Performance Design of Low-rise Sprinklered Shopping Centers for Fire Safety

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ABSTRACT: Shopping center buildings are complicated buildings which may not be able to be cost-effectively designed to the deemed-to-satisfy provisions of the building regulations. An extensive research project, which looked at most aspects of fire safety in shopping centers, has been undertaken in Australia under the direction of the Fire Code Reform Centre. The outcomes from this project have been used to develop a more rational performance-based design approach. Findings from the research project and aspects of the design approach are presented. The paper only addresses low-rise, sprinklered shopping center buildings with four stories or less above ground.

KEY WORDS: fire safety, fire tests, performance design, shopping centers, sprinklers

INTRODUCTION

THE CONSTRUCTION AND extension of large shopping centers is an area of commercial development which is being pursued actively in Australia. There is a belief that some aspects of the current *deemed-to-satisfy* provisions for these buildings may be unnecessarily onerous, imposing unnecessary financial burdens on developers and owners and which do not relate to the risk-to-life from fire in these buildings. Furthermore, it is recognized that it is extremely difficult to design aspects of these buildings to deemed-to-satisfy provisions.

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A two-year intensive research project was conducted to study all significant aspects relating to fire safety in shopping centers. The project was conducted under the guidance of the Fire Code Reform Center (FCRC) – a now defunct organization set up within Australia to evaluate the provisions of the Building Code of Australia (BCA) and to develop tools and information relevant to the performance-based design of buildings. The purpose of this particular project was to review the requirements in the Building Code of Australia (BCA) [1] which apply to low-rise sprinklered shopping centers and to propose a more rational set of fire-safety requirements to improve the cost effectiveness of these buildings (both in terms of construction costs and maintenance in operation) while maintaining the current high levels of fire safety.

A set of reports [2–8] which describe the various aspects of the research work have been published. The final report [9], also published as an FCRC document, summarizes the research and systematically evaluates fire-safety aspects of shopping center buildings making recommendations for the design of such buildings. Since that time, further evaluation and testing have been conducted and the design principles and procedures given in the above publications have been extended in light of new information. The design principles and procedures have taken into account the methodologies and fire-safety system structure given in the Fire Engineering Guidelines [10] prepared by FCRC and endorsed by the Australian Building Codes Board.

It is important to note that shopping center buildings are examples of buildings for which there are strong economic motives to avoid a significant fire, and management practices within these buildings are often conducive to achieving this outcome. Examples of these practices are:

Avoiding fire starts

- house-keeping audits
- audits of electrical cabinets (e.g., infrared evaluation)
- residual current protection
- regular replacement of old electrical (light) installations
- maintenance of electrical equipment

Minimizing fire size

- camera surveillance within center (security)
- fire awareness and fire-fighting training for all staff
- sprinkler management policies

None of the above factors are considered in building codes or regulations, yet it is possible that these may have a bigger impact on fire safety than the specific matters addressed by the regulations. In reality, the fire safety of these buildings is a complex function of building management, the reliability of systems, occupant behavior, smoke management, building layout, fire-fighting facilities and personnel, and the behavior of the building structure.

METHOD OF APPROACH

The method of approach adopted in the above-mentioned research project (Project 6) was broken down into the parts listed below. Reports dealing specifically with some of these parts have been published and are referenced below; where parts are not referenced they are dealt with in the final report [9] for the project.

- Understand current regulatory requirements [2].
- Undertake an in-depth survey and study of current shopping centers [3].
- Identify the key issues and objectives of the project [4].
- Collect and analyze published accounts of fires in retail buildings [5].
- Obtain and review fire statistics for USA and Australian buildings [6].
- Undertake fire tests to better understand fire characteristics [7].
- Determine the effectiveness (i.e., efficacy and reliability) of sprinkler and smoke exhaust/venting systems [8] based on historical data and fault tree analysis.
- Determine the various fire scenarios that can occur in shopping centers and their probability of occurrence given a fire start and the various fire-safety systems.
- Understand the behavior of occupants in building both with respect to fire fighting and evacuation.
- Study the impact of smoke, associated with the range of fire scenarios, on the occupants of the building taking into account smoke exhaust and venting, building geometry, occupant behavior and types and positions of exits.
- Study the role of the building structure in providing fire safety and determine the fire resistance levels required for the various parts of the building, taking into account the range of fire scenarios.
- Evaluate other Building Code of Australia requirements relating to aspects of building construction – doors, mixed occupancy parts of buildings, the presence of atria.
- Understand the role and impact of the fire brigade in relation to each fire scenario.
- Determine conclusions and recommendations based on the above parts of the research project.

