations have been extended, in some instances, to include certain habitability requirements, notably provision for ventilation, heating, lighting and sound separation between occupancies.

In Canada, provincial governments hold control over most safety matters and legislate directly for safety in the distribution and use of electricity, gas and oil, and other specialized items such as boilers, pressure vessels and elevators. In most other safety matters, the provinces have allowed their municipalities to pass by-laws for the regulation of building in the public interest. This approach while advantageous in permitting the ready resolution of local problems at the local level, leads to large numbers of quite arbitrary differences in the content and sophistication of building safety requirements throughout the 4,000 municipalities in Canada. In this context, the development of the National Building Code of Canada is of special significance and it is appropriate to make brief reference to it.

The idea of a model building code to promote rationalization and greater uniformity of building by-laws was developed about 35 years ago when the Government of Canada introduced the first National Housing Act. The first National Building Code was issued in 1941. The second edition completed in 1953 was prepared by an Associate Committee of the National Research Council with the assistance of the newly established Division of Building Research. Subsequently, there have been new editions in 1960, 1965 and 1970, prepared under the same auspices.

During this period, an increased number of municipalities have adopted or made reference to it in their building by-laws. Today, about 80% of the population in Canada

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live in municipalities that have adopted the National Building Code in whole or in part. In addition, it is employed by Federal Government agencies such as Central Mortgage and Housing Corporation and the Department of Public Works.

Further developments toward uniform building regulations are now taking place with several provinces about to take, or having taken, steps to adopt a provincial building code. Uniform regulations for the whole country will only be achieved, however, if all provinces agree to adopt the same code with a minimum of change, the NBC being the obvious choice.

Uniformity of building regulations, while a major step forward, does not ensure uniform or rational regulation of building. Uniform interpretation, administration and enforcement is also involved if practical uniformity is to be achieved. Furthermore, codes and the many standards to which they refer are far from perfect. They have developed, over the years, in response to problems as they arose — in response to serious deficiencies that have occurred in practice, most often evidenced in the form of a disaster. In a sense, they have originated as a series of emergency measures developed in the context of the tradition of building of the time, measures that have subsequently become a part of the tradition of building safety requirements.

One of the principal difficulties of tradition based regulations, arising largely from historic knowledge, is that they do not readily provide for alternative approaches to the provision of safety — nor are they readily applicable to new situations, new building forms, new building uses and activities, new materials and components. There is no assurance that they provide an appropriate level of safety, even in the context from which they were developed.

How Much Risk?

In rational terms, safety involves reducing the risk of a hazard to an acceptable level of probability. Usually it is not practicable to adopt measures that eliminate all risk. In principle, the degree of protection should depend on the consequences of the hazard relative to the cost of the measures to avoid it.

With life safety, it is, in principle, the responsibility of society to determine an acceptable level of risk. These decisions are not made explicitly but depend on the net effect of the pressures exerted by different elements of society. The job of those responsible for the preparation of building codes is to attempt to develop requirements in technical terms that will provide this vaguely defined level of safety.

In general, basic or scientific knowledge of the various factors that determine safety levels, and their interrelations, has not progressed to the point where these can be predicted in rigorous numerical terms. It is a difficult problem to envisage all the combinations of factors that may lead to failure and to assign probabilities to their simultaneous occurrence. Current average levels of safety can be measured in terms of the frequency with which hazardous events actually occur. Table I[1] gives a comparison of the risk of death for various activities. It is interesting to note that a much higher risk exists in the case of automobile accidents than for building failures; and that in the case of buildings, the risk of death due to fire is two orders higher than that due to structural collapse.

Prediction of safety levels from past experience presents some serious limitations. If society will accept only a remote possibility of a failure, many years may be required to produce a statistically significant record of events for analysis. If innovation and change is to be permitted, the factors that gave rise to past events may no longer be in existence and new factors may exist. Thus accumulated experience may be invalid, or at least inadequate as a basis for establishing probabilities of failures of current buildings, not to mention those to be erected in the future.