RESEARCH ACTIVITIES AND KEY FINDINGS

Some of the key findings from the project are now described. A much fuller description is given elsewhere [9].

Fire Incidents – Historical data

A detailed report giving an analysis of the available case studies has been published [5]. In that study, 97 accounts of fires in retail buildings were considered. Generally, the fires reported in the literature were larger fires, as these are more "newsworthy" than smaller fires that have been easily extinguished. The analysis of the case studies revealed a number of apparent trends, although caution should be exercised in drawing general conclusions due to the limited data. The following observations can be made:

- In the majority of situations fires only developed to a significant size if the fire was initiated in unpopulated areas (e.g., storage areas or ceiling spaces) or when the building was unoccupied. It appears that very few fires were allowed to develop in areas which were directly observable by the occupants.
- In a few situations, combustible ceiling tiles led to rapid fire spread across the enclosure leading to a serious fire-safety scenario.
- A major mechanism of fire spread to other parts of the building appears to have been through the ceiling space – irrespective of whether there were combustibles in the ceiling space. There were many situations where the ceiling space was not sprinklered and where the building was not sprinklered.
- Other cases were noted where the building was essentially sprinklered throughout but where combustibles or combustible construction within parts of the building (e.g., ceiling space construction or combustibles associated with verandas and awnings) allowed a significant fire to develop such that the sprinklers were overwhelmed and were not able to adequately control the fire.
- It appears that fires that were able to be extinguished rapidly by the fire brigade tended to be small. For this to be the case, the brigade had to have arrived and located the fire in a short period of time or the fire had to be kept small due to the action of the occupants or the sprinkler system. In other cases where there were walls giving fire separation (these may not have been required fire-resistant walls) or partial sprinklering, the brigade was able to confine the fire to an area such as the shop of fire origin. Otherwise, for the cases reviewed, the extent of flame spread was very large and significant parts of the center were destroyed.

Fire Statistics

Fatalities

The incidence of fire deaths in retail premises in Australia is very small, and it is assumed here that the broad conclusions drawn from an analysis of the much larger USA database would be valid for Australian shopping centers. This assumption is borne out by a recent analysis of the statistics for fires in retail premises for New South Wales. The following remarks relate to all fatal fires in USA retail premises recorded in the NFIRS database.

There have been 86 deaths in 77,996 retail fires over 10 years in the USA. The nature of these deaths in retail fires has been assessed and it appears that about ten of the victims were asleep at the time of alarm, about twenty were likely to have been asleep and about six more could have been asleep at the time. Of the remainder, abut seven appear likely to have been involved in incendiary fires, another seven in suspicious fires – in some cases possibly involved in starting the fires or possibly subject to the attack themselves. It appears that fires in or from cars might have resulted in a further two of the fatalities and that a further twelve of the victims were bedridden, too young to act or too old to act, this contributing to their death. It appears that a further sixteen of the victims might have been intimately involved in the ignition (but not in an incendiary or suspicious manner).

Thus, in these retail buildings it appears that well over one third of the fatalities might have been asleep at the time of ignition, a further one sixth "impaired" in some way (bedridden, too young, too old) resulting in over half of the victims likely to have been unable to respond to the fire. This outcome might seem surprising but the retail statistics refer not just to "shopping center" buildings but also to retail buildings that have associated sleeping accommodation (e.g., shop with living area at the rear or over the top). The deaths may also include persons (e.g., security staff) who were asleep at the time of the fire. A further one third might have died as a result of having been intimately involved in the ignition (not necessarily in an incendiary or suspicious manner). Thus it appears that over two thirds of the fatalities might have resulted from circumstances and involvement such that the behavior, age or condition of the person was a significant contributing factor in their death in the fire.

It is clear, both from the USA data and from the rather more limited data from Australia, that retail premises do not present a significant risk to life from fire. The USA retail data shows that the average fatality rate for civilians (as opposed to fire fighters) is 1.12 deaths per 1000 fires, which may be compared with the figure for residential apartments, from the same source, of 7.4 civilian fatalities per 1000 fires. There is a general trend, as might be expected, for the numbers of civilian deaths and injuries to increase with size of the fire. In fact it is shown in the analysis given in Reference [6] that if, by some means, all fires could be confined to the object first ignited, the civilian fatality rate would probably fall by a factor of nine.

Fire Spread

The USA statistics record the extent of flame damage in the following categories:

- confined to object of origin
- confined to part of room or area of fire origin
- confined to room of fire origin
- confined to fire-rated compartment of fire origin
- confined to floor of fire origin
- confined to structure of origin
- extended beyond structure of fire origin

Where flame damage was recorded, the largest category of fires, 47%, are those confined to the object of fire origin: 80% of fires were confined to the room of fire origin. From the NSW data, the comparable figure for the latter is 78%. Very few fires which spread beyond the room of fire origin are *confined* to the compartment of fire origin. Only 3% of fires where flame damage is recorded spread beyond the structure of fire origin.

Time of Day

More fires occur in the day than at night. However, the statistics show that daytime fires have a much greater chance of being confined to the object of origin and room of fire origin, while night-time fires have a greater chance of becoming large. In parallel, the rate of civilian deaths in fire is greater at night, but the rate of injuries is greater in the day. It must be understood that recorded injuries can be anything from minor smoke irritation to severe burns.

Fire Tests

In designing shopping centers for fire safety, it is essential to have some understanding of the characteristics of fires that may occur in these buildings, and because of the paucity of relevant tests, it was considered essential to conduct a series of fire tests that would provide such data. The results of the tests are reported in detail in Reference [7] and a videotape is available.

Eleven full-scale fire tests were conducted to investigate the effects of fires in specialty shops and major stores in a shopping center. Two tests were conducted to simulate a fire in a toy store (Figures 1 and 2) and two to

Figure 1. *Sprinklered toy shop fire test.*

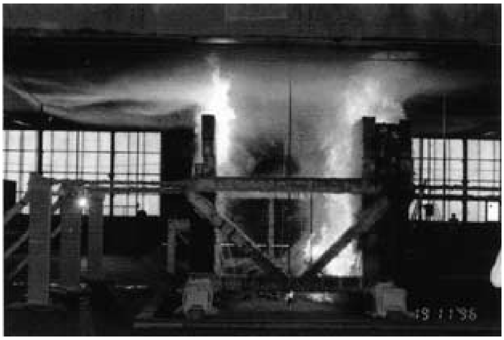


Figure 2. *Unsprinklered toy shop fire test.*

simulate fire in the storage area of a shoe shop. These situations were chosen because they were considered to be representative of worst-case scenarios as they involved substantially plastic material stored in a shelved arrangement. The presence of shelving means that the fire is likely to grow more rapidly and that it may interfere with the application of water to the seat of the fire, in the case of the sprinklered situations. Both sprinklered and unsprinklered situations were considered. Again, the unsprinklered tests were considered to be representative of the fastest growing fires due to the type and arrangement of combustibles. The unsprinklered fire involving two racks of toys grew at a rate faster than an "ultrafast" fire and peaked at an estimated 25 MW. The fire was started at the bottom of one rack and developed upwards spreading to the adjacent rack after about three minutes. Had there been more fuel available (which would be the case in practice), the peak heat release rate would have been much greater. The sprinklered test of the same situation illustrated the ability of sprinklers to limit the rate of fire growth and resultant severity. The unsprinklered tests involving two racks of shoes and boxes was a slow developing fire but eventually reached about 40 MW. The sprinklered test of the same situation demonstrated the importance of checking that the sprinkler system can adequately deal with the particular situation under consideration.