It is thus clear that codes, of themselves, cannot guarantee a consistent level of safety so long as change is to be permitted. The possibilities of hazards in new designs, arrangements and uses of buildings, and appropriate means of coping with these hazards, can only be identified by the trained mind exercising judgement and predicting performance through knowledge. In practice, the building official often exercises the power to interpret and pass judgement on situations affecting safety. It is unreasonable, however, to expect him to have all the knowledge necessary to deal adequately with all the problems presented by a range of new complex situations. If these matters are left entirely to his judgment, he may be criticised for hindering new development or for failing to protect the public.

The solution, in principle, is to define safety objectives as clearly as possible; and to develop sufficient knowledge

Table 1. Risk of Death for various activities.

Activity or Danger	Deaths per Million People per Hour of Exposure	Hours of Exposure per year for a "Typical" Individual	Risk Per Year Per Cent
Automobile Travel (International Figures)	1.04	340	0.036
Swimming	3.50	20	0.007
Cigarette Smoking	2.60	200	0.052
Building Fires			0.003
Structural Collapse			
(1) Construction workers (Ontario)			0.003
(2) All others (Canada)			0.00002
Total			
(1) For smoking construction worker			0.101
(2) For non-smoking office worker			0.046

so that competent practising professionals can make acceptable judgments on the adequacy of a proposed solution with which extensive experience is lacking. There has been a gradual evolution from descriptive to performance statements in codes as knowledge and a corresponding profession for its application have developed. In this and other respects the National Building Code of Canada can be regarded as one of the most progressive in the world.

Structural Safety

This evolution is well advanced in the structural field where assurance for safety, including the establishment of design standards, is essentially in the hands of structural design engineers. Design concepts, including safety factors, have evolved from a knowledge of loads, material strengths, and behaviour of structural elements and systems. In the past, rather simple rules were justified since low stresses and arbitrary rules governing heights, thicknesses, and spans generally resulted in conservative design. The actual safety, however, was not uniform.

In the past two decades, considerable advance has been made in knowledge of loads to which buildings are subjected, particularly those imposed by nature. Corresponding advances in structural analysis and materials have resulted in more sophisticated and less conservative designs. One notable trend has been the tendency toward lighter and taller buildings with, for example, a significant reduction in the weight per square foot of structural steel. This has increased the need for a better understanding of the dynamic characteristics of such buildings to predict their response to dynamic forces such as wind and earthquakes.

Advances in technology have permitted a more accurate prediction of the ultimate strength of most structures. Such advances lose their value, however, as long as safety rules remain oversimplified. Furthermore, although traditional safety factors and design procedures may be satisfactory with traditional construction on which design procedures are based, they cannot always be extrapolated with assurance to cover new types of materials and construction. An example is the failure due to progressive collapse of the apartment at Ronan Point in England, constructed of factory built, load bearing panels, which failed to incorporate sufficient structural redundancy or continuity even though built according to the existing code.

What is needed is a safety concept which recognizes directly the inherent variability of material strengths, loads and workmanship, the probability of occurrence of load combinations, and the consequences of failure. Current codes for steel and concrete have, or are in the process of, rationalizing these factors in their safety requirements, and a study group of the ACNBC is attempting to develop safety rules that are consistent for all structures, regardless of material.

A fully satisfactory and soundly based set of safety rules, is however, still in the research phase. Many researchers and technical societies are engaged in these studies which will undoubtedly be in the centre of the most important structural developments in the next decade or so. A number of difficult questions make progress slow. These include:

a) inadequate statistical information on the variability of those materials and loads;
b) uncertainty regarding how to handle factors that cannot be handled statistically, for example, gross errors, accidents and consequences of failure;
c) definition of the acceptable level of risk, particularly in relation to human safety;
d) the translation of a theoretically complex safety concept into workable rules for everyday design.