In the case of the sprinklered tests, the smoke remained buoyant away from the area of fire origin and it was possible to remain below the smoke layer. The quantity and density of smoke was very much less than that associated with the unsprinklered fires.

A series of five sprinklered fire tests was conducted to look at the smoke generated during sprinklered fires in clothing stores. This was considered important as clothing and the like constitute a high proportion of the floor area of a modern shopping center. The tests on a simulated clothing store were conducted to obtain activation times for both normal response, fast response, and concealed sprinkler heads. Fire development was fast but the lower ceilings resulted in faster sprinkler operation. Activation times (as measured from the start of the fire) varied from 63 s to several minutes for the concealed heads. Sprinkler suppression was very effective but the fire reignited once the sprinklers were turned off.

Finally, two sprinklered tests were conducted to investigate the smoke generated in a sprinklered bookshop/newsagent fire. These tests were conducted to study the amount of smoke developed where there were predominantly cellulosic combustibles. In the case of the bookstore tests, fire development was much slower. Sprinkler suppression was very effective even though the fire was significantly shielded from the sprinkler spray by the shelf construction.

None of the specialty shop sprinklered tests resulted in smoke outside of the enclosure that would have presented a threat to occupants outside of the shop within the mall.

The testing demonstrated the likely serious consequences (toxic smoke and heat) associated with major unsprinklered fires in shopping center buildings. It is therefore of paramount importance that designers seek to eliminate the possibility of such fires through appropriate design and management.

Sprinkler Effectiveness

Sprinklers have an essential role to play for both life safety and property protection. The benefits of a functioning sprinkler system have been demonstrated from the fire tests conducted as part of the project and the difference in the size of fires associated with the sprinklered and unsprinklered situations. The anecdotal evidence presented by the case studies testifies to the value of sprinkler systems in providing life safety and property protection, as does the statistical evidence given in Reference [6].

In discussing sprinkler effectiveness, it is helpful to consider two other terms – *efficacy* and *reliability*. These terms are each represented numerically by a number between 0 and 1. Sprinkler *efficacy* is defined here as the ability of the sprinkler system to function in accordance with AS 2118 [11] assuming that the system has activated. This is the definition of efficacy adopted in this paper but other definitions have been used [12]. Sprinkler *reliability*, on the other hand, is concerned with whether the system will activate (deliver water) and takes into account such matters as isolation of the system and failure of the water supply.

Sprinkler *effectiveness* is defined as:

$$effectiveness = reliability \times efficacy$$

Statistical data from fire incident returns provide one basis for gauging the reliability and efficacy of sprinkler systems. However, this data gives a historical overview which will include the effects of past practices and regulations – and therefore should not be assumed to necessarily apply to modern shopping centers with improved design and management practices.

Efficacy

The efficacy of a sprinkler system in *controlling* a fire is a function of many factors, including the type and arrangement of fuel, the type and arrangement of sprinkler heads, the design-delivery rate, and the absence of partial sprinklering.

The sprinkler system required for shopping center buildings is an ORDINARY HAZARD III (OH III) system [11] and the sprinkler spacing and water delivery rates are considered to give a high level of protection to retail buildings. Recent trends with high shelving within stores and a greater presence of plastic materials – giving a faster rate of fire growth and greater shielding of the fire from water – has raised concerns as to the adequacy of an OH III system to control some fires. High shelving manifests itself in toy stores, shoe storage areas, and some major stores including variety stores and supermarkets. Furthermore, the spacing between shelves may be substantially less than the sprinkler head spacing and the heads may be positioned well away from the location of a fire.

Fire tests described previously considered two of these situations. In one of these tests, it was recognized that the location of sprinkler heads was inadequate given the height and nature of the combustibles. Better positioning of the heads would have resulted in rapid control of the fire. Therefore, in the case of high fire load areas such as shoe storage, where combustibles are stored in racks that will interfere significantly with the application of water to the fire, sprinkler heads should be relocated or added to ensure that heads are located between the racks. In-rack sprinklers would be effective but are very often not practical. The development of a sprinkler system giving faster response for racking fires (at least those associated with typical retail rack situations) but without the intrusiveness of a traditional in-rack system, would be beneficial.

There is little value in incorporating a sprinkler system into a building if it is not commensurate with the hazard. Sprinklers must be designed and the placement and location of combustibles managed so that the efficacy of the sprinkler system is high.

Reliability

The reliability of a sprinkler system depends very much on how it is managed with respect to modifications taking place within the building. The system must be managed to minimize the amount of time that the sprinkler system is taken out of service, and additional precautions taken when this occurs.

Based on a statistical analysis, the current average reliability for sprinklered retail buildings in NSW (typical of Australian buildings) is 98%. The corresponding value for the USA is 93.5%. However, if the sprinkler system is soundly managed, the following average values of reliability can be adopted:

Sprinkler zones associated with specialty shops	98.5%
Sprinkler zones associated with major stores	99.5%

These estimates of reliability were determined on the basis of fault tree analysis that took into account the various uncertainties associated with sprinkler systems within shopping center complexes. Provided the systems are properly commissioned, then the major sources of uncertainty are associated with failure of the water supply or that the system has been isolated to allow tenancy upgrade and refurbishment. Data on the frequency and duration of sprinkler isolations was obtained from shopping center records [3]. These values of reliability assume that there are *separate sprinkler zones for major stores and specialty shop areas*. Sound management of the sprinkler system includes a number of requirements which are given in Reference [9]. The use of monitored valves will support sound management as notification of isolation is required and time of reinstatement just prior to the event.

Occupant Behavior and Response

Detection and Fire Fighting

The occupants of the building have an important role to play with respect to both fire detection and fire fighting. Statistical data shows that it is much more likely that fires will spread beyond the area of fire origin during the night than the day. This fact suggests that there is a much greater likelihood of a fire being detected when people are present in the building. Generally, the more people throughout a building, the greater the likelihood of detection, and of the fire being extinguished while it is small. It follows that increased surveillance of ‘‘higher risk’’ areas such as storage areas in an option for further improving fire safety. The provision of extinguishers throughout these buildings, and associated staff training is important.

Evacuation Behavior

The time for evacuation of the occupants from a particular part of a shopping center building may be taken as:

$$t_e = t_{pm} + t_m$$

where t_{pm} is the premovement time and includes all of the events required to make the decision to evacuate, and t_m is the movement time for the occupants to move to a safe place. This movement time is a function of the choice of exit, the speed of travel and the number of people queuing at the exits. The premovement time is found to be a function of many factors including the intensity of cues (the quantity and density of smoke) and instructions and visible presence from shopping center staff. Alarms were not found to be effective in getting people to evacuate. If a severe fire developed, then people closest to the fire would move much more quickly than if the fire is nonthreatening.

It was found that the occupants will generally try to evacuate using the normal access and egress paths. Fire-isolated stairs within major stores will only be used if there is no other exit choice and fire-isolated passages from the mall are unlikely to be used at all.

Fire Scenarios

Fires can be conveniently grouped into 3 broad classes according to their size:

C1 – fires which are kept small without the presence of sprinklers.
C2 – fires controlled by the presence of sprinklers.
C3 – fires which are typically more severe than C1 and C2.

Reference [9] discusses in detail the nature of each class of fire. Suffice to say, the vast majority of fires will be C1 fires, a small percentage C2 fires, and an extremely small percentage, C3 fires. It is recommended that shopping centers be primarily designed for C2 fires, but that the impact of a C3 fire needs to be considered.

The same fire scenarios should be used when assessing each of the fire-safety systems. Subsequent analysis has demonstrated that it is extremely difficult to design a shopping center for any substantial C3 fire. It is therefore recommended [9,13] that although such fires are to be considered, the risk level associated with such fires needs to be lowered by reducing the *probability of occurrence* of such fires. This is achieved through the application of risk management procedures to fire safety as well as appropriate attention to design aspects.