While structural design is already at a relatively sophisticated level of development and the incidence of failures, and particularly the resultant loss of life, is very low, economic design, new ways of building and full utilization of new materials will be hampered without further advancement in structural design theory and practice.

Standards for Health

Current practices in the design of buildings generally provide conditions above the level at which there is risk of any serious health problem. The design of sewage and water supply systems is highly regulated in codes, and is intended to ensure that supply and waste are positively separated, and that there is a positive seal between the building and the sewage drainage system.

The details of the waste piping and fixtures depend heavily on tradition. Lack of a design procedure based on a knowledge of the flow phenomena and of detailed performance requirements for the system and components has placed some limitations on innovation and optimum design. Technology is evolving, however, and an increased engineering component in plumbing design can be anticipated. Improved design from the standpoint of the number of fixtures required for different occupancies will require better definition, through study, of the way in which buildings are actually used.

With the increasing concern for conservation of water resources and for reduction in costs of water treatment and distribution, and sewage collection and treatment, it can be anticipated that, in some locations at least, regulations will require fixtures that employ less water. Thinking in this general direction has already reached the point where, even in Canada with our general abundance of water, studies are underway on the development of a self-contained waste water renovation system suitable for use in large apartment buildings. The objective would be to eliminate the need for connection to any exterior sewage disposal system and to require only a relatively small amount of make-up water. It appears that such systems could be economically competitive with central municipal systems under certain conditions in the future. Assuming the technological problems of developing an economical, fail-safe system can be solved, there remains a psychological problem to overcome. It seems probable, however, that such systems will be used in special situations within the next decade. Their widespread use will ultimately depend on economic considerations.

Air quality is usually regulated in building codes by specifying a minimum amount of openable window area, or, alternatively, minimum rates of fresh air supply, and exhaust from spaces that may be a source of objectionable contaminants. The adequacy of building ventilation, as well as heating and air-conditioning, is dependent upon the heating, ventilating and air-conditioning engineering profession supported by a relatively sophisticated and continually developing technology. Normal practice provides air conditions in buildings that exceed those required for health in the limited sense, measured in terms of comfort or well being.

However, air conditions provided in many buildings are far from perfect. The limitations are not due generally to a lack of knowledge but to "cutting corners" in design for economic reasons. The profession is concerned about adequate design and has carried out much research on system performance and human comfort. Considerable emphasis is now being placed on design standards, which ultimately will be reflected in more rigorous specifications, if not in regulations.

A somewhat similar situation exists in respect to lighting and acoustics. While building design specialists have not developed to the same extent in these areas, there is a steadily increasing store of scientific knowledge on which to base design. Practice in North America has been in the direction of ever-increasing levels of artificial lighting probably to the point of diminishing returns in some instances if all implications are considered. Much lower levels of lighting are regarded as acceptable in most European countries.

While recommended practices for illumination have been developed by the profession in North America, similar standards have not been published for acoustical design of buildings. There will no doubt be increased regulation of these aspects of building environment in the future. In the case of lighting, the pressure will come from the need to conserve energy. In acoustics, it will come as a result of increasing levels of exterior noise and the demand for more acoustical privacy.

Fire Safety

A very large part of building codes is devoted to regulations related to fire safety. The situation in respect to design for fire safety is quite different from that for structural safety. There does not exist either a comparable background of research and codified knowledge, or a large and qualified body of specialist consultants. This is partly because the provision of fire safety is an extremely complex matter involving a number of separate but related elements all contributing toward the final result. These include: prevention; detection and alarm; movement of occupants to safe regions; control of rate of development and severity of fire; confinement or compartmentation, that is, limiting the size of building space involved in a fire and preventing its spread to adjacent buildings; structural fire protection, that is, ensuring that the structural system continues to support the building during a fire; emergency operation of building services; and extinguishment. Others could be added to the list and each represents a complex subject.