Smoke Management

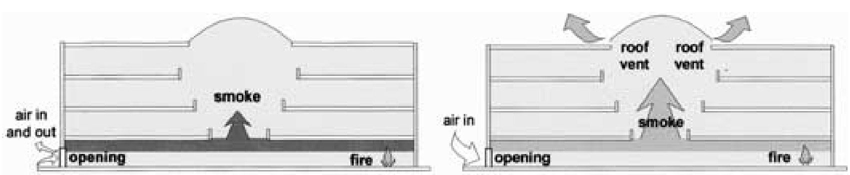
It is known that a primary cause of death in fire is exposure to the products of combustion – smoke. In the event of a fire, because it is hotter than air, smoke will rise and move through a building including enclosures and pathways used by the occupants – thereby putting them at risk. Smoke management, when understood in the broadest sense, is concerned with managing smoke within the building such that the likelihood of exposure of the occupants to *debilitating smoke* is minimized. This means that both smoke control and evacuation of the occupants are key components of the smoke management system. Strategies for achieving these objectives include:

- keeping the fire small – small fires generate small quantities of smoke.
- providing adequate exit paths and evacuation strategies – to quickly move people away from the smoke affected areas.
- providing sufficient smoke reservoirs – allow the smoke to accumulate above the occupants so as not to envelop them too quickly (or even at all).
- providing adequate venting/extraction where appropriate – removing smoke from the building and away from the occupants.

Modern shopping centers contain large open spaces and this is beneficial from a life safety viewpoint as it means that the occupants can move away from a fire and that such buildings would appear to have a significant capacity to absorb smoke. This is particularly the case with the malls associated with larger centers. Access to the various levels of these buildings is provided at a number of points – from adjacent carpark levels or streets, or from another level within the mall by means of escalators or open stairs. In the event of a fire emergency, the usual means of access and egress are the means of egress that will be used by the occupants – rather than emergency exits connected to tunnels leading to other parts of the building or to outside.

Detailed recommendations with respect to smoke control and design of evacuation are given in Reference [13]. In that publication particular conditions are set out whereby the mall and adjacent carparks can be regarded as "safe-places". This is important as, in the event of a fire, the mall will provide a *natural haven* for people seeking to move away from the fire. These parts are to be designed to remain tenable such that they do not present a threat to the occupants. However, before considering how this might best be achieved in a mall situation it is helpful to consider some findings with respect to the movement of smoke through horizontal openings as will be found in a mall. The situation shown below (Figure 3(a)) represents a four story mall where openings are provided in the floors.

However, at his stage, no roof vents are provided. The diagram also shows an opening to outside on the lowest level through which air can be drawn and smoke vented. There are no other openings to the outside. Given a fire on the lowest level, the height of the smoke will be largely controlled by the area and height of the vent to the outside. If there was no vent to the outside, then the height of the smoke is dependent on the size of the reservoir for a given size fire. It is interesting to note that the presence of the floor opening has little influence on the level of smoke in the lower level. Eventually, however, smoke migrates upward to the other levels and, depending on the size of the fire, those levels will progressively fill with smoke. The lowest level will initially have the densest smoke. A vent in the roof is now introduced (Figure 3(b)) and this greatly accelerates the movement of smoke to the upper levels and in time affects the level of smoke in the lowest level – but not initially. As the smoke flows upwards through the holes, most of it passes through the vent to the outside. However, as the smoke passes the edges of the holes, it spills into these upper levels and is mixed, resulting in the smoke not being well layered in these upper levels. This is illustrated by the model test shown in Figure 4. Once again, the lowest level has the densest smoke while the upper levels have progressively less smoke. The amount of smoke entering these levels is dependent on the size of the roof vent and the size of the fire. The provision of baffles around



(a) ***(b)***

Figure 3. *Smoke movement in 4 storey mall.*

Figure 4. *Model Test.*

the floor and roof openings may not resolve this problem of mixing; nor will the use of roof fans.

These findings are very significant as they illustrate that if tenable conditions are to be maintained within the mall then the smoke entering the mall must be significantly restricted. This is despite the potentially significant reservoirs provided by the mall areas. Thus, particular attention must be paid to minimizing the size of any fire through appropriate sprinkler design and management of these systems. Containment or extraction of smoke within a specialty shop or major store through wall and ceiling construction will also be beneficial but this will only be effective if the size of the fire is kept relatively small (e.g. $< 5\,\text{MW}$). This does not necessarily require elements with high levels of fire resistance, since it is the openings from the store that allow smoke to move outside and fires of the above size are unlikely to threaten the adequacy of even minimal construction. Extraction from within a major store will also be beneficial.

Building Structure

Provided the building has a soundly managed sprinkler system and the risks are well managed, it is appropriate to only assess the building structure for exposure to C2 fires. Sprinklered fires will have little impact on the structure as evidenced by the results of the sprinklered fire tests reported above. Even a C3 fire will have a greater impact on the occupants of the building than on the building structure.

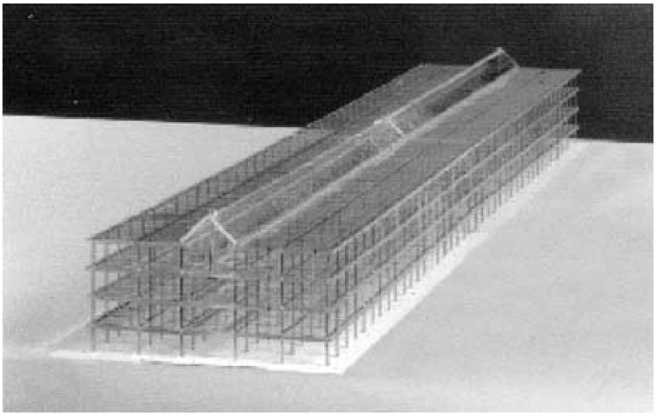


Figure 5. *Model of part of a four story shopping center building.*

This is because the smoke from such a fire will have a *global* impact on the building while the structure will only be affected *locally*. That this is so can also be realized from the model building shown in Figure 5 which illustrates the large number of structural members associated with such buildings. It is now recognized that parts of buildings exposed to local fires will behave much better than expected from individual member behavior. This is due to the redistribution of load and the mobilization of other mechanisms of load resistance. Assuming the presence of a C3 fire, floors (including beams) should have sufficient fire resistance to allow direct movement of the occupants within the fire level and those directly supported by the floor above the fire into a mall, carpark, street, or into a stair shaft, as the case my be. The fire resistance required for a floor will generally be less than that required for a column as it is only necessary to allow for movement of the occupants on the floor directly above the fire and on the fire floor.

In a well managed building, References [9] and [13] recommend levels of fire resistance which are much lower than current requirements (180 min); namely: unprotected steel beams in all levels (provided the exposed surface area-to-mass ratio is less than a limiting value), and similarly, unprotected steel columns for the two upper levels. Columns in the lowest levels (unless carparks) are required to have a fire resistance of 60 min.

DESIGN AND MANAGEMENT FOR FIRE SAFETY

Any performance-based design will be based on a number of assumptions and these must be underpinned by appropriate risk management. The design process should allow these assumptions to be identified and communicated to management and the owner. The fire engineer should be involved in the development of risk management plans for the building and in reviewing the implementation of these plans.

The incorporation of large openings within the floors and walls to allow openness and movement throughout modern shopping centers results in a breakdown of any real form of compartmentation in relation to major non-sprinklered fires. The need to avoid such fires has become clear and this has been achieved historically by the incorporation of sprinklers within the building. Accordingly, the fire engineer will design the smoke control systems within a sprinklered shopping center building for sprinklered fires or relatively small nonsprinklered fires in high roof areas where sprinklers may not be provided or may not activate. Little thought is given to the possibility of a major nonsprinklered fire and the associated consequences. On the other hand, the structural elements associated with these buildings are usually required to resist major fires since high levels of fire resistance are specified.