Traditionally, once alerted, responsibility for action to be taken on the scene of a fire rests with the fire services, as does responsibility for ensuring that certain fire prevention and safety practices are followed. Fire protection engineering has not yet developed as a broad, science-based discipline and design for fire safety is highly regulated through building codes, fire safety standards and enforcement officials. It is left to the architect to see to it that the design of the building complies with the applicable regulations. Usually no special drawings are prepared identifying the fire safety elements of the building and heavy reliance is placed on the enforcement official.

Some basic concepts have evolved, however, and there is a gradually growing body of fire technology. This has been greatly aided by the development, mainly in the last two decades, of a few science-based research laboratories dedicated to a better understanding of the nature of building fires and the relevant properties of buildings and their components. For example, considerable progress has been made toward the development of knowledge required for an engineering approach to structural fire protection.

It would appear practicable, within the next decade, that this competence could be included within the structural engineering discipline. It will require the acquisition of additional knowledge involving heat transfer, the relevant properties of structural materials at elevated temperature, and fire severity. Codes could then refer to acceptable methods of design instead of describing acceptable arrangements or requiring individual tests in all cases. It appears anomalous that structural engineers are currently responsible for the adequacy of the structural design under all conditions except when exposed to fire.

During the last few years, there has been a significant increase in the number of high buildings erected in Canada and this trend can be expected to continue. A high office building might accommodate up to 15,000 people, and a high apartment up to 2,000. Such buildings introduce problems of fire safety that are very different in degree and type from those encountered in more traditional buildings. Probabilities of fire incidents are obviously increased with increases in building population and activities, and a fire may involve all the occupants in some degree of danger. Certain relatively recent developments in such buildings have tended to increase the severity of the fire problem; for example, central air-handling systems, large open floor office arrangements, combustible wall, ceiling and floor coverings, and increased use of combustible organic materials for construction, services and furnishings.

The major cause for concern with increasing height is that the time required for evacuation increases in proportion to the number of storeys and can be much greater than the time required for the development of untenable smoke conditions in stairwells, floors and other points far removed from the fire. Recent studies by the Division of Building Research of controlled evacuations of high buildings indicate an evacuation time of about 14 minutes for a 20-storey building with a relatively dense office population. For the same population density the time increases in proportion to the number of floors, i.e., the time for a 40-storey building would be 28 minutes. The National Building Code allows population densities of up to 60 persons per floor per 22-inch exit width of emergency stairs, about three times greater than those for which these measured times are applicable, so that, hypothetically, evacuation times could be three times greater. It is quite clear that with such buildings as presently designed, occupants will be in them for substantial periods after the outbreak of fire, perhaps for the duration.

Coping with Smoke

Experience has shown that the principal hazard to the majority of occupants of a high building in the event of fire is smoke rather than fire. While the building may be well designed to resist the spread of fire, research has shown that buildings as normally constructed are quite leaky and that air, and thus smoke, can move readily throughout them.

Several mechanisms can be involved, but one of special importance in Canadian climates is building stack effect in winter which causes air and thus smoke to flow from low to high levels in a building, mainly through the vertical shafts. There have been several recent incidents, the loss of life fortunately having been small. Calculations by computer have shown that, for a representative case, once fire has developed on a lower floor, tolerable smoke concentrations can be exceeded throughout elevator shafts and lower parts of stairwells after only five minutes. After fifteen minutes, the stairwells can be smoke-logged to mid-height and above this most of the floors can be smoke-filled. This not only presents a situation extremely hazardous to occupants, but one which can greatly inhibit the fire service from effectively fulfilling its responsibilities.

There is now much concern about adequate requirements for life safety in high buildings and new building regulations are being framed in Canada and elsewhere. These invariably involve some means of dealing with the hazard of smoke. Techniques relying on the control of smoke movement or smoke concentration involve manipulation of air volumes and building pressures in a critical way, through both natural and mechanical means. These are safety requirements that require a high level of technical competence and sophistication in design. They cannot, therefore, be handled well on a descriptive basis in building by-laws.

Some design concepts are evolving but additional basic knowledge is required on such matters as the air leakage characteristics of building enclosures and internal separations; on the quantities and nature of smoke and gas generated in fires; on the mixing process of smoke and unpolluted air entering vertical shafts, and on methods of coping with fires originating in vertical shafts containing combustible piping and conduit. The required knowledge and science-based design methods must eventually become part of the competence of those responsible for the physical aspects of the building environment. The heating and air-conditioning engineer must accept some responsibility for developing and codifying adequate design procedures. Steps have begun in this direction and real progress can be anticipated in the next decade.

Complex Large Buildings

Large buildings with new components, arrangements of space and activity thus present fire-hazard situations which are not necessarily envisaged in building code requirements and with which the building designer is currently not well equipped to cope. Knowledge is inadequate and fundamental approaches to design are only in the development stages.

Enclosed mall shopping complexes represent another example. The merchandising concept requires open unrestricted interior space permitting random circulation and maximum visual access to the various parts. The fronts of stores provide little fire resistance and, in fact, may be eliminated. The enclosed mall presents a situation quite different from that of the unrestricted open space above an ordinary street from the standpoint of both dispersal of smoke and gas and the behaviour of flame issuing from the front of a shop. While the wall between shops may provide adequate fire resistance, there is little to prevent communication of flame from store front to store front. The circulation of smoke is likewise uninhibited. Safe egress of occupants and access for fire fighting present special difficulties.

New designs and arrangements of activities not only require new concepts and methods of fire and smoke detection, of control, and of fire fighting, but new concepts and procedures for the management of people in an emergency. A body of knowledge is required on the detailed nature of activities in buildings, and on the factors influencing the behaviour of occupants under emergency conditions, including space and egress relationships. For example, in the case of a fire in a large enclosed mall complex will people rush forward to view the fire, as they might in an open street, or will they attempt to flee the mall? This type of information is needed not only to deal with new situations in buildings but to rationalize requirements and restrictions in present codes based on occupancy classifications and building heights and areas. Such "user" studies and their implications for design should be of special concern to the architect.

These examples of fire-safety problems have emphasized the inadequacy of present knowledge for the rational design for fire safety of large buildings in the future. A number of other significant gaps might well have been identified. For example, the propensity for fire to spread, both in corridors and in large occupied spaces, is regarded as a critical aspect of fire safety. Codes attempt to exercise some control through regulation of flame spread characteristics of lining materials. Basic information is, however, lacking on the various factors influencing the rate of propagation of fire, including flammability of surface coverings. Until this and other knowledge becomes more adequate, a highly regulated and sometimes arbitrary approach to fire safety will continue. Some new materials, systems and design concepts may be unduly restricted, in some instances, while in others their introduction may result in an excessively hazardous condition.

To change this situation, fire research must be increased and design for fire protection must be developed as a special discipline. As this becomes a reality consideration of fire safety will become an integral part of the design process, related to activities to be accommodated and to space relationships. Building fire regulations will be increasingly expressed in terms of objectives or performance to be met, rather than in terms of descriptive specifications, and more responsibility for safety will be shifted to the professional designers. Building operation and management will become a more important component of safety, as buildings become larger and more complex and will involve education of occupants in regard to dangers and procedures in case of an emergency. Detection systems will become more sophisticated and there will be increased use of automatic means of extinguishment and confinement of fire and of smoke control. Very large buildings may have their own internal fire service co-ordinated with that of the municipality.

Safety objectives will become more clearly defined and alternative means of achieving the objectives will be considered, taking into account the interrelation of the various elements involved. It will then be possible to consider the appropriate level of safety in relation to the value of building and contents, as well as in relation to life safety. □

Reference

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