The research project described in this paper demonstrated several things:

- major fires are *possible* due to the quantity, type and distribution of combustibles and given the uncertainties associated with sprinkler systems
- major fires are unstable and may continue to grow and could become very severe
- it is extremely difficult to design smoke control systems for major fires
- sprinkler systems have an effectiveness of less than 1.0
- sprinkler systems effectiveness is a function of design and management

Accordingly the performance-design approach developed in Reference [13] and briefly described in this paper is based on a risk management approach. It recognizes that the risk level associated with a possible fire event is represented by:

$$\text{risk level} = \text{likelihood of event} \times \text{consequences}$$

Thus, rare events with major consequences may result in significant levels of risk. However, it is an accepted principle of risk management that it is better to substantially reduce the probability of occurrence of events with major consequences than try to design for these events. It follows that it is better to *seek* to eliminate the possibility of occurrence of a severe fire (with major consequences) than attempt to design a shopping centre building for fire safety when exposed to such a fire. This approach demands that fire-safety systems such as sprinkler systems be designed and managed to maximize their effectiveness. Sprinkler systems need to be designed to be commensu-

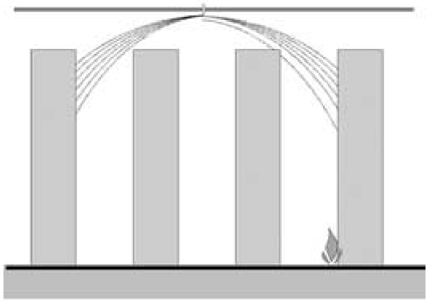


Figure 6. *Potential shielding.*

rate with the hazards encountered in modern shopping centers with their use of racking of various heights and spacing. The effect of potential shielding needs to be considered (see Figure 6) as does the height of sprinklers above the combustibles.

Sprinkler systems throughout the building must be managed to minimize the time that systems are isolated and to guard against poor work practices. A risk management approach requires that all aspects of shopping center buildings relating to potential fire starts or potential fire development be subject to risk management procedures. This is already being done in many shopping centers and is driven by property protection concerns and the recognition that fires can be commercially disastrous. Thus, the practices listed in the introduction to this paper – auditing of combustibles and electrical installations, upgrading and regular maintenance of electrical equipment, etc., occur in many centers to varying degrees. Similarly, fire awareness and fire fighting training is common and surveillance personnel are trained to have an understanding of fire starts. The important aspects of a risk management plan are given in Reference [13].

CONCLUSIONS

This paper only applies to sprinklered, low-rise (stories above ground of less than four) shopping centers.

Modern shopping centers are complex buildings for which it is sometimes difficult to satisfy the prescriptive deemed-to-satisfy provisions and achieve the desired functionality. Access between levels is important and this, combined with the desire to have buildings that are more open and connected, means that substantial openings are provided between levels. Traditional "compartmentation" therefore has little meaning and is unlikely to offer much assistance in containing the effects of a major fire. This, combined with the fact that these buildings contain massive quantities of combustibles, means that extremely severe fires could develop within these buildings. Such fires could have disastrous effect due to the associated smoke and heat.

The fire safety of these buildings must be addressed through the application of a rational fire-engineering approach. The study described in this paper has found that the achievement of high levels of fire safety will be almost totally dependent on limiting the fire size and providing alternative paths for occupants to move to safer places within the building. Although it can be argued that such a philosophy could be applied to every building, it is particularly critical with such buildings because of their size and interconnectedness. Current deemed-to-satisfy regulations are confused on this matter as they frequently allow smoke exhaust systems to be designed for relatively small fires but the structure (which is only affected locally) is required to have very high levels of fire resistance, suggesting a much more severe fire. The reality is that it will be impossible to design a smoke exhaust system for a major unsprinklered fire – yet testing undertaken as part of this research has illustrated the fact that such fires are quite possible.

The achievement of high levels of safety in these buildings is actually a risk management exercise where the objective could be taken as eliminating the occurrence of a major unsprinklered fire. This will be achieved through appropriate design and through proper management of the fire-safety systems. Therefore, fire-safety practitioners must have significant input into developing and maintaining appropriate management practices and procedures. Under these circumstances, it can be argued that the design fires appropriate to all fire-safety systems (including the building structure) should be sprinklered fires.

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